CAN COMPOST FROM A NITROGEN-FIXING TREE, *FALCATARIA MOLUCCANA*, REPLACE CHEMICAL FERTILIZER AND STORE CARBON IN AGRICULTURAL SYSTEMS?

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Abstract

The challenges of food production, invasive species control, and climate change are intersecting, as they all stem from our ongoing use of land and energy on a global scale. In East Hawaiʻi, two problems involving these issues are reflective of global trends. First, an expansion of agriculture is needed here, yet upland agricultural tracts are typically troubled by inherent low fertility, physically degraded and depleted of soil carbon from tillage, and require fertilizer inputs that are environmentally costly. Second, the invasive, nitrogen-fixing tree *Falcataria moluccana* (albizia) is dominating landscapes and altering ecosystems with rapid-cycling carbon and nitrogen inputs. These two problems are predicted to intensify with climate change, as growing conditions in each region shift and higher temperatures and carbon dioxide levels favor fast-growing, N-fixing species. Yet each of these problems could hold a remedy for the other, using practices described in the new field of climate-smart agriculture (CSA). Hawaiʻi Island presents a unique opportunity to test whether or not accumulated nutrients from *F. moluccana* growth can benefit agricultural systems lacking in fertility, due to the intensity and grave consequences of the *F. moluccana* invasion, as well as the underutilization of agricultural land and lack of food self-sufficiency in Hawaiʻi. This study examined whether compost from *F. moluccana* can replace chemical fertilizer and store carbon in agricultural lands in East Hawaiʻi. Trials were conducted over one growing season and included two crops, *Zea mays* (corn) and *Manihot esculenta* (cassava), and 4 replicates across a spectrum of East Hawaiʻi farmland sites representative of varying soil conditions and land use history. Treatments included a control, a typical application of chemical fertilizer (1N nitrogen applied), two levels of *F. moluccana* compost (1N and 2N levels of nitrogen applied), and two levels of combinations of chemical fertilizer and compost (1N and 2N). Harvest yield results showed that the *F. moluccana* compost was not an adequate replacement for chemical fertilizer in the corn crops. In contrast, *F. moluccana* compost produced cassava yields equal to chemical fertilizer, and economic and carbon costs were also similar across treatments. Variation among locations and within locations was larger than variation due to treatment in the cassava trial, but results suggest that the compost application was more effective on more degraded farm sites. Economic and carbon costs associated with the chemical fertilizer and *F. moluccana* compost applications were generally not different across treatments, and a partial analysis of carbon gained or lost was also similar across treatments. The results of these field trials show that CSA using *F. moluccana* compost is a viable alternative to chemical fertilizer, when the site is in need of organic matter (OM), and when the crop has favorable characteristics (long-season, rooting, and/or able to grow in low fertility areas). This research was designed and completed with the partnership of invasive species managers and farmers to maximize the usefulness of the research to the local community.

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Introduction

Agriculture accounts for most land conversion globally, and this large-scale depletion of earth's surface biomass and soil, along with further offsite emissions, accounts for a quarter of total climate change forcing (IPCC 2014). Agriculture typically depletes biotic stores of carbon and nitrogen through deforestation, depletes soil carbon through tillage and erosion, shunts nitrogen to waterways and the atmosphere, and releases more fossil carbon to the atmosphere through mechanical and industrial processes (FAO 2013). Soil carbon pools, for instance, have been depleted by 78 ± 12 Pg globally since the beginnings of agriculture and land use change; this carbon is now in the form of carbon dioxide, along with the cumulative 292 Pg of CO_2 released to date through fossil fuel combustion (Lal 2010). In addition, much of the greenhouse gases (GHGs) released from agriculture come from molecules other than CO_2, such as nitrous oxide (N_2O) and methane (CH_4) (Robertson & Grace 2004). Fertilizer production and use contributes over half of total nitrous oxide (N_2O) emissions to the atmosphere, delivering 296 times the climate forcing effect as CO_2 per molecule over 100 years (Robertson & Grace 2004). These emissions are heavily influenced by local conditions and application techniques (Matson et al. 2012).

The UN has adopted a conceptual framework of climate-smart agriculture (CSA) to inform how agriculture can address climate change while continuing to feed the global population. CSA involves best management practices but also a rethinking of goals and decision factors surrounding agriculture (FAO 2013). The FAO (2013) predicts that a full adoption of climate-smart agriculture could lead to carbon storage and emissions reductions comprising 70% of the total emissions from the agricultural sector. Under proper management, the global terrestrial carbon pool, made up of (80% soil and 20% biotic) (Lal 2007) could store up to 50 parts per million of atmospheric CO_2 for the next 100-150 years (Hansen et al. 2008). Due to the continued need for intensive agriculture for food production, they also estimate that 90% of the mitigation from CSA practices would come from increased carbon storage in soils and biomass, and only 10% from emissions reduction in agriculture fertilization and energy use (Westermann et al. 2018).

The depleted state of agricultural soil carbon (Stewart et al. 2008) and the inefficiencies of some practices make agricultural a promising sector for carbon sequestration (Lal 2010) and emissions reduction (Steenwerth et al. 2014). Some recommended management practices (RMPs) within this framework are application of compost, cover crops, conservation tillage, and targeted fertilization (Steenwerth et al. 2014). All of the RMPs suggested by climate-smart agriculture also have co-benefits that will assist in climate change resilience, such as lessening the losses due to drought or flooding, and protecting against heat stress (Steenwerth et al. 2014). Those co-benefits might be more important factors to the farmer implementing CSA practices, as they affect food and income security in a more immediate time frame. Though croplands are generally less carbon-rich than lands in their natural state or lands returned to fallow (Pimentel et al. 2005), they present one clear advantage for conservation action: people are already working on that land. If farming can be transformed to have a net positive effect on GHG emissions, then mitigation can begin to happen in the course of daily activities, on land that must remain deforested for food production.

Composting is one of the more labor-intensive recommended management practices in climate smart agriculture, compared to planting cover crops or reducing tillage, but it is a targeted way to bring carbon to especially depleted soils and rehabilitate agricultural fields (Lal 2007; Kang et al. 2013). The addition of composted carbon-rich material has been shown to increase plant yields and total organic carbon (Miyasaka et al. 2001), provide a long-term slow release of nitrogen and improve soil texture and moisture through increased soil organic matter (SOM) (FAO 2013). While increases in SOM are a dependable result of compost application, crop yield results vary more; yields can increase (Howeler 2011a), remain similar to yields from chemical fertilizer (Bittenbender et al. 1998), or at times decrease (Kass 1995; de Moura et al. 2016). Nitrogen release from compost can be slower than that from chemical fertilizer, and microbial activity in unfinished compost can bind nitrogen and make it temporarily unavailable for plant uptake (Veeken et al. 2002); these processes lessen plant available N in the short term and contribute to decreases in yield, but they are part of the process of rebuilding soil fertility and reducing N losses to the environment (Drinkwater et al. 1998). While crop yields from composting practices can vary, the increase in SOM invariably helps build crop resilience to climate change. Improved soil texture and soil organic matter decrease erosion, heat, and water stress during conditions predicted with climate change, such as heat waves, drought, flooding, and extreme weather events (IPCC 2014).

An additional benefit of compost production and application comes when the feedstock used is an invasive species. Invasive species are defined by their ability to accumulate carbon and nitrogen in growing biomass to the point of being problematic, but these are generally short term stores that decompose quickly and lead to rapid nutrient cycling through the ecosystem and higher overall losses to the atmosphere and waterways (Allison & Vitousek 2004; Ashton et al. 2005; Hughes & Uowolo 2006). Removing these species from ecosystems and possibly storing their nutrients in stable pools in the soil can lead to a net sequestration of C and N, compared with an uncontrolled invasion. Nitrogen fixers are often invasive, since they are released from N-limitation by their ability to gather their nitrogen from the air through associations with bacteria (Kurokawa et al. 2010). Through that process they bring large quantities of a limiting nutrient into terrestrial soil cycles (Steenwerth et al. 2014). The chemical composition of compost from wood chips of nitrogen-fixing species suggests that it is especially well-suited to aid in soil carbon storage. While the carbon content of this biomass is similar to most, approximately 50% by mass, other molecules alter the way that carbon moves into the three pools of soil carbon: labile, resistant, and stable (Paul et al. 2008). The high lignin content of the compost (compared to non-wood compost) and the high nitrogen content of the compost (compared to other wood composts) are both factors that have been found to increase soil carbon storage. Lignin and nitrogen are both components of humus, the fraction of soil carbon that is most recalcitrant or stable, so additions of these molecules encourage accumulation of long-term soil carbon (Six et al. 2002). Nitrogen also stimulates soil microbial activity, which is the first step in incorporating new carbon and nitrogen inputs into the soil profile (Cusack et al. 2010).

The purpose of this research is to develop and test a CSA method of compost application using invasive species. The methods studied here have been shown to maintain or increase crop yields and increase soil carbon, but there remain gaps in knowledge about compost application (Fabrizio et al. 2009) and the heterogeneity of crop response in different settings. The potential benefits from this approach include controlling invasive species, sequestering carbon, avoiding fertilizer use, and slowing reactive nitrogen emissions, all mitigations to climate change (Lal 2010). However, the body of research on similar alternative techniques shows large variations in cost per yield and carbon/nitrogen fluxes over time, in response to soil type, weather cycles, and land treatments (Bittenbender et al. 1998; Howeler 2014). Time span is a complicating factor in these trials, as many treatments that add organic matter take years to begin producing positive yield or soil carbon results (Pimentel et al. 2005). Alternative techniques need to be tested in the local environment and quantified next to status quo practices if they are to be suggested to farmers (Howeler 2011b).

The trade-offs between environmental costs/benefits and crop yields need to be examined closely because agriculture involves many conflicting priorities. In some agricultural trials, intensifying production with synthetic fertilizers can lead to lower net GHG emissions per yield than organic methods, because higher yields per area lets more land stay uncultivated and in its natural state (West & Marland 2003). In other trials, organic methods produce equivalent yields to fertilizer, but the labor involved with the organic methods makes them prohibitively costly (Kass 1995; Bittenbender et al. 1998; Miyasaka et al. 2001). Furthermore, the same results can have varying net costs across locations due to local differences in fertilizer cost and labor cost. Currently, carbon emissions do not have a monetary cost but global discussions on implementing a carbon tax suggest that environmental costs might translate more directly into economic costs in the future. The latest climate report from the IPCC asserts that a price on carbon between $135 and $5,500 per ton of carbon dioxide would need to be instituted globally by 2030 to keep overall global warming below 1.5 degrees Celsius (IPCC 2018). This would change the costs of agriculture drastically. Much current research has concluded that a combination of synthetic fertilizer and organic amendments can deliver some environmental benefits while increasing yields (Escalada & Ratilla 1998; Makinde & Agboola 2002), or has called for more research on these combinations (Bittenbender et al. 1998; Miyasaka et al. 2001). This “both/and” approach protects farmers’ incomes and food supply as farming systems slowly adopt more sustainable techniques.

