EXPLORING THE IMPACTS OF INTENSIFIED PINEAPPLE CULTIVATION ON SOIL HEALTH IN ‘OPUNOHU VALLEY, MO’OREA, FRENCH POLYNESIA

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Abstract. Island ecosystems suffer from limited resource availability and are threatened by intensified cultivation and land use. This study investigates the impacts of intensified pineapple cultivation on the island of Mo’orea, French Polynesia by assessing soil health in response to conventional and alternative farming regimes. Soil health was explored by comparing soil samples from four different field types at the ‘Opunohu Valley Agricultural School in ‘Opunohu Valley, Mo’orea, French Polynesia. Bulk soil samples were collected from four different pineapple fields, all being used for the same amount of time but managed with different agricultural practices: conventional fields (CF), diversified farming system fields (one with interspersed weeds (LIW DFS) and one without (LINW DFS)), and a non-agricultural (NAG) field located on the school’s property. Conventional fields were classified as any field being managed with herbicides, pesticides, or synthetic fertilizers. Diversified farming systems (DFS) fields were determined based on use of fallow periods, cover crops, incorporation of surrounding biodiversity, natural fences, and the use of natural additives. Non-agricultural samples were taken from an area that had not been used for any form of cultivation. Various soil science analyses were used to determine the overall health of soil: color, composition, pH, moisture content, nutrients availability (nitrogen, phosphorous, potassium), infiltration rate, aggregate stability, and loss on ignition as a proxy for available organic carbon. Differences in physical and chemical soil characteristics between samples collected from fields managed under different regimes suggests that different agricultural practices have different impacts on soil health. Additionally, samples collected from low-input non-weedy DFS presented a soil health that was most like non-agricultural samples, suggesting that environmentally friendly agricultural practices promote biodiversity conservation and support the movement towards sustainable farming.

Keywords: soil; soil health; agroecology; resource management; conventional farming; sustainable farming; diversified farming systems; Mo’orea; French Polynesia

INTRODUCTION

The Society Islands are one of five oceanic archipelagos that make up French Polynesia in the South Pacific. Of the 118 islands and atolls that compose this widely dispersed nation, only 67 are inhabited. Tahiti and Mo’orea, two of the largest islands within the Windward group of the Societies, are home to nearly 70% of the nation’s population (CIA 2018, Reavis 2018). The high island of Mo’orea is roughly 1.5 – 2.0 million years old, consisting of shield-stage basaltic lavas, with an annual temperature of 26°C and 1700mm of rainfall (Yamamoto et al. 2007). Volcanic soils, the product of basaltic lavas, cover 1% of the Earth’s surface and are mainly found in areas that fall near the Pacific rim, like that of Tahiti and Mo’orea (Neall 2009). Volcanic soils support nearly 10% of the world’s population,
including some of the highest population densities primarily due to their high natural fertility. However, unequal distribution of elements in volcanic parent material can impact the health of organisms that reside in these environments (Neall 2009).

Mo’orea’s natural soil composition can be broken down into two main classifications: ultisols and haplic ferralsols (International Soil Reference and Information Centre 2018). Ultisols are soils that are found and formed in human areas that are susceptible to intense weathering. According to the Soil Science Society of America, ultisols usually contain a small subsoil horizon that is acidic, has relatively low levels of fertility, and contains a relatively large amounts of translocated clay (Soil Science Society of America 2018). Ferralsols represent the ‘classic’, extremely weathered soils of the tropics. The International Soil Reference and Information Centre describes ferralsols as having good physical properties but are chemically poor. Soils of this classification supply limited nutrients (nitrogen, phosphorous, potassium) to organisms existing in these environments, but stable microstructures allow for high rates of permeability, which is beneficial for agricultural purposes (International Soil Reference and Information Center 2018).

Aside from the high influx of tourism, the Society’s main form of economy is fishing and agriculture. With only 12.5% of land within French Polynesia being used for agricultural purposes, intensification of farming and non-sustainable practices can be detrimental to surrounding ecosystems (CIA 2018). In French Polynesia, and in Mo’orea specifically, pineapple is one of highest yield crops (Slot 2015). In most agricultural settings, pineapple cultivation is dominated by conventional monocropping, with high levels of chemical additives, due to low levels of nutrients availability, weed management practices, and intensified crop production (Darnaudery et al. 2016). Roughly 54 hectares of ‘Opunohu Valley in Mo’orea are being used for pineapple cultivation, but the opening of the Rotui Juice Factory in 1980 created a need for year round intensified cultivation of pineapple (Slot 2015). In 2015, the Minister of Agriculture allocated an additional 4.3 hectares (ha) of land to the Mo’orea pineapple planters cooperative (COPAM) for a total of 58.3 ha of land exclusively used for pineapple cultivation, with a predicted annual production of 2,600 tons in total with the added land (Slot 2015). Pineapple is one of the most important crop plants grown on Mo’orea, making the cultivation and study of this species extremely important for the island. However, this intensified cultivation has the potential to greatly deplete, pollute, and erode the fragile soils found in tropical ecosystems (Darnaudery et al. 2016).

Soil and soil-based ecosystems are at greatest threat when faced with overproduction and intensified use of land for farming (Ravi 1991). Island ecosystems suffer greatly from limited resource availability, making sustainable agricultural practices quintessential to resource conservation and continual use of land management. Soil is an important and complex component of a thriving global ecosystem but is most susceptible to erosion, element loss, and other biological, geochemical, and anthropogenic processes that can strip it of its many unique properties (Pimentel et al. 1995). As over utilization of land resources increase, the stability, levels of available nutrients, and overall efficacy of the soil can greatly decline. Soil health is a term used in relation to sustainable agriculture to refer to “the general condition or quality of the soil resource” (Doran and Zeiss 2000). Soil quality is often used interchangeably with soil health but is deemed as a reductionist technique because it focuses heavily on soil condition with respect to abiotic indicators without considering potential biotic influences (Kibblewhite et al 2008). Alternatively, the integrated approach to determining soil health, specifically for this study, assumes that soil quality is more than the summation of a specific set of components, and that the interactions between different
properties and processes contribute holistically to the quality of the soil (Kibblewhite et al. 2008). Kibblewhite et al. (2008) suggests that soil responds to change as if it were a living system and defines soil health as an environment that has the capacity to produce food that can sufficiently support human subsistence and best conserves biodiversity.

Diversified farming systems (DFS) are agricultural alternatives to conventional methods of farming and aim to maintain or increase overall soil health and ecosystem services (Kremen et al. 2012). Kremen et al. (2012) writes that DFS are “agricultural practices and landscapes that intentionally include functional biodiversity at multiple spatial and/or temporal scales [to] maintain ecosystem services that provide critical inputs to agriculture, such as soil fertility, pest and disease control, water use efficiency, and pollination” (Bacon et al. 2012). DFS are studied at the plot, field, and landscape scale, looking at polycultures, genetic variations within species, mixed crop systems, natural or semi-natural communities of plants and animals, as well as natural fences, fallow fields and how these shape health and sustainability of agricultural systems (Bacon et al. 2012). These ecosystem-oriented farming practices provide natural supplemental nutrients, stability, and additives that are not as prominent in conventional agricultural practices. High-input farming systems can be detrimental to not only soil health, but water quality and biodiversity, making the switch to more sustainable farming practices extremely important (Kremen and Miles 2012).

The ‘Opunohu Valley Agricultural School in ‘Opunohu Valley, Mo’orea, French Polynesia has 8 hectares of land devoted to agricultural research and production, of which 2 hectares are exclusively used for year-round pineapple (Ananas cosmos) cultivation (Ellis 2018). The 2 ha of pineapple fields offer a unique opportunity for soil health to be studied, primarily due to the mix of diversified field system practices (natural fences, mulch) and conventional practices (pesticides, herbicides, chemical fertilizers) (Ellis 2018).

This study aims to evaluate the impact of intensified pineapple farming in conventional and diversified field systems on soil health at the ‘Opunohu Valley Agricultural School, in ‘Opunohu Valley, Mo’orea, French Polynesia. This study was divided into three main objectives to determine the impact of intensified agriculture on soil health: 1) Investigate how long-term pineapple cultivation alters soil health, 2) understand how soil health differs under conventional vs. low-input management regimes, and 3) explore how soil health differs between fields with and without interspersed weeds. Fundamental soil science knowledge suggests that: 1) Pineapple fields will be significantly nutrient deficient compared to natural environments, specifically in terms of N,P, K stability, infiltration rate, and moisture content, 2) low-input diversified field systems will have higher soil quality indicators than conventionally managed field systems, and 3) low-input weedy fields will have higher soil stability than low-input non-weedy and conventionally farmed fields, with similar stability and soil nutrients to natural areas. Soil science analysis will be conducted on four different field systems including two DFS fields, one with interspersed weeds and one without, one sample from a conventional field system, and one sample from a non-agricultural area as a baseline comparison for all other field types.

METHODS

Field Site

This study took place in ‘Opunohu Valley on the island of Mo’orea in French Polynesia. In particular, the ‘Opunohu Valley Agricultural School (‘OPVAS) was chosen for this field study because of its long-standing history of pineapple cultivation and land management practices. The ‘OPVAS first opened in 1968, with continual pineapple
cultivation occurring on the same fields for the past 50 years (Ellis 2018). The ‘Opunohu Valley Agricultural School in ‘Opunohu Valley has over 8 hectares of land devoted to agricultural studies, 2 hectares of which are exclusively used for year-round cultivation of pineapple (*Ananas cosmoss*) (Ellis 2018). Of the 2 hectares being used for pineapple cultivation, 1.5 hectares are used solely by the agricultural school, while the remaining land is rented to community groups. Pineapple cultivated on fields used by the ‘Opunohu Valley Agricultural School fall under the sub-category of low-input farming practices within diversified farming systems, avoiding pesticides, chemical fertilizers, weed control, and allow for fallow periods and the use of natural fences such as bananas (*Musa acuminata*), pomelos (*Citrus maxima*), or soursop (*Annona muricata*) (Ellis 2018). Conversely, pineapple cultivated in areas used by community groups are conventionally farmed, including pesticides, weeding, and use of chemical fertilizers.

**Sampling Methodology**

Four pineapple fields were chosen for study from the agricultural school based on background information provided by the Farming Director, Philippe Mahe. Each pineapple field was selected based on relative elevation, life stage of field, and overall use history. All fields were at relatively similar elevations, had been used continuously for pineapple cultivation over the past 50 years, and had all just been retiled after being worked for the past three years (Ellis 2018). Samples were collected from the following types: two DFS low-input fields, one with interspersed weeds (LIW) and one without interspersed weeds (LINW), one conventionally farmed

![Sampling units from various fields are also shown, both outlined for collection (red) and shown after collection was complete (yellow).](image-url)
field (CF), and one non-agricultural field (NAG), for a total of four fields. Field locations and size can be seen in Figure 1 (Google earth 2018). Once fields were selected and identified, an x-y coordinate system, with the x-axis running north to south and the y-axis running east to west, was used to determine points for random bulk soil sampling. Length and width measurements of each field were taken, and a random number generator was used to determine the x and y point of intersection. Once a coordinate was determined, samples were taken at the point of intersection, with the generated point always being the northeastern corner of each sampling unit. Following this procedure, 13 bulk soil samples were taken from each field, with each sampling unit being approximately 25cm (l) x 25 cm (w) x 20cm (d) in size. Bulk soil samples were collected in 4-liter plastic bags, transported back to UC Berkeley Gump Station, sorted and stored in the research facility’s soils lab. Each sample was given a unique sample identification number, weighed, and sorted into respective bags for further lab analysis (described below).