Hawaiʻi presents a unique set of conditions for testing alternative methods of agricultural production and invasive species control. In pre-contact times, Hawaiʻi supported an indigenous population of over 500,000 people with only locally grown food (Melrose et al. 2016), and later went on to host sugar and pineapple industrial agriculture during the 1800’s and 1900’s. As of 2015, however, less than half of former ag lands are under cultivation (152,000 acres) and only

17,000 acres are growing diversified crops for local consumption (Melrose et al. 2016); 85 % of the state's food supply is imported by barge (Kent 2015). All synthetic fertilizers and farm amendments also need to be imported by barge. The lack of food sustainability in Hawaiʻi is a subject of much concern here, both because of the under-utilization of available land and the vulnerability that dependence on long-distance shipping brings to the food supply. The governor has set a statewide goal of doubling local food production by 2020 (Hawaii 2019). While production of plants for food is lacking, other plants that are invasive species are growing vigorously. Invasive species dominate many human landscapes and encroach into native environments, and this trend is particularly acute in Hawaiʻi , where the native flora often cannot utilize resources as quickly as invaders (Ostertag & Verville 2002). The slim number of native species and their generally conservative use of resources is a product of evolution in Hawai'i's oceanic island environment, but these features also give invasive species less competition and increase the conservation importance of remaining native ecosystems (Ostertag et al. 2009; Funk & Throop 2010).

One nitrogen-fixing tree that has become problematic throughout the islands of Hawaiʻi is *Falcataria moluccana* (albizia), which was brought to the islands from Indonesia in 1917 in an effort to restore watersheds by reforestation (Hughes & Uowolo 2006). *F. moluccana* displaces native forest and deposits large amounts of carbon and nitrogen into soils which drive further invasion (Resh et al. 2002; Hughes & Denslow 2005). The lightweight canopy tree grows to great heights quickly and with little root system, posing a treefall hazard to populated areas and powerlines during high winds. The danger presented by these trees was made clear during 2014's Tropical Storm Iselle, when *F. moluccana* treefall accounted for the vast majority of over $13 million in damage and left many households throughout the Puna district cut off from services for weeks (BIISC 2019). The Big Island Invasive Species Committee (BIISC) is tasked with developing a strategic approach to *F. moluccana* control. *F. moluccana* populations have only recently begun to invade prime farmland on the Hamakua Coast but BIISC predicts that much of this land could be overgrown and considered too costly to farm within five years (S. Kaye, pers. comm.). Still, efforts of BIISC and others to control *F. moluccana* remain underfunded, and without funded effort or an economic incentive much rural land, including farmland and the last areas of remaining native lowland forest in all of Hawaiʻi, will continue to succumb to the invasion. The management of the *F. moluccana* invasion would be aided by an economic incentive to utilize the composted biomass from the trees, and in this way the research supports BIISC's mission.

This research has been done with a focus on asking useful questions and providing useful results to managers and the public, including invasive species managers such as BIISC but also farmers, gardeners, and residents of Hawaiʻi. This project was developed to create a work of climate science that was applicable to the needs of residents and land managers who are in the field doing the work that could impact, and is impacted by, the changing climate. This cross-disciplinary approach to asking and answering a research question follows research by Wall et al. (2016) on the importance of creating knowledge in partnership with managers and community members to increase usability of the resulting science. This is especially important in the field of climate science, where mitigation or adaptation action is frequently recommended by the science; when scientists work together with those that implement management decisions throughout the process, the research is much more likely to be utilized. With that focus in mind, I crafted a research question together with BIISC and local farmers that also considered questions related to climate science. Could an approach to invasive species control also help farmers? Could an alternative agriculture technique also address the invasive species issue? Could any of these approaches also help farmland and invaded lands adapt to climate change, and/or store carbon to mitigate climate change? The results of this study have been framed to address these issues, and sharing the results with managers, farmers, and residents is an integral part of this research approach. The involvement of BIISC and farmers throughout the research has helped to keep this study integrated and applicable across disciplines.

This study was conducted on the east side of Hawaiʻi Island, where a combination of environmental factors and land use history provide a gradient of moisture, temperature, substrate age, and soil quality that can facilitate comparisons across study sites at different levels of these variables (Vitousek et al. 1997). The slopes of Kohala Mountains, Mauna Kea, and Mauna Loa are each a different geologic age due to the volcanic genesis of the Hawaiian Islands, and the elevational change of each mountain creates gradients of moisture and temperature. Much of the available farmland on this side of the island was cultivated for sugarcane production for nearly a century, which has left those areas with reduced SOM (Mathews & Senock 1998); some land is still being farmed, and much has laid fallow for 20 years or more. The sites were selected to represent different agricultural zones and land use histories, so treatment effect across this spectrum could be investigated.

This research seeks to answer the following questions: How does application of albizia (*F. moluccana*—I will use the common name when referring to the compost treatments hereafter*)* compost to crops affect plant yield, plant and soil nutrient levels, and soil aggregation compared to chemical fertilizer with equivalent levels of available nitrogen? What are the differences in carbon emissions and/or storage arising from the fertilizer production and use, mechanical fuel needs, and soil carbon stored from the different treatments? Treatments include a control, chemical fertilizer applied in typical amounts (1N amount of nitrogen), compost applied at two levels (1N and 2N), and 2 levels of combinations of chemical fertilizer and compost (1N combo and 2N combo). The effects on two different crops were tested. The first, corn (*Zea mays*) is a short-season and N-intensive crop (Brewbaker 2003). The second, cassava (*Manihot esculenta*), is a long-season root crop that can tolerate low soil fertility (Howeler 2014). I expected that corn would respond more readily to easily mobilized N additions from chemical fertilizer, while cassava would respond to both chemical N additions and slower-release N additions from the albizia compost. I hypothesized that yields would be similar between the chemical fertilizer treatment and the 2N albizia compost treatment and 1N combo, with the control and the 1N albizia compost being lower and 2N combo perhaps showing highest yields. I also hypothesized that trends would be more pronounced in cassava due to its long growing season in which it can extract nutrients, while corn yields would favor the treatments with chemical fertilizer due to their high, shorter-term N demands. Soil carbon and aggregation were expected to increase with compost application treatments, although the change in concentration might not be evident in the short time span of the study. Plant and soil nutrients were expected to show some increase in the treatments involving compost, though highest levels would be expected in the 2N combination treatment due to its high level of total nutrient application.

Methods

Study system

Study sites were secured with the help of community partners, including BIISC and local land managers and farmers. The four study sites used here represent four different points along gradients within the agricultural areas of East Hawai'i: Kapaʻau, located in Kohala, is a stream-valley site with Ainakea soils that are approximately 250,000 years old; soils have more mature development here than at the other three sites, all located on Mauna Kea soils, but lower precipitation in Kapaʻau has led to less intense weathering (Table 1) (B. Mathews, pers. comm.,Wolfe & Morris 1996). The other sites are in Honokaa-type soils of the Kaiwiki and Hilo soil series (Table 2) (NRCS 2017), approximately 70,000 years old (Wolfe & Morris 1996). These soils are high in clay comprised of poorly crystalline Al-silicates and ferrihydrate, which affects availability of soil carbon and nitrogen. Soil organic matter (comprised of both carbon and nitrogen stores) in these soils tends to be more highly protected than similar levels of SOM in other types of soil (Osher et al. 2003). Reasons for this include physical protection of organic matter within soil micropores, complexation with aluminum and iron oxide surfaces, and low microbial activity due to typically low phosphorus content (Deenik 2006). Adding organic matter to these soils is highly recommended to combat low nitrogen mineralization and low microbial activity, though inputs must be sustained over many years to see change in these soil qualities (Deenik 2006). Among these three Honokaa-type soil sites, Pepeʻekeo is at a much higher elevation within the agricultural zone, while Honomū and Kolekole are both at a more typical elevation for cassava and corn production (Table 1).

Land use histories within agricultural areas on the windward side of Hawaiʻi Island also vary. All three sites in Honokaa-type soils were farmed for decades with sugarcane (Sato et al. 1973). Pepeʻekeo has been heavily plowed and used for agriculture leading up to this trial (C. Bardwell-Jones, pers. comm.), and the Kolekole site has also been under recent continuous cultivation (G. Hirowatari, pers. comm.). This site had its topsoil removed years ago as part of a soil pathogen response by previous farmers, a common local practice at one point (pers. comm., B. Mathews, G. Hirowatari). The Honomū site was sugarcane farmland up until twenty years ago but has been fallow for the last ten years (pers. comm., S. Kaye). The site at Kapa‘au was not used for industrial sugarcane production, most likely, due to its position in a small stream valley. It is, however, in a perfect position to have supported Hawaiian traditional agriculture production in previous centuries, and some evidence on the land suggests that it was used in this way (A.Kobsa, pers. comm.) (Table 2).

Table 1. Locations, elevations, and annual precipitation of sites (Giambelluca et al. 2013).

Site	Lat. °	Long. °	Elev. asl (m)	Annual precip. (mm)
Pepe‘ekeo	19.8211	-155.1328	342	5290
Kolekole	19.8756	-155.1197	95	3580
Honomū	19.8642	-155.1086	102	3450
Kapa‘au	20.2197	-155.7556	53	1720

Table 2. Soil series, taxonomic class, and land use history for study sites (Melrose et al. 2016; NRCS 2017, 2019).

Site	soil series	Taxonomic class	Land use history
Pepe‘ekeo	Kaiwiki hydrous silty clay loam	Hydrous, ferrihydritic, isothermic Acrudoxic Hydrudands	sugarcane, then sweet potato
Kolekole	Hilo hydrous silty clay loam	medial over hydrous, ferrihydritic, isohyperthermic Acrudoxic Hydrudands	sugarcane, sweet potato, cassava
Honomū	Hilo hydrous silty clay loam	medial over hydrous, ferrihydritic, isohyperthermic Acrudoxic Hydrudands	sugarcane, then fallow
Kapa‘au	Ainakea medial silty clay loam	medial, ferrihydritic,isohyperthermic, Acrudoxic Hydric Hapludands	fallow

Collection and preparation of materials

Albizia (*F. moluccana*) chips were collected from trees growing from Hilo to Honomū, felled with chainsaws either by Asplundh tree-trimmers or by the researcher and helpers, starting in spring of 2016 and continuing into fall of 2016. Access to this material was secured with the help of BIISC and local land managers, and the decision on how to process and apply the albizia to cropland was also made in cooperation with these partners after assessing the practicality and cost of different application methods. Chips consisted of leaves, branches, and trunks up to 10 cm in diameter of living albizia trees that had not been subjected to herbicide. Due to the size limitations of the chipper, this usually included all the large and small branches of the trees but not the main trunk. Most chips came from trees that were 3-5 years old and 10-12 m high. Material was chipped with a commercial grade chipper powered by gasoline, piled into mounds up to 1.5 m high on top of weedmat, and then covered with a waterproof tarp and left at the Kolekole site for composting to occur. This site had average daily high temps of 25-28° C and low temps of 18-21 C° throughout the year. Piles were turned every month and aeration was delivered into the piles with perforated tubing; all piles were left to compost until they were no longer producing heat; heat production was assessed by touch. This process took one year; piles remained covered until they were dispersed to planting sites, which was 3-6 months after compost piles were done producing heat.

Crops

Two plant species were selected as test crops. Corn (*Zea mays*) is a short-season (85 days) crop with high nitrogen demand; UH Hybrid Sweet Corn: Hawaiian Supersweet #10 was the variety used (Brewbaker 2003). Cassava (*Manihot esculenta*) is a long-season annual crop (10 months or more), usually grown for its starchy edible roots, with a longer period of nitrogen demand and ability to grow in low-nutrient soil (Howeler 2014). Clonal stem material of the same cassava variety was used as planting material for all plots. These two crops were selected to represent extremes along multiple spectrums of crop traits, such as differences in growing time, timing of nutrient demands, and part of the plant that is of interest for harvest. Also, both plants are widely used throughout the world and have been used in many yield trials, ensuring that the research done here is applicable to farming around the world and can be compared to other research on these species. While corn is a major U.S. crop and has been bred to be used with chemical fertilizer for quick nitrogen uptake (Brewbaker 2003; Matson et al. 2012), cassava is less common in the U.S. but is one of the most important subsistence and industrial crops in tropical regions of all continents (Howeler 2014). Neither crop is grown at scale in Hawai‘i for local human consumption (Melrose et al. 2016), but both are important staple crops around the world and an increase in local food production would likely include both crops. In many areas, including the Phillipines (Escalada & Ratilla 1998) and Africa (Makinde & Agboola 2002), corn, cassava, and albizia are all grown together or in succession to meet a variety of needs. In addition, the range of tropical crops such as cassava will expand and spread into the continental U.S. and corn production will shift as the climate continues to warm.

Site preparation

Hogwire fencing that was 1.2 meters tall was installed at sites that were not already protected from pests, namely feral pigs. Land was prepared by eliminating weedy material with herbicide 2 months before planting (glyphosate, Monsanto Corp.), followed by weed whacking (Stihl F350 gas-powered weed trimmer). Most weedy debris were removed from sites immediately before soil was turned with a rototiller (Powermate rear-tine rotary tiller, model no. PRTT196E.1), to 4-6 inches depth. Planting was done within one week of tilling. All sites were tested for available phosphorus (modified Truog, 1:100 soil solution,), exchangeable cations Ca, K, Mg, and Na (ammonium acetate, 1:20 soil solution,)(Hue et al. 2000), pH, and microelements Cu, Fe, Mn, Zn (Brazilian Mehlich-1, 1:10 soil solution) (Bortolon & Gianello 2012) (Appendix 1). Sites that were deficient in any of these nutrients or elements were supplemented to ensure that these were not factors in limiting plant growth (Appendix A.2a and b) (Tamimi et al. 2000). Supplements used were triple-phosphate, muriate of potash, dolomitic limestone, and Hi-Cal Mix (see Appendix A.3 for composition) (Cameron Micronutrients)). These supplements were tilled into the soil before planting.

Plot design

Treatment plots were each 29.16 m^2 (5.4 m x 5.4 m), and each site had 6 treatment plots for each crop (Fig. 1). Treatment 1 had no additions as the control plot, while Treatment 2 represented typical N fertilizer usage, applied as urea (1N fertilizer). Treatments 3 (1N compost) and 4 (2N compost) were two levels of the compost treatment; nitrogen in the compost was analyzed before application, and then compost amounts for these two treatments were calculated to apply the same quantity of nitrogen (Treatment 3) and double the nitrogen (Treatment 4) as Treatment 2. Since organic matter typically releases 50% of its nutrients within a season (Hue & Silva 2000), Treatment 4's 2N level of compost was predicted to more closely approximate available N from 1N fertilizer. Treatments 5 and 6 looked at synergistic effects of chemical fertilizer and compost combined, with Treatment 5 (1N combo) replacing half of fertilizer (0.5N) used with the lower level of compost (1N), and then Treatment 6 (2N combo) representing a doubling of total N delivered, full fertilizer (1N) in addition to the higher level of compost (2N) applied. These treatments will be referred to by the names in Figure 1 throughout this paper.

Tr.1 control	Tr. 3 1N albizia compost	Tr. 5 1N combo
Tr. 2 1N fertilizer	Tr. 4 2N albizia compost	Tr. 6 2N combo

Fig. 1. Treatment numbers and description at each site for each crop. Albizia is the common name for the invasive N-fixing tree *Falcataria moluccana*.

For the cassava crop, 1N was 80 kg N/ha, the typical recommendations (Howeler 2014); and for corn, 1N was 100 kg N/ha, a relatively low level for corn, reflective of fertilization rates practiced in countries where fertilizer is less affordable (B. Mathews, pers. comm., Sileshi et al., 2012). This level of corn fertilization reduces N losses to the environment seen with higher fertilization and is representative of levels available to many tropical corn farmers outside of industrial production (Matson et al. 2012). The composted albizia mulch was tested for total C and N (Costech Elemental Analyzer, (Zimmerman et al. 1997)), and the averaged results for nitrogen were used to calculate the amount of compost that was equivalent to chemical fertilizer N applied as urea. The dry albizia compost was 2.11 % N and 45.93 % C (22:1 C:N ratio), and the wet compost was 77 % water, so 211 g of wet albizia compost was needed to deliver 1 g of elemental nitrogen, while 2.17 g of urea (46 % N) was needed to deliver 1 g of N.

Treatment plots were placed at each site with attention to slope and partial randomization; while land area was chosen that appeared consistently fertile and with a minimum of slope, treatments with less additives were placed at the upper portion of the slope that did exist, while richer treatments were placed at the bottom of the slope. Treatments 2 and 3 were randomized with respect to each other at each site, as were Treatments 4 and 5. Treatment 1 was always at the top corner of the slope and Treatment 6 was always at the bottom. Treatments were placed directly adjacent to one another and crops were planted up to the edge of each plot. A one-meter border inside each plot was left out of harvest and yield calculations, so that the effective plot size was 3.4 m x 3.4 m.

Planting and harvest

Corn was planted at the beginning of June 2018. Supplements and the treatments were tilled into 4 rows before planting, and double rows of corn seeds were planted within for a final spacing between rows of 0.68 m between rows, and corn plants thinned to 10-15 cm within the rows. The urea fertilizer was applied one half at planting and the second half at one month after planting. Weeding was done by hand and with a weedwhacker through the growing season. Corn ears and biomass in Oct 2018 were harvested at 3 months after planting. At harvest, the 1-meter border was measured inside each plot, and plants only from within the inner plot were counted and weighed. Each inner plot held 90-100 corn plants, and areas where corn did not germinate were taken out of the area measured so that yields reflect plots at full plant density.

Corn plants were separated into corn ears and aboveground biomass (no corn roots were collected). Fresh weight for each plant part was measured in the field, and at least 15 samples of each plant part were dried at 70°C until dry weight did not change to determine the wet-dry ratio so that all biomass weights could be converted into dry biomass values.

Cassava was planted in January 2018 at all four sites, using 20 cm long stem pieces from the same variety of cassava. Stem pieces were planted upright, halfway into the soil, with 42 plants equally spaced in the plots. Fertilizer or compost was applied at one month after planting. Compost was applied in a ring 15-25 cm outside of each stem planting and turned into the soil, and urea fertilizer was applied in a crescent-shaped divet 15 cm away from each stem and covered, one half of the quantity at one month after planting and the other half two months after planting. Weeding of the plots was done at one month after planting and as needed throughout the growing period, by hand and with a weedwhacker. Cassava plants were harvested in November 2018; the growing period was 11 months. At harvest, a 1-meter border was measured inside each plot, and the 20 plants from within the inner plot were counted and weighed. Areas where the cassava did not germinate were taken out of the area calculations. Cassava plants were separated by plant part (roots, stumps, woody stems, and twigs and leaves), and processed in the same way as the corn, although for cassava the entire biomass was weighed instead of only aboveground biomass for the corn.

Nutrient and soil aggregation analysis

Soil carbon can take many years to increase in response to alternative treatments (Pimentel et al. 2005); here, though soil carbon increase is an expected benefit, a noticeable difference is not expected within the time span of this work. For that reason, dissolved organic carbon and soil aggregation are measured here as proxies for longer-term soil carbon storage trends. Dissolved organic carbon, while part of the labile carbon pool, is a precursor to more protected carbon stores (Six et al. 2002). Soil aggregation is associated with lower erosion (Hallet & Bengough 2013) and higher soil microbial activity (Lange et al. 2015), both of which lead to higher soil carbon storage.

For both crops, leaf samples were taken before harvest for nutrient analysis; the first corn leaf above the top corn ear was used for corn, and the top cassava leaf that was fully formed was used for cassava. Fourteen leaves were harvested from each plot and grouped for analysis (Hue et al. 2000). Resin bags for both nitrogen and phosphorus were constructed out of 86 mesh silkscreen into 6 cm X 7.5 cm bags filled with 6.0 g mixed bed exchange resin (J.T. Baker), then one was buried 6 cm deep in each plot one month before harvest and removed after 28 days, before plant harvest, for analysis. Available phosphorus and nitrate plus ammonium collected through resin bags were extracted with 0.5 M HCl and 2 M KCl, respectively, shaken for 6 hours in solution then analyzed with a Pulse Autoanalyzer (P) and a Costech Elemental Analyzer (N) (Ostertag et al. 2016).

Soil samples to a depth of 15 cm were taken at harvest, with ten equal soil samples combined from each plot. Soil samples were mixed and sieved with a 5 mm screen. Soil samples were tested for percent water, and then wet soil was tested on a dry-mass equivalent basis for a variety of nutrients. Available nitrate plus ammonium (1M KCl, 1:10 soil solution, Lachat Quikchem 8500), extractable phosphorus (modified Truog, 1:100 soil solution, Lachat Quikchem 8500), extractable cations Ca, K, Mg, Na (1:20 soil solution, Elemental Analyzer ICP-OES) and pH were analyzed. All tests of available nitrate plus nitrite will be referred to as only nitrate throughout the text, as nitrite is generally present in soil in small and unstable amounts. Dried soil was tested for total C and N with high temperature combustion (Costech Elemental Analyzer, (Zimmerman et al. 1997)). All tests followed protocols set out by Hue et al. (2000).

Soil aggregation was measured in the cassava soil samples by wet sieving soil through a 1 mm sieve. Soil was gently shaken in the sieve until no more passed through, and the proportion of soil that did not pass was the percent soil aggregation. This measure has been found to be a useful indicator of healthy soils in Andisols, the soils in this study; soils which are over 50 % aggregates are reliably better suited for seed germination, row crops, and erosion resistance (Hallet & Bengough 2013), . Soil aggregation was not measured in corn plots because the growing season was not expected to be long enough to allow aggregation changes to accrue in the soil.