Soil Science Analysis

Physical and chemical indicators are extremely important in determining the soil health and overall quality of the area in question (Arias et al. 2005). To address the 3 objectives of this field study, six different soil science analyses were used to determine overall soil health and quality. Each sample from respective field sites were weighed, sorted, and conducted under the same environmental and lab conditions. Of the 13 samples collected from each field, only 10 will be used for in lab analysis, for a total of 40 individual samples.

Soil Composition and Color

Soil composition and color are two basic physical soil characteristics that can be indicative of soil health. The composition (parts soil to clay to loam) can impact the amount of available nutrients and can affect how stable or permeable the soil is to erosion and rainfall (Arias et al. 2005). A standard protocol adopted from Maher (2017) was used for each sample to determine color and composition. Soil composition flow chart used can be found in Appendix A.

For soil composition, approximately 25 grams of room temperature, air-dried soil was taken from each sample and held in the palm of the hand. Water was added via pipette to break down all soil aggregates. A soil composition flowchart was used to determine whether soil taken from the agriculture school was composed of various proportions of loam, clay, and sand (Maher 2017). To determine an accurate color, both wet and dry soils were compared to Munsell Soil Color Charts (2013 revision washable edition). Soil samples were individually placed under the Munsell book pages and color was recorded (Kirch 2016).

Moisture Content

Moisture content and moisture availability can greatly alter physical properties of soil. Standard protocol from Department of Sustainable Natural Resources (Craze 1990) was used to determine soil moisture content of samples taken from various fields. Each sample was weighed to approximately 45 g. Samples were placed in the Quincy Lab Model 40 GC oven at 40 °C for 40 hours before being cooled and weighed. Moisture content was then calculated by taking it as a percentage of its oven-dried soil weight (Craze 1990). The following equation was used to calculate the moisture content percentage:

\[
MC\% = \frac{W_2 - W_3}{W_3 - W_1} \times 100
\]

\(W_1 = \) weight of tin (g)
\(W_2 = \) weight of moist soil + tin (g)
\(W_3 = \) weight of dried soil + tin (g)

pH
pH affects the solubility of minerals in soil, free nutrients for plant uptake, and biodiversity of other plants and microorganisms living in the substrate (Arias et al. 2005). High acidity and alkalinity can indicate nutrients availability and environmental conditions but can also be heavily impacted by intensified cultivation (Kibblewhite et al. 2008). A standard protocol for testing pH compiled by Murray (2011) was used to test the pH of soil samples collected for this study. Dried soil samples were ground with a mortar and pestle, then sieved through a 2mm geological sieve. Approximately 10g of soil were added to beakers with 50ml of deionized water and mixed with a glass rod until soil is fully saturated (Vacca 2017). Soil and water mixtures were left to sit for 30 min before being tested. Calibration of the pH meter was done with a 7.0 buffer and 4.01 buffer, rinsing the probe with deionized water after using each buffer. The pH probe was added to the supernatant of each soil sample and stirred gently for 60 seconds before recording the pH value and temperature. Probes were rinsed before each sample, recalibrated at the end of each set of samples. Each sample being tested a total of three times to get an average reading.

NPK Availability

Crops typically grown in the South Pacific are heavily depleted of nutrients (Asghar et al. 1986). Initially low concentration levels of available nutrients in parent material can set precedence for available nitrogen, phosphorous, and potassium found in later forms of soil. Agriculture and intensified cultivation heavily impact nutrients presence by fixing or stripping certain elements from the soil (Kansas State University 2013a). NPK Soil Kit 3-5880 was used to determine presence levels of nitrates, phosphorous, and potassium in collected samples (LaMotte 2005). A soil extract consisting of 30ml of deionized water, 5g of soil, and 2 Floc-Ex tablets, was created to determine nutrients presence. Individual nitrate, phosphorous, and potassium solutions were then made from the primary extract, and color saturation was then compared the NPK LaMotte color chart. Nutrients availability was divided into high, medium, and low presence levels, with a range of 0 – 100 ppm (Kansas State University 2013a). A range was recorded for each sample and an average was taken for each field.

Exact ppm values could not be calculated under given conditions, but average ppm values were assigned to samples based on given range. Color chart used to determine classification and ppm ranges associated with assigned classification can be found in Appendix A.

Loss on Ignition

Individual field production and health tend to be higher with higher levels of available organic carbon in soil (Heiri et al. 2001). Higher organic carbon levels lead to better soil structure and stability, creating an ideal environment for crop production (Cornell University 2016). Loss on ignition (LOI) is a commonly used method to estimate organic material which can be used as a proxy to determine available carbon levels in collected soil samples (Heiri et al. 1999). The LOI process consists of two main reactions: the first reaction oxidizes all organic matter, while the, in the second reaction, carbon dioxide is evolved from carbonate, leaving oxide (Heiri et al. 1999). Sub-samples collected from multiple fields will be subjected to loss on ignition according to procedure described by Dean (1974) to determine the amount of organic material. Approximately 5g of soil was sieved, added to porcelain crucibles, and dried in the oven at 100° C overnight. Samples were then weighed, to determine oven-dried weight, and then placed in a desiccator to prevent any weight gain. Samples were then added to a pre-heated oven set to 560° C for one hour before being placed in a desiccator to cool for 30 minutes (Kirch 2016). After reaching room temperature, crucibles were weighed to obtain
a final weight, from which the percentage of available carbon lost was calculated.