Statistical analysis

To examine if experimental treatments affected yields, linear models (ANOVAs or Kruskal-Wallis tests) were conducted on yields of the edible plant part only (roots or corn ears) and yields of total biomass (cassava) and total aboveground biomass (corn). Yield values for corn ears and corn aboveground biomass were logged before analysis, but cassava yields were not logged as they were normally distributed. Plant and soil nutrients as response variables were also examined in this way. Tukey's test or the Wilcoxon test were used to do pair-wise comparisons across treatments where differences were found. To look at relationships between individual plant and soil nutrients and yield, correlation tests were run, using Pearson's method or Spearman's method for non-normal variables. The above tests were completed with R (R Core Team 2013).

The lack of significance in the cassava trial by treatment indicated that location might be a more important factor than treatment. All the above ANOVAs or Kruskal-Wallis tests were completed for yields, plant, and soil nutrients by location as they were by treatment, in order to investigate this factor. Tukey's test or the Wilcoxon test were used to do pair-wise comparisons across treatments where differences were found.

Principal components analysis was done on each crop, with all plant and soil nutrient variables entered as components (Primer 6 software program) (Clarke & Gorley 2015). Exceptions to this were when variables were highly correlated with each other; in the corn PCA, total soil N and soil ammonium through the resin method were removed prior to analysis, and in the cassava PCA, soil P, soil C, total soil N, plant Cu and plant Fe were removed. Resulting scores for each plot in principal components 1 and 2 were analyzed for a correlation with total biomass (cassava) or aboveground biomass (corn) yields, using R software (R Core Team 2013).

Economic and carbon use/storage comparison

A partial analysis of costs and carbon emissions/storage was done for treatments, given in terms per yield of harvest product (for carbon emissions and cost in dollars) and per area (for total carbon storage or loss). Costs that were the same across treatments, such as land prep, weeding labor, harvest labor, were not included. Economic costs included urea fertilizer and fuel cost for chipper use, both calculated based on published averages and local costs in March 2019. Carbon costs included carbon emitted from fertilizer production and transport, which is 4.5 kg CO_2 eq per 1 kg N applied as urea (Robertson & Grace 2004), and carbon emitted from chipper use. Carbon costs of fertilizer transport were based on worldwide averages, which is lower than the costs associated with transporting fertilizer to Hawaiʻi, so it should be noted that this carbon cost is conservative for this situation. Carbon emissions from chipper use show a wide range of values from different sources: 0.5 L diesel per m^3 of fresh, loose chips, which is 1.34 kg CO_2 per m^3 chips (Spinelli & Magagnotti 2014); 3.14 kg CO_2 per m^3 chips (Prada et al. 2015); 5.36 kg CO_2 per m^3 chips from a meta-analysis (Cosola et al. 2016); and 2.37 kg CO_2 per m^3 chips (Eriksson & Gustavsson 2010). An average of these values was used here. Fresh woodchips have been found to decrease in volume by 36.7 % after 100 days of composting (Breitenbeck & Schellinger 2004), and by 30 % during the course of total composting (WSU 2019) and so an average of these values was used to calculate the amount of kg CO_2 that was spent to make measured quantities of finished compost. Total carbon gain or loss per area was calculated by subtracting the carbon in CO_2 emissions per ha and adding the measured soil C increase compared to the control plot. This percent C increase was converted into Mg C increase per hectare of soil with bulk density measurements taken to a depth of 10 cm 3 months after the end of the growing season. Five representative samples were taken from the control plot at each site. Volume of finished compost applied per plot and yield per plot were measured variables used in the equation to report carbon emissions by treatment on a per yield basis. Results of these cost calculations were analyzed with ANOVAs and Kruskal-Wallis tests in R software to detect differences between treatments.

Results

Corn trial

Plate 1. Corn at 1 month after planting (1 MAP) growing at Kolekole. Tr. 1 (control) is in foreground, Tr. 2 (1N fertilizer) is in background. Photo credit for all photos: J. Norton.

Plate 2. Corn reaching maturity (2.5 MAP) at Honomū, multiple plots are shown.

Corn aboveground biomass was found to be higher in the treatment with 1N fertilizer than the treatment with 2N albizia compost, but all other treatments were similar ($F_{5,18} = 3.61$, $p = 0.02$, Figure 2). Corn biomass for the 1N fertilizer treatment was 2.56 ± 1.211 (standard deviation) Mg per ha and for the 2N albizia compost, 0.85 ± 0.34 Mg per ha (Appendix A.4). The power of this test was 1.0. See Plates 1 and 2 for pictures of corn plants during the growing season.

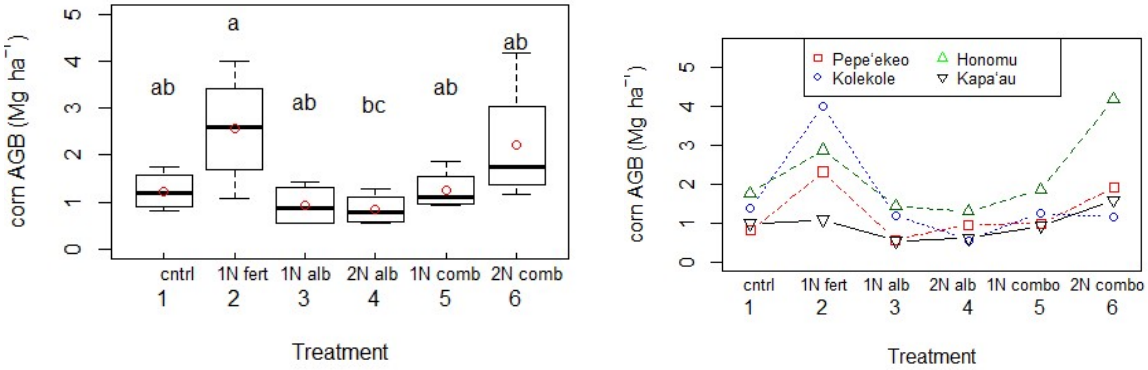


Fig 2a and 2b. 2a. Boxplot of corn aboveground biomass (AGB) yields by treatment. Means are represented by red circles, medians by the midline of each box, edges of the box shows the upper and lower quartiles, whiskers show the highest and lowest value excluding outliers. and letters indicate groupings with different means. 2b. Interaction plot of corn AGB yields by treatment, lines showing yields by site.

An analysis of corn ears harvested rather than aboveground biomass, showed a similar pattern ($F_{5,18}= 4.43$, $p = 0.01$) though existing differences were exaggerated in ear yield. Here the yields for 1N albizia compost along with the 2N albizia compost were lower than yields for the 1N fertilizer (Appendix A.4). Site differences among log aboveground biomass yields and log corn ear yields in the corn experiment were not significant (Appendix A.5).

Corn nutrients

Principal components analysis for measured corn plant and soil nutrients showed that plots largely grouped by site, with Kapaʻau separated from the other sites along PC1 (Fig 3), in which Kapaʻau was higher in all soil nutrient variables besides soil NO_3 resin (Appendix A.6). Honomū separated from the other sites along PC2, which was highly influenced by soil available nitrogen, leaf N, Ca, Mg, and micronutrients Mn, Cu, and Zn (Appendix A.6).

The first two principal component vectors explained 63 % of the variation between plots (Appendix A.7), and while PC1 did not correlate with corn aboveground biomass yield (rho = -0.090, S = 2506, p = 0.676), PC2 did correlate with yield (rho = -0.577, S = 3628, p = 0.004).

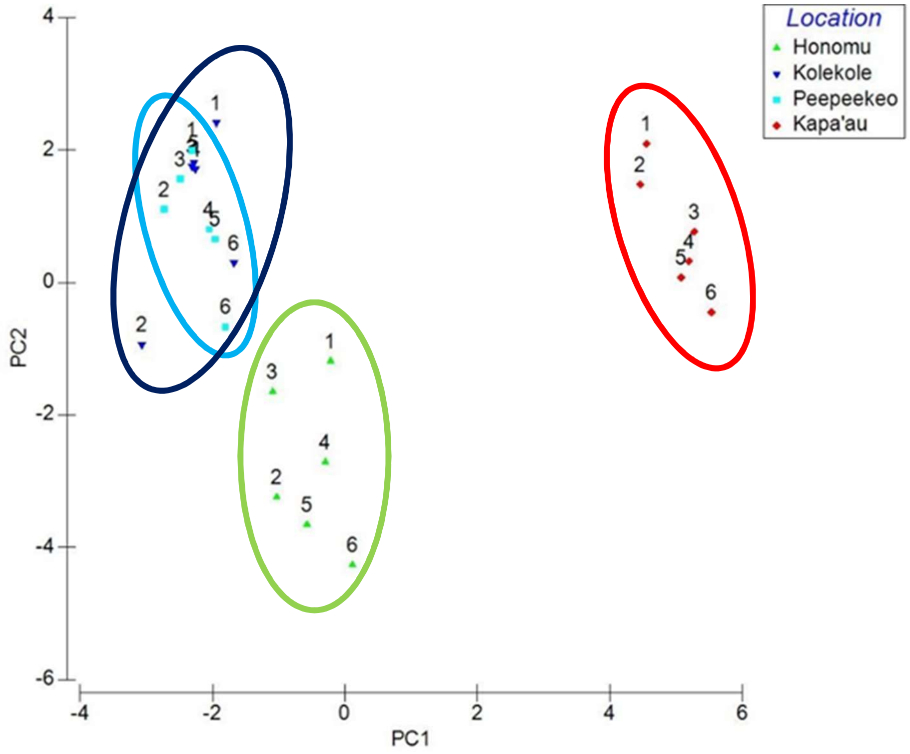


Fig 3. Principal components analysis for corn nutrients. Each point represents a treatment at one of the sites, numbers indicate treatment number and shapes/colors indicate site. Color-coded circles surround the six treatments for each site. See Figure 1 for description of Treatments 1-6, Tables 1 and 2 for description of sites.

Nutrients in plant tissue and soils were individually analyzed by treatment, and no difference was found among treatments (Appendix A.8). The nutrients were also analyzed by location and there were differences found for almost every plant and soil nutrient (Appendix A.9). In most tests, Kapa‘au site had higher levels of the measured variable than the other sites. Nutrients found to be different were pH, soil P, soil Ca, soil Mg, soil NO_3, soil NH_4, soil N, soil C, soil DOC, soil P through resin method, and leaf tissue N, Ca, K, Mg, Mn, and Zn (Appendix A.9).

Corn aboveground biomass yields were also analyzed for correlation with plant and soil nutrients at the plot level (Appendix A.10). Biomass was found to correlate with leaf tissue N and Cu (Appendix B.1a and 1b). Corn ear yield was found to have a similar relationship to plant and soil nutrients as biomass; leaf tissue N and Cu were again the only significantly correlated variables (Appendix A.11).

Economic and carbon costs and carbon storage

The chemical fertilizer and 1N albizia, 1N combo, and 2N combo treatments all had similar economic costs and CO_2 emissions per yield in the corn trial (Table 3). The 2N albizia treatment had higher costs and emissions than the control treatment, though each was similar to all other treatments. Carbon gained or lost in each treatment was similar across all treatments.

Table 3. Economic and carbon costs, and soil carbon gain or loss for each treatment in the corn trial. Results of ANOVAs and Kruskal-Wallis tests are listed, significant p values are in bold. Letters that are similar within a column are not significantly different. Standard deviation in parentheses.

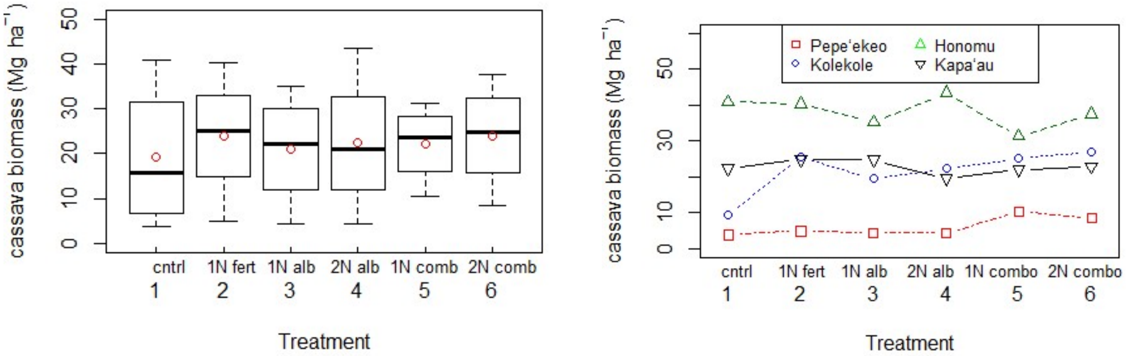
Treatment	**economic cost ($ kg yield^{-1})**	**CO_2 emissions (kg CO_2 kg yield^{-1})**	**increase in soil C (Mg C ha^{-1})**	**CO_2 emissions (Mg CO_2 ha^{-1})**	**total C gain or loss (Mg ha^{-1})**
(1)control	0.00 (0.00) ^{a}	0.00 (0.00) ^{a}	0 (0)	0.00	0 (0)
(2)1N fert	0.31 (0.22) ^{ab}	0.46 (0.33) ^{ab}	-1.19 (5.85)	0.45	-1.31 (5.85)
(3)1N albizia	0.93 (0.73) ^{ab}	2.43 (1.90) ^{ab}	2.45 (1.17)	0.43	2.33 (1.17)
(4)2N albizia	1.53 (0.98) ^{b}	4.00 (2.56) ^{b}	4.11 (2.80)	0.86	3.88 (2.80)
(5)1N combo	0.64 (0.23) ^{ab}	1.33 (0.48) ^{ab}	1.16 (2.42)	0.65	0.98 (2.42)
(6)2N combo	0.68 (0.34) ^{ab}	1.41 (0.70) ^{ab}	6.42 (5.25)	1.31	6.07 (5.25)
F stat					2.259
Chi-sq	14.774	17.205			
df	5	5			5,18
p-value	**0.011**	**0.004**			0.093
transformed	no	no			no

Cassava trial

Plate 3. Cassava at 6 MAP growing at Honomū, multiple plots shown.

Plate 4. Cassava at 6 MAP growing at Pepeʻekeo, multiple plots shown.

Cassava total biomass was compared across treatments, and no difference was found among all treatments. Total biomass means ranged from 19.1 ± 16.5 Mg per ha to 24.0 ± 12.1 Mg per ha but no statistical difference was found among treatments ($F_{5,18} = 0.072$, $p = 0.996$) (Figs. 6a and b) (Appendix A.12). Due to the wide variation in data points for each treatment, a power test was done. The power of this analysis was 5.4 %. Cassava root yields showed a similar pattern, with no difference found across treatments (Appendix A.12).



Figs 4a and 4b. 4a. Boxplot for cassava total biomass yield by treatment. Means are represented by red circles, medians by the midline of each box, edges of the box shows the upper and lower quartiles, and whiskers show the highest and lowest value excluding outliers. 4b. Interaction plot showing same yields, lines indicate yields for each site.

Site differences

Results of the cassava total biomass yields showed significant difference by location ($F_{3,20} = 56.956$, $p = <0.001$) (Fig. 5) (see Plates 3 and 4), as did the cassava root yields ($F_{3,20} = 15.360$, $p = <0.001$) (Appendix A.13). Differences between sites varied between the biomass and the root yields. Kolekole biomass yields were lower than Honomū, but in root yields, they had similarly high values compared to the other two sites (Appendix A.13).

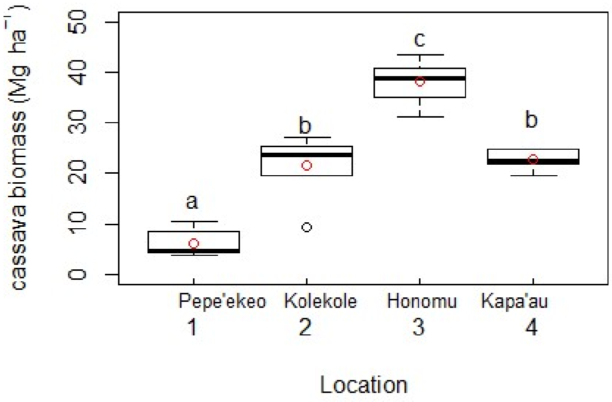


Fig. 5. Boxplot of cassava biomass by location. Means are represented by red circles, medians by the midline of each box, edges of the box shows the upper and lower quartiles, whiskers show the highest and lowest value excluding outliers, and letters indicate groupings with different means.

Cassava nutrients

Principal components analysis of cassava plant and soil nutrients showed that most component variables had a contribution to the pattern below, which was largely grouped by site (Fig. 6). Sites were drawn apart along PC axis 1, which had a similar contribution from all of the soil nutrients with the exception of soil available ammonium, and most of the leaf tissue nutrients as well except leaf C, Mg, and Mn (Appendix A.14). Kapa'au was higher in all of these variables than the other sites. The first two principal component vectors explained 61% of variation in plant and soil nutrients (Appendix A.15). The first two PC vectors did not correlate highly with yield (PC1: rho = -0.250, S = 2875, p = 0.239; PC2: r = 0.021, t = 0.099, df = 22, p = 0.922).

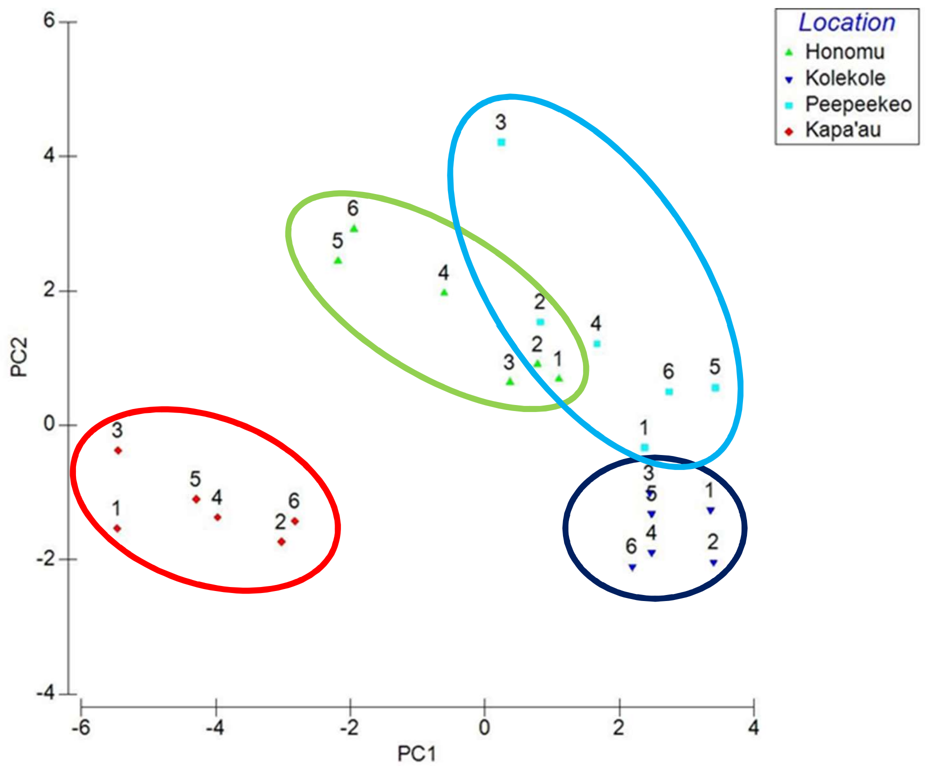


Fig 6. Principal components analysis for cassava nutrients. Each point represents a treatment at one of the sites, numbers indicate treatment number and shapes/colors indicate site. Color-coded circles surround the six treatments for each site.

No difference was found for any plant or soil nutrient by treatment for cassava (Appendix A.16). Cassava nutrients in soil were significantly different among locations, however, except for soil ammonium and soil P measured with resin bags (Appendix A.17). Most variables were much higher at the Kapa‘au location with the other three sites grouping together. All plant tissue nutrients measured other than plant C and minor elements Fe, Cu, Mn, and Zn were different among locations. This difference did not have a pattern across sites as the soil nutrients did; rather, the ranking of site leaf nutrient amounts changed with each nutrient measured (Appendix A.17).

Correlation tests between cassava yields and nutrient levels showed significant positive correlation between biomass yield and soil NO_3, leaf Fe, and a negative relationship with leaf Mn (Appendix A.18) (Appendix B.2abc). Cassava root yield showed a similar pattern although the only significant correlation was the negative relationship between root yield and leaf Mn (Appendix A.19).

Soil aggregation

Soil aggregation was measured in the cassava plots, as the growing season of 11 months was long enough to permit microbial aggregation of the soil. However, results of this ANOVA indicate that there was no difference between any of the treatments in soil aggregation (($F_{5,18}$ = 1.6, p = 0.211) (Appendix A.12). When soil aggregation was analyzed by location, however, differences were evident. Kolekole and Honomū had similarly high levels of soil aggregation, and Pepe‘ekeo had the lowest (Figs 7a and b).

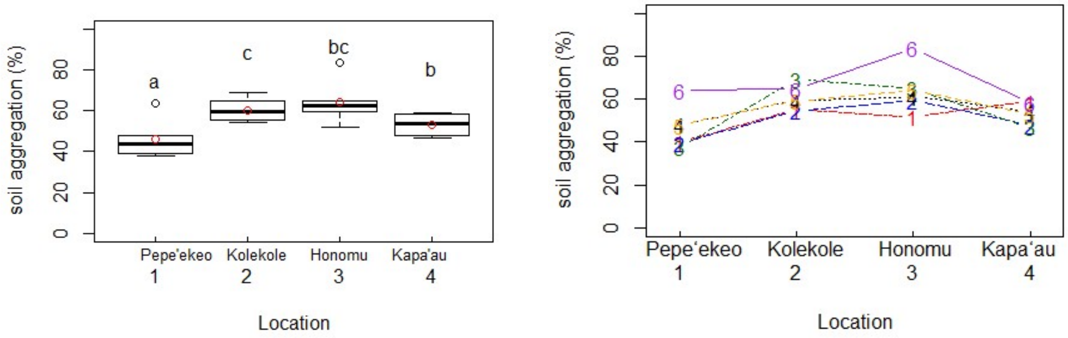


Fig 7a and 7b. 7a. Boxplot of soil aggregation by location. Means are represented by red circles, medians by the midline of each box, edges of the box shows the upper and lower quartiles, whiskers show the highest and lowest value excluding outliers. and letters indicate groupings with different means. 7b. Interaction plot of soil aggregation by location, lines indicate each treatment.