**Soil Aggregate Stability**

Soil aggregates consist of many soil particles bound together that are usually formed by bioturbation and interactions between soil biota and the surrounding plant communities. Soil aggregates and aggregate stability plays a major role in the movement and storage of water, erosion prevention, root development, and crop growth (Arias et al. 2005). A slake test (aggregate stability test) was employed to determine the level of vulnerability that each soil sample had to destructive forces, such as rainfall (Arias et al. 2005). A combination of protocols from Almajmaie (2016) and the National Resources Conservation Services (2001) were used to determine aggregate stability. Samples for aggregate stability were taken from bulk samples, kept indoors under low-lighting for approximately a week before being tested. Aggregate stability was determined via 3 rounds of wet sieving, where 50g of soil were placed in a 250 µm sieve within a shallow tray filled with distilled water. The sieve was then slowly immersed and mechanically raised and lowered for approximately 3 minutes, with 36 dipping cycles per minute. Aggregate stability was then calculated by comparing the amount of aggregates retained on the sieve to a standardized coverage chart (NRCS 2001, Borthwick 2015). Percent coverage chart can be found in Appendix A. The higher the percent coverage after each 60 second interval, the higher the aggregate stability of the sample being tested.

**Infiltration Rate**

Infiltration rate of soil is greatly impacted by changes in land management, soil use, bioturbation, and availability of organic matter (Arias et al. 2005). Soil texture, type, and stability can all impact the permeability of soil to rainfall and irrigation and can change fertility in agricultural fields. Protocol from Kansas State University: Horticulture and Natural Resources (2013b) was used to determine infiltration rate for collected samples. To test for infiltration rate, a medium sized funnel was placed on top of a 200ml graduated cylinder. Filter paper was placed into the funnel, followed by 50g of air-dried soil. Approximately 30ml of distilled water was poured over the funnel, recording the time, from start to finish, that all the water took to filter through the sample. An additional 30ml of water was added, for a total of 60ml, and time taken for water to filter through the sample was recorded. Relative times for infiltration are recoded and then ranked and averaged to determine the infiltration rate of the sample.

**Statistical Analyses**

All statistical analyses were performed using Past (V.321) (Hammer et al. 2006). An ANOVA with alpha = 0.05 was used to analyze differences in physical soil properties (color and composition, pH, moisture content, soil aggregate stability, infiltration rate, nutrients availability, and available organic carbon) for each sample. A Tukey’s honestly significant difference (HSD) post hoc pairwise test was then used to determine which fields were significantly different from each other for each given test. The compound factors of these analyses were then compared to one another to determine which field and, in turn, which agricultural practices produce healthier soils as a byproduct of pineapple cultivation.

To understand how pineapple cultivation under different agricultural regimes impacts soil health, a linear discriminant analysis (LDA) was used to determine the relationships between each individual factor tested and how they differ between fields managed under different agricultural practices.
RESULTS

Field names have been abbreviated for convenience: conventional field (CF), low-input non-weedy DFS (LINW), low-input weedy DFS (LIW), and non-agricultural fields. These abbreviations will be used throughout the course of this study.

Conventional vs. Diversified Field Systems

Comparisons between conventional and diversified field systems were determined using soil science analysis. ANOVA was used to determine whether there were likely significant differences between collected samples, with a Tukey’s pairwise test being used to determine which fields were significantly different for each parameter tested.

Moisture Content

Moisture content analysis was conducted twice for each soil sample collected. ANOVA analysis of estimated moisture content round one (MC1), produced values of F(3,36) = 4.594 and p = 0.008005, revealing a statistically significant difference in samples collected from different field types. Tukey’s pairwise test revealed that LINW DFS samples were significantly different from NAG samples, with p = 0.006871. Moisture content round two (MC2) was also analyzed via ANOVA, producing values of F(3, 36) = 5.872 and p = 0.002266, confirming statistically significant differences in samples collected from different field types. Tukey’s pairwise test revealed that both CF and LINW samples were significantly different from NAG samples, with p = 0.008671 for CF-NAG samples and p = 0.005221 for LINW-NAG samples. Variation in moisture content for MC1 and MC2 can be found in Figure 2.

LINW DFS have the lowest moisture content percentage amongst all four field samples, with an average MC1 percentage of 35.30%. Conventional field samples have a MC1 percentage of 37.30%, falling between LINW DFS and LIW DFS with an average MC1 of 39.84%. Non-agricultural samples have the highest MC1 percentage with an average of 41.93%.

For moisture content trial 2 (MC2), LINW DFS samples had the lowest average MC2 percentage (35.86%), followed by conventional field samples (36.22%). LIW DFS samples had a MC2 percentage of 40.87%, with NAG samples having the highest average MC2 percentage at 42.21%.

pH

pH analysis was tested three times per soil sample, with the average pH used for ANOVA analysis. ANOVA analysis of average pH for collected soil samples produced values of
F(3,36) = 144.6 and \( p = 3.92 \times 10^{-20} \), showing statistically significant differences in pH between samples collected from different field types. Tukey’s pairwise test was then used to determine which fields were significantly different. LIW DFS samples were significantly different from the three other field types, with \( p = 0.0001714 \) for LIW-CF samples and \( p = 0 \) for both LINW-LIW and LIW-NAG samples. CF samples were also significantly different from LINW and NAG samples, with \( p = 0 \) for CF-LINW samples and \( p < 0.01 \) for CF-NAG samples. Average pH values for all 40 soil samples from all four field types can be seen in Figure 3.

LIW DFS samples had the lowest average pH value (4.399) making it the most acidic of the four fields tested. CF samples followed with an average pH value of 4.81, while NAG samples had an average pH of 4.74. LINW DFS samples had the highest average pH of samples fields with a pH value of 5.94.

**Nutrients Availability**

NPK soil tests were used to determine approximate levels of fixed elements available in soil samples collected from different field types. NPK soil test were broken down into three different presence ranges: low, medium, and high, with different ppm (parts per million) value assigned for each range. Exact ppm values can be found in Appendix A. Exact ppm values could not be calculated under given conditions, but average ppm values were assigned to samples based on given range. Figure 4 shows various levels of elements available in samples for each field type.

![Figure 3: Range of pH for all 40 samples taken from different field types. Field type is found on the x-axis, with pH value on the y-axis.](image)

![Figure 4: Available element levels from different field types are represented in the stacked bar graph. Field types are found on the x-axis, with level of available elements (ppm) on the y-axis.](image)

Each field exhibited low levels of available nitrogen, with varying levels of phosphorous and potassium. LIW DFS samples exhibited low levels of phosphorus and medium levels of potassium. Conventional field samples exhibited medium levels of phosphorous and high levels of potassium, while both LINW DFS samples and non-agricultural areas displayed medium levels of phosphorous and high levels of potassium. Overall, LINW and NAG samples appear to be chemically the same.
Loss on Ignition

Loss on ignition as a proxy for available organic carbon is currently being worked on in the Soils Lab in the Archaeological Research Facility at UC Berkeley. Data from this process will be added to this study prior to release on eScholarship.

Low-input weedy vs. Low-input non-weedy

Infiltration rate and aggregate stability was tested for all four field types via in lab analysis. Variation between all four fields was determined via ANOVA.

Soil aggregate stability

Soil aggregate stability was determined at three different time intervals: 1 minute, 2 minutes, and 3 minutes, with 36 dipping cycles per minute. ANOVA was used to determine significant statistical differences between each field type after 108 dipping cycles. After 3 minutes of water immersion, ANOVA produced values of $F(3,36) = 4.65$ and $p = 0.007563$, revealing that there are statistically significant differences in aggregate stability amongst samples within the complete time interval.

Tukey’s pairwise analysis was used to determine significant differences between field type and revealed that LINW samples were significantly different from LIW and CF samples with $p = 0.023$ for LINW-LIW samples and $p = 0.008729$ for LINW-CF samples. The range of aggregate stability for each sample at the end of the three minute time interval can be seen in Figure 5. Ch samples had the lowest average aggregate stability (37.5%), followed by LIW DFS samples (39%), NAG samples (43.5%), and LINW DFS samples with an average 51% coverage.

There are consistent trends in aggregate stability amongst different field types as number of dipping cycles and immersion time increase. CF samples slowly decreased in aggregate stability as time increased. LINW DFS samples showed high levels of aggregate stability as time progressed, while LIW DFS samples were consistently poor in aggregate stability. NAG samples fluctuated between low-stability to medium-stability as time increased.

Infiltration Rate

Infiltration rate (IF) was determined at two different volumes of water, 30ml and 60ml. ANOVA analysis of infiltration rate produced values of $F(3,36) = 1.391$ and $p = 0.2612$, revealing that at 30ml of water, there are no statistically significant differences between samples collected from different field types. Tukey’s pairwise revealed that there were no significant differences between fields for infiltration rate after 30ml of water. ANOVA was also used to determine differences in infiltration rate at 60ml of water and produced values of $F(3,36) = 0.884$ and $p = 0.4586$, revealing that there are not statistically significant differences between samples collected from different field types. Tukey’s
pairwise revealed that there were no significant differences between fields for infiltration rate after 60 ml of water. Results for infiltration rate after 30 ml (IF1) and 60 ml (IF2) of water for each sample are represented in Figure 6. Averages for infiltration rate for field type are represented by dots, with tick marks denoting standard error. LIW DFS samples exhibited the highest infiltration rate for trial 1 (91.727 sec), followed by CF samples (89.476 sec), NAG samples (72.922 sec), and LINW samples with the lowest IF1 of 51.089 seconds. LIW DFS samples had the highest IF2 (218.905 sec), followed closely by NAG samples (218.265 sec), CF samples (183.369 sec), and LINW DFS samples with the lowest IF2 of 149.941 seconds.

There are consistent trends in infiltration rate as the volume of water increases from 30 ml to 60 ml. LIW DFS samples have consistently high infiltration rates for both volumes, while LINW DFS samples have consistently slow infiltration rates for both volumes. CF samples and NAG samples fluctuate in infiltration rates in both trials but have significantly higher IF values than LINW DFS samples.

Soil Health

Seven soil sample analyses were used to determine the overall impact of intensified pineapple cultivation on soil health: moisture content, infiltration rate, aggregate stability, pH, element fixation, color, and composition. A linear discriminant analysis (LDA) was used to analyze the relationships between all seven factors tested for: color, composition, moisture content, pH, nutrients availability, loss on ignition as a proxy for available carbon, aggregate stability, and infiltration rate. Each axis is a linear combination of the multiple soil science analyses ran; the LDA then averages the result from each sample in each group, and separates each group based on their individual averages. LDA maximizes the component axes, to give the higher degree of class-separation under the set parameters.

Relationships between all 40 samples from each field types are mapped onto the first three axes, shown in Figure 7. Individual points on the graph correspond to samples collected from each field, with field type being differentiated via color and shape. Physical soil properties are projected as different axes within multivariate space. All soil science tests create a dynamic space for different field types to be projected in. The clustering between different group types show that each parameter studied works with other processes or properties to alter soil health. Non-agricultural samples were used as a baseline comparison for the natural ecosystem, with the goal of cultivated field samples being as closely related to those results.

Obvious group clustering appears amongst the various field types, with a distribution of samples across axis 1, but a clear group separation about axis 3. There are clear groupings between low-input DFS, conventional fields, and low-input non-weedy DFS samples, with non-agricultural samples having a larger range of variance across all three axes. Of all four field types, LIW DFS samples were extremely different from the
other cultivated samples and the most different from the NAG samples. CF samples fell in between the LIW DFS samples and the NAG samples, being more closely related to the LIW DFS samples than the NAG samples. LINW samples had some overlap with NAG samples, suggesting that they are more similar in health than the other cultivated fields. With NAG samples being the standard for soil health under different agricultural regimes, LINW DFS soil can be classified as healthier than soil from other cultivated samples.