Soil aggregation was also found to correlate positively with cassava biomass yields (r = 0.59, p = 0.002) (Fig. 8) (Appendix A.18). A similar pattern was shown with cassava root yields but results were not significant (Appendix A.19).

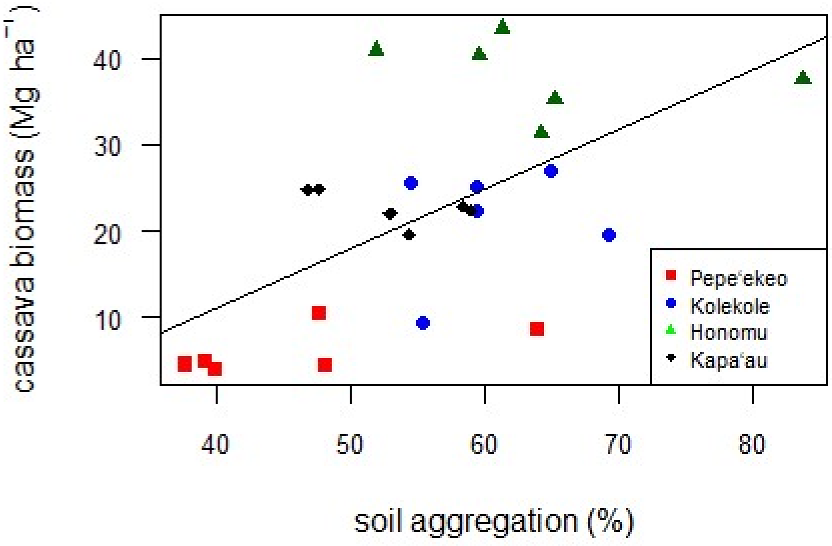


Fig 8. Scatterplot of cassava biomass and soil aggregation. Sites are indicated by colors and symbols of data points.

Economic and carbon costs and carbon storage

The chemical fertilizer and 1N albizia, 2N albizia, and 1N combo treatments all had similar economic costs and CO_2 emissions per yield in the cassava trial (Table 4). The 2N combo treatment had higher costs and emissions than the control treatment, though each were similar to all other treatments. Carbon gained or lost was similar across all treatments.

Table 4. Economic and carbon costs, carbon storage for each treatment in the cassava trials. Letters that are similar within a column are not significantly different.

Treatment	**economic cost (\$ kg yield^{-1})**	**CO_2 emissions (kg CO_2 kg yield^{-1})**	**increase in soil C (Mg C ha^{-1})**	**CO_2 emissions (Mg CO_2 ha^{-1})**	**total C gain or loss (Mg ha^{-1})**
(1)control	0.00 (0.00) ^{a}	0 (0) ^{a}	0 (0)	0.00	0 (0)
(2)1N fert	0.041 (0.037) ^{ab}	0.061 (0.055) ^{ab}	7.38 (9.27)	0.36	7.28 (9.27)
(3)1N albizia	0.024 (0.022) ^{ab}	0.064 (0.059) ^{ab}	7.94 (10.2)	0.32	7.86 (10.2)
(4)2N albizia	0.048 (0.046) ^{ab}	0.126 (0.119) ^{ab}	7.11 (9.33)	0.64	6.94 (9.33)
(5)1N combo	0.033 (0.012) ^{ab}	0.067 (0.024) ^{ab}	6.96 (10.2)	0.50	6.83 (10.2)
(6)2N combo	0.072 (0.040) ^{b}	0.148 (0.083) ^{b}	8.02 (11.3)	1.00	7.75 (11.3)
F stat					
Chi sq	13.91	13.93			10.003
df	5	5			5
p-value	**0.016**	**0.016**			0.075
transformed	no	no			no

Discussion

Is albizia compost a viable CSA method?

As the IPCC's latest report has made clear, action must be taken on all fronts to draw down emissions and store carbon in appropriate sinks if the globe is to avoid catastrophic warming (IPCC 2018). Climate-smart agriculture must be a part of the solution, both for mitigation and for adaptation to an extreme, warming climate (Lal 2010). Composting is one of the most accessible and low-tech CSA strategies for farmers and can yield a co-benefit by turning waste material in the nearby environment into fertile soil. Composting will be a viable CSA technique, where it can lead to acceptable yields, have a lower economic cost, and effectively remove carbon dioxide from the atmosphere (FAO 2013). This research tested one composting method using a highly invasive nitrogen-fixing tree. *F. moluccana* can be very hazardous due to treefall near residential areas, and it is exceedingly expensive to remove the large trees after the first few years of growth (Hughes et al. 2011), so early removal of these pest trees presents a clear economic and public safety value. When left to invade, *F. moluccana* will quickly displace native ecosystems and alter nutrient cycling, increasing soil N by up to 120 times on some substrates (Hughes et al. 2011) and increasing dissolved N in adjacent streams to the point that algae are released from N limitation and stream chemistry is drastically altered (Wiegner et al. 2013). These same nutrient qualities make *F. moluccana* a prime material for composting. The results of these field trials show that CSA using albizia (*F. moluccana)* compost can be a viable and equivalent method to chemical fertilizer, depending on the species and importantly, the site conditions.

Crop species had a large influence on the effectiveness of the albizia compost. In the corn trial, a crop with a short growing season and high nitrogen demand early in the season (Brewbaker 2003), compost alone was not as good as chemical fertilizer. However, the 2N combo (2N albizia +1N) fertilizer was as effective as fertilizer alone. The data suggests that this treatment could lead to an overall increase in soil carbon while maintaining yields, though the results here were non-significant due to the large variation within sites (Table 3). This result follows the FAO analysis that most benefits of CSA (90%) will accrue through carbon storage rather than reduction in fertilizer emissions due to the continued need for high yields and efficient food production (FAO 2013). The compost alone did not fare any better than the control, indicating that the nitrogen from the compost was not released in synchrony with crop demand. Nitrogen release in Honokaa-type soils, which are present in 3 of the 4 sites, has been found to be particularly depressed during the first 100 days after fertilizer application compared to other soils (Deenik 2006). The results suggest that in these soils a short-season, N-intensive crop such as corn does not respond to albizia compost and would not be a viable method for farmers.

Studies in other soils have found similar low corn yields with organic additions (Makinde & Agboola 2002; Pimentel et al. 2005) or decreased tillage (West & Marland 2003; Matson et al. 2012) compared to conventional tillage and chemical fertilizer. For example, Makinde and Agboola (2002) found that inorganic fertilizer or a mix of inorganic and organic produced corn yields twice as high as those under organic fertilization only. These researchers also tested cassava in the same treatments, and found that a mix of organic and inorganic fertilizers supported higher yields in the long-season cassava crop, but the quicker mobilization of N with inorganic fertilizer was key to producing high yields for corn (Makinde & Agboola 2002). The contrast of these two crops, in length of season and key growth factors, illustrate ends of a spectrum along which most annual crops fall, both for the study mentioned above and for the research done here. An economic and carbon cost analysis of the corn trial shows that the chemical fertilizer is equivalent to the 1N and combo treatments, while the 2N albizia compost had the highest costs and emissions per yield due in large part to the low yield in that treatment (Table 3). Carbon gain or loss (comprised of the CO_2 emissions of each treatment and the soil carbon % change) did vary with treatment but due to the large variation between sites no significant difference was detected. While farmers will undoubtedly avoid a method that is more expensive per yield (Howeler 2011b), there is some indication that with longer duration or an otherwise modified method compost application could increase soil carbon in corn fields. Subsequent tillage could negate those carbon gains, however; an approach that coupled compost application with reduced or no tillage would more likely stabilize any soil carbon gains (Grandy & Robertson 2007).

In the cassava trial, the albizia compost produced equal yields to the chemical fertilizer; for this crop, composting can be a viable substitute for fertilizer while delivering CSA co-benefits. Many cassava studies have reported similar positive results with organic compost or green manures either alone or in combination with chemical fertilizer (Estoquia 1997; Escalada & Ratilla 1998; Makinde & Agboola 2002; Howeler 2011a). The Makinde and Agboola (2002) study of both corn and cassava found that cassava fared better with a mix of organic and inorganic fertilizers, with higher available P, higher pH, and better nutrient-use efficiency resulting from use of the organic fertilizer. Crop traits for cassava such as tolerance of low levels of soil fertility (Howeler 2014) and a yearlong growing season during which to utilize the applied treatments are qualities that work well with this CSA technique. Root crops might also be more responsive than fruit or grain crops to improvements in soil structure after composting, as soil aggregation in this trial was found to correlate highly with cassava biomass yield. Cassava is especially dependent on mycorrhiza, which are abundant in highly aggregated soils, for phosphorus absorption and proper root development (Howeler 2011c). Similar benefits with compost application were found in taro in the same soils in which this research was conducted (Miyasaka et al. 2001).

The economic and carbon cost analysis for cassava (Table 4) indicates that all treatments had similar costs and emissions, as well as carbon gained or lost. The 2N combo treatment had higher costs and emissions per yield than the control treatment, showing that the nutrients applied were not efficiently used at the highest level of application and that plots with no additions could still produce comparable yields. These results suggest that albizia compost could be an economical and emissions-neutral alternative to chemical fertilizer while turning local waste biomass into usable farm amendments and soil carbon. As carbon pricing becomes policy, as it is already in Canada and as suggested by the IPCC (IPCC 2018), fertilizer costs will rise due to their heavy dependence on fossil fuels (Robertson & Grace 2004) and alternative fuels for chipper operation could become more available. This economic incorporation of environmental costs will shift the values in this cost calculation and give the alternative compost treatment a growing economic and carbon advantage. While the results here do not indicate a net gain of stored carbon over the chemical fertilizer treatment, another phase of experimentation that continued over many seasons or altered part of the compost method could begin to show an increase in soil carbon and thus provide a climate-smart alternative.

How do site conditions and land use history affect the viability of albizia compost?

Differential fertility is seen along gradients of soil development (Vitousek et al. 1997), and also between similarly developed soils with different levels of degradation or use. Managers of sugarcane lands in these same soils, working with Mauna Kea Sugar Company, found that physical characteristics of the soil due to use history led to large differences in yield in soils with similar nutrient profiles (B. Mathews, pers. comm.), indicating that this use history was a key factor in determining crop yields. Soil pedons at the same site can be quite different from each other due to these physical factors; a slope or erosion can lead to a drastic gradient in soil development in one small area, while at other times intensive monocropping or topsoil removal can create patches of infertile soil next to much more fertile patches. These site and micro-site factors appeared to have a large effect in this study, as seen in the analyses of yields and nutrients by location.