**DISCUSSION**

Soil ecosystems suffer the most in terms of quality and health when placed in high stress environments. As the global ecosystem continues to be threatened, members of the science community are actively working to find solutions to environmental issues that stem from anthropogenic cause. One of the most obvious environmental concerns is the impact large-scale intensified, agricultural has on the environment. Natural ecosystems and ecosystem biodiversity are at the forefront of concern when making the conscious decision to move towards sustainable agricultural practices that have a lower overall impact on ecosystem health. In traditional terms, soil health was defined only within the context of yield and production but is becoming increasingly concerned with biological and physical soil properties and how they impact the surrounding environment (Haney et al. 2018, Arias et al. 2005).

**FIG. 7.** LDA analysis of various soil science analyses. Axis 1 has a given eigenvalue of 14.42, accounting for 86.59% of the variance. Axis two has an eigenvalue of 1.277, accounting for 7.688% of LDA variance. Infiltration Rate 2 (IF2) is projected as the third axis in the LDA and was given an eigenvalue of 0.957, accounting for 5.744% of sample variance. Field type is denoted by color and shape with DFS LIW (green triangles) clustering within the far left space, with CF samples (red squares) falling closer to the center of the figure. NAG (yellow triangles) and DFS LINW (blue dots) are found clustered on the far right end of the space, with some overlap suggesting their similarity in soil health.
This study explored the impact of intensified pineapple cultivation on soil health via soil science analysis of conventional and diversified field systems at the Opunohu Valley Agricultural School in Opunohu Valley, Mo’orea, French Polynesia. Four different fields were studied: low-input weedy diversified field systems (LIW DFS), conventional fields (CF), low-input non-weedy field systems (LINW DFS), and a non-agricultural field (NAG) adjacent to the study area. This project had three main objectives: 1) Determine how long-term pineapple cultivation alters soil health, 2) determine how soil health differs under conventional vs. low-input management regimes, and 3) determine how soil health differs between crops with and without interspersed weeds.

Soil quality and dynamic soil health

Soil health was addressed using soil science analyses of bulk samples collected from two diversified field systems (DFS), one conventional field, and one non-agricultural area. Physical and chemical soil characteristics were the focus of this project, with a series of soil science analyses being used to collectively determine soil health differences between agricultural fields cultivated with different farming practices.

Low-input DFS (LIW DFS) samples are composed of sandy loam material, dark brown to dark yellowish brown in color, and have an average pH value of 4.40. Samples were expected to be more orange in color due to nutrient leaching and overall low levels of parent nutrients. Darker color suggests more available nutrients and organic matter which are better suited for agricultural purposes. When tested for available soil nutrients, LIW DFS samples expressed extremely low levels of available nitrates, low levels of available phosphorous, and medium levels of available potassium. On average, LIW DFS samples had a moisture content of 39.84% for trial 1 and 40.87% for moisture content trial 2. Fields with interspersed weeds should be drier due to water being pulled from soil by root systems. Samples taken from this field had consistently poor soil stability and infiltration rate as time progressed throughout each process. The average infiltration rate for 30ml of water for LIW DFS samples was 91.727 seconds and 218.905 seconds for 60ml of water. These samples expressed the lowest infiltration rate of all samples collected. Aggregate stability greatly decreased throughout the trial with average percent coverage dropping for 69% at 60 seconds, to 49% coverage at 120 seconds, and ending with 39% coverage at 180 seconds. Soil aggregate stability was predicted to be higher with interspersed weeds because of soil clumping that would normally occur within plant roots (Southorn 2003). However, a three minute slake test revealed that LIW DFS samples have the lowest overall aggregate stability, most likely due to porous soil resulting from innervating weeds (Bunemann et al. 2018).

Conventional field (CF) samples are sandy loam in composition, dark brown to dark yellowish brown in color, and have an average pH value of 4.81. CF samples also expressed low levels of available nitrates, medium levels of phosphorous, and high levels of available potassium. CF samples had a lower percentage of moisture content with an MC1 value of 37.41% and an MC2 value of 36.22%. Although lower than LIW DFS samples, these percentages fall in between the range of LIW and LINW DFS samples. CF samples had poor soil stability and had an increasingly low infiltration rate. The average infiltration rate for collected samples began with 89.48 seconds for the first 30ml of water and increased to 183.4 seconds for 60ml of water. Aggregate stability for CF samples declined the most throughout the trial, beginning with 83% coverage at 60 seconds, 59% coverage at 120 seconds, and ending with 37.5% coverage at 180 seconds. This decline in soil stability might be due to chemical erosion of aggregates as a result of added pesticides and fertilizers (Tittonell 2014). This lack of soil stability could
be due to over utilization of the land (Tittonell 2014).

Low-input non-weedy DFS (LINW DFS) samples are primarily loam and sandy loam in composition, dark brown and dark yellowish brown in color, and have an average pH value of 5.94, the highest pH of total samples collected. LINW DFS samples have low levels of available nitrates, medium levels of phosphorous, and high levels of available potassium. Samples collected from LINW DFS expressed the lowest levels of moisture content, with 35.30% for the first trial and 35.86% for the second trial. Low moisture content percentage suggests that the lack of interspersed weeds and chemical additives allowed soil aggregates to retain more water (Horrigan et al. 2002). Soil aggregates are more likely to stay in larger peds if not being broken up by root systems or additives that are more likely to cause soil erosion (Horrigan et al. 2002). LINW DFS samples expressed the highest infiltration rate and the second highest aggregate stability, being roughly consistent throughout the trial. Infiltration rate for these samples had an average of 51.09 seconds for 30ml of water and 140.9 seconds for 60ml of water. LINW DFS samples had the least amount of change in percent coverage for aggregate stability. Collected samples expressed an average of 76% coverage at 60 seconds, 61% coverage at 120 seconds, and 51% coverage at the end of the process. This is most likely due to individual aggregates being more compact than fields treated with chemical additives and innervating root systems (Bunemann et al. 2018).