Site conditions including soil nutrients and land use history outweighed the treatment effect for cassava, but not for corn. All nutrients were different by site in the cassava trials, and yields were positively correlated with soil NO_3 and leaf Fe and negatively with leaf Mn. These differing overall levels of soil fertility and production capability by site were large enough to obscure any patterns due to treatment. Soil aggregation was also different by locations, and a positive correlation between cassava biomass and soil aggregation indicates that soil structure and microbial activity are some of the more important factors driving cassava growth. These factors are also key to increasing soil carbon storage (Six et al. 2002; Grandy & Robertson 2007; Jastrow et al. 2007), although inherent soil mineral characteristics are also of key importance to carbon storage in volcanic ash soils (Andisols) (Osher et al. 2003).

A closer look at cassava yields at each site suggest that site quality played a large role in determining if the treatment would be beneficial. Overall, the cassava trial showed no difference among any of the treatments including the control treatment. However, this result is at least partially due to a large variation of response between sites, and variation between individual plots at the same site that resulted in different micro-site conditions despite efforts to keep those similar. The two sites that had previously been fallow, Honomū and Kapa‘au, had high yields in the control plot, indicating that soil fertility was not a limiting factor for cassava growth at these sites. In addition, both sites had unexpected conditions that appeared to lower yields in some plots. At Honomū, the above-ground growth blew over during a storm six months into the growing season in the two combo treatments, and while the plants kept growing, lower root yields indicate that energy was diverted to replacing above-ground growth rather than root storage after this event. At Kapa‘au, treatments with 2N compost and both combo treatments frequently had conditions of waterlogged soil due to unexpected drainage patterns from the nearby road, the slight downward slope of the trial, and those plots’ position closer to the bottom of that slope. When looking at just the Kolekole and Pepe‘ekeo sites, the interaction plot (Fig. 4b) shows the yield pattern that was hypothesized for this research, where the 2N albizia plot produces similar yields to the chemical fertilizer, and the combination treatments increase yields slightly beyond that. This pattern suggests that this alternative method might be feasible specifically in cropland that has been degraded by constant use and depletion of OM (Deenik 2006); further research in sites that were all degraded cropland would be needed to assess this hypothesis.

When looking at corn yields by location, the pattern seen in cassava was reversed. There was no difference between sites; the variation due to treatment was large enough to obscure any patterns due to location. Principal components analysis of these variables do show an overall clear grouping by location, however, and many soil and plant nutrients were individually different by location. These differences did not drive yield patterns in the corn crop as they did for the cassava. Together these results indicate that levels of immediately available nitrogen, largely consumed before soil and plant tissue samples were taken, are more important than site differences of climate or soil nutrient levels in determining corn yields (Matson et al. 2012). Pimentel et al. (2005) found similar results for the first 5 years of a 22-year comparison of corn grown with organic and inorganic fertilizers, but after 5 years the resilience and the accrued fertility of the organic systems produced higher yields in times of drought, and similar yields in fair weather, all while using only 70% of the energy inputs needed for the inorganic treatments. This result suggests that high corn yields with inorganic fertilizer is a net extractive process that can function in degraded farmland, but that after a period of rehabilitation of the underlying fertility, those same yields can be achieved in a more sustainable approach. The research here takes place during a very short time span; perhaps a longer period of repeated plantings would begin to bear this pattern out.

Soil classifications of the sites help explain the different responses of the two crops, based on the synchrony of nitrogen availability and plant needs. Nitrogen mineralization has been found to be delayed in the Honokaa-type soils present at three of the test sites, due to the ferrihydritic clays which bind cation plant nutrients to Al and Fe oxides (Deenik 2006). This quality exaggerates the expected pattern of improved corn yields with highly available nitrogen inputs from synthetic fertilizer, and the somewhat better response to the compost seen in the cassava trial. Repeated addition of organic matter through mulching and composting is recommended for these soils, but it can take multiple seasons for the benefit to be seen in crop performance (Mathews & Senock 1998; Deenik 2006). While this pattern is seen in other soils and climates (Pimentel et al. 2005), the soil mineralogy here strengthens that pattern of delayed response to OM additions. It is possible that other schedules of compost application, such as months before planting, or repeated over many years, would produce different results and increase synchrony of plant needs and nutrient mineralization from the soil. Regardless of yield responses, addition of organic matter is highly recommended throughout tropical regions, where rain can leach nutrients quickly and soil is vulnerable to erosion (Perrin et al. 2014; de Moura et al. 2016).

Though the two crops responded differently to the competing influences of treatment and location, a principal component analysis of both trials shows that soil and plant nutrient variables grouped largely by site and showed similar trends between species. This is to be expected, as the trials for each species were adjacent to each other at each site. Both highly degraded sites, Kolekole and Pepeʻekeo, clustered closely together and the other two sites occupied distinct areas of the PCA graph, apart from each other and the degraded sites. The analysis shows that many variables were influential (Appendices A.6 and A.14); it appears to be an additive system of many component variables that typify these different locations. However, it can also be seen that land over-use leads to the same suite of soil and plant qualities in the PCA, while the two more fertile sites are distinctly different from each other (Mathews & Senock 1998). Since Honomū soils are similar to the Kolekole and Pepeʻekeo soils (Deenik & McClellan 2007), it appears that degraded land in that region mainly changes along the variables heavily represented in principal component 2, although those component variables differed between crop trials. In the corn trial, principal component variables that decreased in degraded soils were soil NO_3 and NH_4, plant N, Ca, and micronutrients Mn, Cu, and Zn, while plant Mg increased. In the cassava trial lowered pH and a loss of soil and plant K, soil P, soil available NH_4, soil C, and soil aggregation was seen with land degradation. Decreases in all of these important plant nutrients as well as manganese toxicity are common problems associated with intensive agriculture in Hawaiʻi Island soils where long-term N fertilization and heavy rainfall have lowered pH and leached nutrients (Mathews & Senock 1998). Lands in sugarcane production in Hawaiʻi have lowered carbon stocks (Osher et al. 2003), similar to results in other tropical agricultural systems (Davidson et al. 2008; Fabrizzi et al. 2009). In addition, repeated tillage over decades has been found to destroy soil aggregates and lead to a layer of compacted, OM-depleted soil that slows plant growth and lessens the efficacy of fertilizer application (Mathews & Senock 1998).

This grouping of sites along plant and soil nutrient variables, along with yield results, shows a difference between the two crops. Though sites clustered together similarly in both crop trials, this difference translated into yield differences only in cassava. For the corn trials, yields changed with levels of chemical fertilizer application regardless of site. Soil and plant nutrients appear to affect cassava yields, while corn is less affected by these factors and instead responds to fertilizer additions.

Opportunities and conditions for scaling up this CSA technique

For farmers, knowing soil conditions and characteristics of the crop species is key before deciding whether to use albizia compost or other OM amendments. For those looking to address the *F. moluccana* invasion across Hawaiʻi and elsewhere, research into uses of the biomass can inform and incentivize control activities. Yield studies quantifying costs and benefits of alternative treatments can aid decision-making in agricultural production and land stewardship, and these treatments need to be easy to implement and appropriate to the local conditions if they are to be adopted. It is important that farmers know what to expect and are able to maintain yields while transitioning to more climate-smart methods (Howeler 2011b); in some instances, intensive farming with chemical fertilizer or a combination of chemical and organic can be the most climate-smart choice due to higher yields and efficient nutrient use (Escalada & Ratilla 1998; West & Marland 2003). Other factors such as, for example, the proximity of the *F. moluccana* biomass to the farm and the efficiency of the chipping and composting processes affect the feasibility of alternative treatments (Dahlin et al. 2005). When calculating costs here, the assumption was made that transport of *F. moluccana* trees to the chipper would take minimal energy, and that the labor involved in chipping, composting, and spreading the compost would be equal to the labor involved with chemical fertilizer. These are strong assumptions that are not always met in real world circumstances, and many studies have found that while yields are good with organic methods, the labor required is too much to produce profitable margins (Kass 1995; Miyasaka et al. 2001). Effort would have to go into site choices, mechanization, and fuel and labor efficiency to realize the maximum benefits from this method, as other mulching studies have found (Escalada & Ratilla 1998). Compost for this study took one year to reach a finished state, and that investment in time is also a factor for consideration. The institutional advocates for climate smart agriculture make the point that this transition requires a reordering of priorities and a transformation of energy use, consumption patterns, and valuation of goods and services (FAO 2013; IPCC 2014). The ecosystem services and carbon storage that come with increased soil OM are not currently accounted for economically, though they create lasting benefit (Lal 2011; de Moura et al. 2016). CSA leaders understand that institutional and policy support is necessary to help farmers make the transition, and bridge the gap between beneficial practices and maximum yield (Westermann et al. 2018).

The CSA compost technique studied here shows promise in depleted croplands and with longer-season crops, though differences between sites and within sites can be great and overwhelm any differences due to treatment in studies of this nature. This is consistent with previous findings that the most soil carbon-depleted lands have the highest potential for new carbon stabilization and storage (Stewart et al. 2008). Corn trials show that corn clearly has higher yields when chemical fertilizer is applied and incurred less costs. Cassava trials show, in some sites, that the albizia compost treatment might have equal yields as chemical fertilizer, but the benefit from compost application is missing in soils that are already fertile. In the cassava trial the economic costs and net carbon storage were similar across all treatments, but with less variation between sites. The variation in yield seen at the different sites of the cassava trial is much larger than any variation due to treatment, so studies looking to reveal a pattern with applied treatments of compost and short-term effects on growth would need to be conducted with multiple replications at the same, or similar, farm locations.

These results will be shared with the partners in the community that I have worked with in designing and conducting this research, including BIISC and local farmers and gardeners. This research quantifies the yield and costs/carbon storage benefits for one alternative method, using a local resource generally considered waste. This study sets a framework for analyzing the costs and benefits of different agricultural approaches, incorporating climate and carbon storage concerns as is needed in today’s changing climate. It also points to questions that could be answered next: trials using different compost applications, or done on only degraded land, or done on just one study site could produce more definitive results than those produced here. This study is one early step in testing climate-smart agricultural techniques in Hawai‘i, and while crop species, site, and quantities of compost applied have a large effect on viability of this technique, results point to the potential of organic methods to decrease fertilizer use and store carbon in farmland soils. Future studies that continue to work with community partners and test their options will provide some of the most usable information for those working on the land.