Non-agricultural (NAG) samples were collected and used as a baseline comparison for other field types. Non-agricultural areas that were sampled had never been used for agricultural purposes and serve as proxies for natural or indigenous soils. NAG samples are primarily loam in composition, dark brown in color, and have an average pH value of 5.74. These samples had the highest moisture content percentage with 41.93% for trial 1 and 42.63% for trial 2. Non-agricultural soils experience much lower levels of anthropogenic disturbance, allowing for soil aggregates to have higher stability and retain more moisture (Tittonell 2014). NAG samples tested relatively mediocre for both infiltration rate and aggregate stability. Average infiltration rate for 30ml of water was 72.922 seconds and 218.265 seconds for 60ml of water. Infiltration rate for NAG samples was very different for the first 30ml of water but expressed an extremely similar infiltration rate to LIW DFS samples at 60ml. A slake test revealed similar results for aggregate stability, with percent coverage being 72% at 60 seconds, 54% at 120 seconds, and 43.5% coverage at 180 seconds. NAG and LINW DFS samples expressed similar levels of aggregate stability throughout all three trials, an unexpected result.

Soil health is a complex and dynamic term, working within biological, physical, and chemical limitations. Physical changes impact the biological capacity and chemical composition of the soil, and in turn each factor affects one another. Erosion effects soil stability, heavy rainfall causes soil leeching, and these change the surrounding environment and productivity of soil systems. Anthropogenic influence further changes physical, chemical, and biological characteristics of soil and ultimately altering soil health.

Variation amongst farming practices

Each field type was managed with different agricultural practices but presented similar results for many soil science analyses. Each field type was extremely similar in color and composition. All field types expressed similar levels of nitrates, which could be due to amount of time between collection and testing of samples. Available nitrate levels could also be due to low levels of nitrates in original parent material, causing a smaller level of nutrients to also be present in sampled soils (Southorn 2003). LINW DFS samples and NAG samples were also extremely similar in phosphorous and potassium availability,
expressing medium levels of phosphorus and high levels of potassium. Samples were sent back to UC Berkeley for reanalysis to get exact ppm levels of available nutrients and will be presented in an updated version of this study.

Samples collected from all field types expressed low pH levels, indicating highly acidic soils. pH values ranged from 4.40 for LIW DFS samples (the most acidic) to 6.43 for LINW DFS samples. The DFS samples had the largest variability of pH, with the only differing factor being the presence or absences of interspersed weeds. The presence of weeds could have an impact on the overall pH of the field, depending on the type of nutrients taken up and put back into the soil. Volcanic soils are generally acidic in nature, given their parent materials, but pH lower than 4.4 presents an issue for cultivation (Neall 2009). Soils with pH ranging from 4.5 to 5.6 are generally ideal for pineapple cultivation. However, findings show that LINW DFS samples had a much higher pH value and exhibited a better overall health (Rohrbach 2002).

Moisture content percentages were most similar between LIW DFS samples and NAG samples. This result was expected due to innervating plants and roots retaining moisture from the soil. CF samples had lower moisture content levels, most likely due to chemical pesticides that prevent weeds from interrupting crop production (Parr et al. 1992). Infiltration rate was highly variable amongst all samples, with rates ranging from 51.09 – 89.48 seconds for 30ml and 140.9 – 218.9 seconds for 60ml of water. Amount of time for filtration of water increased by three fold for each sample when tested with 60ml of water, showing no significant difference between field types.

Soil stability

Chemical and physical processes can greatly impact the integrity of soil aggregates. The combination of heavy rainfall and already nutrient deficient fields create easily erodible soils (Parr et al. 1992). Agricultural fields are highly susceptible to erosion, landslides, and flooding if overused and not managed properly.

Aggregate stability between LIW DFS and LINW DFS samples were studied to determine if fields with interspersed weeds provided higher stability for crops. LIW DFS samples expressed low levels of aggregate stability, dropping from 69% coverage to 39% coverage by the end of the three trials. Their stability, aside from the CF samples, was the lowest among all field types tested. It was expected that interspersed weeds would increase the stability of agricultural soils, mainly because they would provide a support matrix for aggregates to be held in (Bunemann et al. 2018). However, innervating roots cause high levels of bioturbation, breaking up soil aggregates and creating hidden air pockets amongst loosely packed dirt (Bunemann et al. 2018). Soils become less stable and are more susceptible to erosion. Conversely, the LINW DFS samples expressed the highest rates of aggregate stability, starting with 76% coverage and falling to 51% coverage by the end of the trial. Minimal levels of interspersed weeds allowed soils to become more compact, providing more stable aggregates and limiting susceptibility to erosion.

Islands in the South Pacific have high levels of rainfall and wind, a bad combination of factors for easily erodible and nutrient deficient soils. Highly organic top soils are at most risk when it comes to these forms of erosion. Land management practices are extremely important for starting and maintaining sustainable agriculture practices and for conserving natural ecosystems.

Moving beyond soil science

Soil science provides scientists with useful information regarding the physical and chemical state of soil ecosystems. Analyzing soil quality as a proxy for soil health only reveals a portion of the biological history and ecological impact that intensified agricultural has on the environment. Soil ecosystems are
one of the largest and most complex environments, integrating biological and physical realms to create dynamic hubs of life. While this study only focused on the soil science component of soil health in relation to intensified pineapple cultivation, there are many other biotic and abiotic factors that impact soil health and fall into the realm of sustainable farming.

Biodiversity

Biodiversity within and amongst fields is crucial in maintaining healthy ecosystem (Tscharntke 2012). Biodiversity of field types were not studied but are one way to assess the dynamic biological ecosystems that exist in agricultural fields. Microorganisms, insects, and other plants and fungi often cohabitate space with crops plants, especially in DFS. Exploration of diversity in cultivated fields would most likely find a correlation between agricultural management regimes and biodiversity levels (Horrigan et al. 2002). From observations, non-agricultural areas had a much higher level of plant and insect biodiversity. LIW DFS and LINW DFS had much lower observable diversity levels because they had been recently used for agricultural purposes. LIW fields had vine plants (not identified during this project) and LINW fields had some unidentified plants species fringing on the edges of the field. It is much more likely that CFs would have the lowest levels of biodiversity due to use of chemical pesticides, followed by LINW fields, LIW fields, and NAG fields. However, further investigation would be needed to confirm these speculations.

Production, energy, and economics

Production and economics fell outside the realm of this study, but further exploration could investigate the production rate and overall yield of the three studied field types. Pineapple is the largest export on the island of Mo’orea, making pineapple cultivation a key commodity for the communities that are invested in its production. Yield from pineapple cultivation could be tracked via a multi-year survey documenting the amount of pineapples planted, harvested, and exported from each field managed under different practices. The cost of production per field type could also be tracked, recording cost for herbicides, pesticides, and other synthetic or natural fertilizers as well as hours spent tending each field, to see if there is a cost difference in managing (Bommarco et al. 2013).

A 2005 study conducted on corn farming compared the cost of energy inputs between conventional and organic field management techniques found that the organic field systems energy inputs were 32% less than their conventional counterparts (Pimentel et al. 2005). The overall net return for the conventional system was roughly $184 per ha, with the organic system being only slightly less at $176 per ha (Pimental et al. 2005). With only a marginal difference in overall net gain for organic farming systems, the movement towards biodiversity conserving agricultural practices should cause little change in economic profit.

Water

Water resources are greatly impacted by intensified agriculture and land management in relation to cultivation. Surface waters and underground aquifers divert water from other potential uses and surrounding water sheds can be polluted by runoff from fields (Horrigan et al. 2002). This is often referred to as eutrophication potential, where the amount of plant material in fresh water and marine ecosystems are measured (Tuomisto et al. 2012). Agricultural run-off, specifically high amounts of nitrogen and phosphorous, can have monumental impacts on biodiversity levels, limit recreational water use, and can change the quantity of available drinking water (Tuomisto et al. 2012). To further understand the global impact that intensified pineapple cultivation has on surrounding freshwater and marine
ecosystems water quality could be tested at a certain radius around the agricultural school. Studies could be done on the watershed quality directly surrounding the agricultural school, local streams and rivers, and runoff that flows down into the adjacent bay.

Agriculture uses about two-thirds of the global water supplies, exceeding the total for municipal and industrial use (Postel 1996). In many cases, aquifers are being drained faster than they can be refilled, resulting in a water shortage that has a much larger impact on surrounding areas and their inhabitants. In areas that are naturally deficient in freshwater resources, like island ecosystems, using freshwater sources at non-renewable rates will be detrimental to communities and the environment. Although islands in the South Pacific receive large amounts of rainfall during the wet season, these heavy amounts of rain can cause landslides making land and resource management extremely important in island environments.

Sustainable Farming Practices

In a world with increasing population size and limited resources, supplying a quickly expanding world with enough ethically grown food can be extremely difficult. In areas with limited resources, like islands, resource management and conscious sustainable farming practices are key to ensuring a healthy population and a healthy environment. Crop management and diversified farming system agricultural practices have shown to increase soil health. Sustainable agricultural and ethically grown produce starts with a stable foundation – soil. Soil quality and soil health is key to ensuring productive agricultural fields and healthy surrounding environments. Finding a balance between agricultural production and the conservation of biodiversity is a challenge. The over-utilization of land for cultivation adds to the already growing issue of yield for biodiversity trade-off (Tscharntke et al. 2012). As the need for crop production increases, the demand for water, land, and soil skyrockets, creating an overconsumption of non-renewable resources that are already reaching a carrying capacity. This study found that intensified agriculture greatly alters soil health, that conventional field practices deplete soil of nutrients and greatly reduces its stability, and that DFS techniques promote better soil health. The need for agriculture to feed populations will never change, but the way those systems are managed can. As our communities face high rates of biodiversity loss, a change in global climate, and the quick depletion of vital resources, the least we can do is take better care of what we have left.

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APPENDIX A

Soil science analyses were used to determine different chemical and physical characteristics of soil. The following diagrams, charts, flow charts were used to classify or determine one or more of the parameters tested.

Soil composition

Soil composition was determined for each sample by following the flow chart below.
NPK Availability

NPK availability for collected soil samples was determined using the color chart provided below. Soil extracts were created from collected samples and then added to LaMotte soil kits to test for nitrogen, phosphorous, and potassium. Element presence classification (low, medium, high) was determined via color comparison. Classifications were given a parts per million (ppm) range by LaMotte and are provided below. Medians of these ppm ranges were used for LDA analysis.

<table>
<thead>
<tr>
<th>LaMotte Level</th>
<th>Nitrogen Level Range (ppm)</th>
<th>Phosphorous Level Range (ppm)</th>
<th>Potassium Level Range (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0-15</td>
<td>0-25</td>
<td>0-60</td>
</tr>
<tr>
<td>Medium</td>
<td>15-30</td>
<td>25-50</td>
<td>60-100</td>
</tr>
<tr>
<td>High</td>
<td>30+</td>
<td>50+</td>
<td>100+</td>
</tr>
</tbody>
</table>

Aggregate Stability

Aggregate stability of each collected sample was determined via a Slake test. Samples were placed on a sieve and mechanically immersed in water for approximately 3 minutes, with 36 dunks per minute. Soil remaining on sieves were then compared to a standard percent coverage chart, provided below.