Summary

Transformations in agricultural practices and invasive species management are necessary to address the global issues of climate change and land degradation. Composting is an accessible climate-smart agriculture strategy and using local invasive species as feedstock could turn a problem waste material into a valued product. The research done here was designed and conducted with the involvement of invasive species managers and local farmers to ensure that the questions asked and the answers reached are useful for the community of people working on the land. This study examined whether albizia compost could replace chemical fertilizer in crop production and lead to higher carbon storage. Harvest results showed that in the corn trial compost alone was not as good as chemical fertilizer. In the cassava trial, the albizia compost produced equal yields to the chemical fertilizer and had similar costs, emissions, and carbon storage. For this crop, composting can be a viable substitute for fertilizer that also stimulates harvesting and use of the invasive tree *F. moluccana* Site conditions including soil nutrients and land use history outweighed the treatment effect for cassava, but not for corn. Awareness of soil conditions and characteristics of the crop species is key before deciding whether to use albizia compost or other organic amendments. This study is one early step in working with community partners to test climate-smart agricultural techniques in Hawaiʻi. While crop species, site, and quantities of compost applied have a large effect on viability of this technique, results point to the potential of organic methods to decrease fertilizer use and store carbon in farmland soils.

Appendix A. Tables

Appendix A.1. Initial soil nutrient levels at study sites. Minimum sufficient values for each nutrient (except Na, which is not a limiting nutrient) (Tamimi et al. 2000) are indicated on the last row and were used to determine if supplements were added at each site.

Location	P (mg kg$^{-1)}$	Cu (mg kg$^{-1)}$	Fe (mg kg$^{-1)}$	Mn (mg kg$^{-1)}$	Zn (mg kg$^{-1)}$	Ca (mg kg$^{-1)}$	K (mg kg$^{-1)}$	Mg (mg kg$^{-1)}$	Na (mg kg$^{-1)}$
Pepe‘ekeo	9	5	354	189	4	212	51	147	65
Kolekole	10	5	322	147	7	41	60	22	30
Honomū	14	6	326	168	16	769	66	101	45
Kapa'au	117	18	2286	244	46	2763	743	1039	148
minimum	50	10	31	9	10	200	200	50	NA

Appendix A.2a and 2b. Supplements added at each site for corn trial (2a) and cassava trial (2b). P and K amounts listed are in elemental form.

Location	P (kg/ha)	micro-elements (kg/ha)	K (kg/ha)	dolomitic limestone (kg/ha)	P (kg/ha)	micro-elements (kg/ha)	K (kg/ha)	dolomitic limestone (kg/ha)
Pepe‘ekeo	140	336	140		112	336	112	
Kolekole	140	336	140	1120	112	336	112	1120
Honomū	140	336	140		112	336	112	
Kapa‘au	0	336	0		0	336	0	

Appendix A.3. Guaranteed analysis of Hi-Cal Mix (Cameron Micronutrients). Derived from Borax, Calcium Carbonate, Copper Oxysulfate, Iron Oxysulfate, Magnesium Oxysulfate, Manganese Oxysulfate, Zinc Oxysulfate.

Magnesium (Mg)	6.00%
Calcium (Ca)	10.00%
Sulfur (S), Combined	5.00%
Boron (B)	1.00%
Copper (Cu)	0.30%
Iron (Fe)	2.00%
Manganese (Mn)	1.50%
Zinc (Zn)	3.00%

Appendix A.4. Corn aboveground biomass means, corn ear biomass means (with standard deviation in parentheses), and percent difference from control of these variables, with results of ANOVA or Kruskal-Wallis tests by treatment. Significant tests have bold p-values. Letters were given to different means in significant comparisons.

Treatment	**mean corn biomass (Mg ha^{-1})**	**mean corn biomass diff from control (%)**	**mean corn ears (Mg ha^{-1})**	**mean corn ears diff from control (%)**
(1)control	1.23 (0.42) ^{ab}	0.0 (0.0)	0.43 (0.28) ^{abc}	0.0 (0.0)
(2)1N fert	2.56 (1.21) ^{a}	112.6 (90.8)	1.29 (0.65) ^{a}	315.9 (399.4)
(3)1N albizia	0.93 (0.45) ^{ab}	-26.7 (14.2)	0.30 (0.25) ^{c}	-23.1 (59.0)
(4)2N albizia	0.85 (0.34) ^{bc}	-26.8 (32.4)	0.31 (0.22) ^{cb}	-30.5 (13.7)
(5)1N combo	1.25 (0.43) ^{ab}	3.0 (14.3)	0.57 (0.30) ^{abc}	50.0 (64.7)
(6)2N combo	2.21 (1.35) ^{ab}	80.0 (73.5)	1.21 (0.82) ^{ab}	181.1 (29.4)
F stat ANOVA	3.61	no test	4.43	no test
df	5,18		5,18	
p-value	**0.020**		**0.010**	
transformed	log		log	

Appendix A.5. Corn aboveground biomass means and corn ear means (with standard deviation in parentheses), with results of ANOVA or Kruskal-Wallis tests by location.

Location	**mean corn biomass (Mg ha^{-1})**	**mean corn ears (Mg ha^{-1})**
Pepe‘ekeo	1.25 (0.69)	0.55 (0.41)
Kolekole	1.59 (1.21)	0.62 (0.69)
Honomū	2.23 (1.10)	1.18 (0.69)
Kapa‘au	0.95 (0.38)	0.39 (0.25)
F stat ANOVA	2.815	2.716
df	3,20	3,20
p-value	0.065	0.072
transformed	log	log

Appendix A.6. Eigenvectors for corn PCA.

Variable	PC1	PC2	PC3	PC4	PC5
pH	0.304	0.066	-0.135	0.039	0.100
log soil P (mg kg^{-1})	0.271	-0.148	-0.023	0.109	0.070
soil Ca (mg kg^{-1})	0.321	0.009	0.007	-0.040	0.068
soil K (mg kg^{-1})	0.310	0.099	0.046	-0.058	0.085
soil Mg (mg kg^{-1})	0.317	0.079	0.022	-0.058	-0.028
soil NO_3 (mg kg^{-1})	0.259	-0.251	0.160	-0.084	0.035
soil NH_4 (mg kg^{-1})	-0.194	-0.254	-0.253	-0.066	0.035
soil C (g kg^{-1})	-0.284	-0.091	0.191	0.198	-0.001
log soil DOC (mg kg^{-1})	0.267	-0.056	0.253	0.067	-0.096
soil resin PO_4	0.257	-0.109	0.183	0.165	0.196
log soil resin NO_3	0.030	-0.152	-0.330	-0.392	-0.306
leaf N (g kg^{-1})	-0.040	-0.480	0.129	-0.066	0.002
leaf C (g kg^{-1})	-0.260	-0.189	-0.014	0.084	0.188
leaf Ca (g kg^{-1})	0.111	-0.429	-0.037	-0.018	-0.229
leaf K (g kg^{-1})	-0.198	-0.084	0.348	0.051	0.257
leaf Mg (g kg^{-1})	-0.155	0.277	-0.317	0.281	-0.231
leaf P (g kg^{-1})	0.073	-0.103	-0.032	0.632	-0.410
log leaf Fe (mg kg^{-1})	0.007	0.109	0.308	-0.329	-0.624
leaf Cu (mg kg^{-1})	-0.198	-0.306	0.219	-0.074	-0.135
leaf Mn (mg kg^{-1})	-0.053	0.257	0.487	0.140	-0.165
leaf Zn (mg kg^{-1})	0.140	-0.259	-0.161	0.342	-0.136

Appendix A.7. Eigenvalues and % variation for top five principal component vectors for corn PCA.

PC	Eigenvalues	%Variation	Cum.%Variation
1	9.42	44.9	44.9
2	3.76	17.9	62.8
3	2.07	9.8	72.6
4	1.59	7.6	80.2
5	1.17	5.6	85.7

Appendix A.8. Corn nutrient level means (with standard deviation in parentheses), and results of ANOVA (F stat) or Kruskal-Wallis (Chi-sq) tests by treatment. Soil resin values are in units of µg N-NO_3^-, N-NH_4^+, or P-PO_4^-/gram anion or cation resin/day.

Treatment	pH	soil P (mg kg^{-1})	soil Ca (mg kg^{-1})	soil K (mg kg^{-1})	soil Mg (mg kg^{-1})	soil NO_3 (mg kg^{-1})	soil NH_4 (mg kg^{-1})
(1)control	6.0 (0.4)	36 (10)	1019 (1246)	321 (533)	418 (607)	3.3 (3.1)	2.8 (1.6)
(2)1N fert	5.8 (0.5)	36 (15)	1035 (1231)	291 (431)	426 (573)	6.1 (3.0)	4.1 (2.4)
(3)1N albizia	6.0 (0.5)	49 (33)	1090 (1291)	359 (602)	398 (563)	3.5 (2.8)	3.8 (2.3)
(4)2N albizia	6.1 (0.4)	51 (24)	1172 (1254)	275 (441)	419 (553)	4.7 (4.1)	3.6 (1.9)
(5)1N combo	6.0 (0.4)	49 (21)	1149 (1313)	325 (508)	386 (495)	4.8 (4.2)	4.2 (4.1)
(6)2N combo	6.0 (0.6)	56 (17)	1475 (1692)	408 (656)	442 (523)	7.9 (4.8)	3.0 (2.1)
F stat		0.768				0.831	0.193
Chi-sq	3.453		1.61	4.26	1.53		
df	5	5,18	5	5	5	5,18	5,18
p-value	0.631	0.585	0.900	0.513	0.910	0.544	0.961
transformed	no	log	no	no	no	no	no

Treatment	**soil N ($g\ kg^{-1}$)**	**soil C ($g\ kg^{-1}$)**	**soil DOC ($mg\ kg^{-1}$)**	**soil resin PO_4**	**soil resin NO_3**	**soil resin NH_4**
(1)control	5.6 (1.2)	75.2 (25.5)	22 (21)	58 (48)	1509 (1601)	500 (545)
(2)1N fert	5.8 (1.6)	74.0 (28.7)	11 (21)	56 (54)	6188 (3592)	1484 (1617)
(3)1N albizia	5.8 (1.4)	79.5 (28.3)	26 (39)	89 (104)	142 (136)	148 (89)
(4)2N albizia	5.9 (1.5)	82.0 (28.4)	9.6 (22)	95 (111)	647 (303)	236 (97)
(5)1N combo	5.5 (1.3)	76.3 (23.7)	15 (26)	140 (118)	1413 (1701)	419 (485)
(6)2N combo	6.4 (1.0)	84.0 (22.6)	15 (19)	140 (92)	1759 (2430)	591 (614)
F stat		0.091	0.267			1.994
Chi-sq	1.72			3.64	5.1447	
df	5	5,18	5,18	5	5	5,16
p-value	0.886	0.993	0.926	0.602	0.399	0.134
transformed	no	no	log	no	no	log

Treatment	**leaf N ($g\ kg^{-1}$)**	**leaf C ($g\ kg^{-1}$)**	**leaf Ca ($g\ kg^{-1}$)**	**leaf K ($g\ kg^{-1}$)**	**leaf Mg ($g\ kg^{-1}$)**
(1)control	17.1 (3.9)	419.6 (15.9)	2.6 (0.6)	7.6 (2.1)	2.9 (0.4)
(2)1N fert	21.0 (4.5)	426.4 (23.4)	2.7 (1.3)	8.6 (0.6)	2.0 (0.3)
(3)1N albizia	18.5 (2.0)	431.6 (10.6)	2.4 (1.1)	7.9 (1.5)	2.8 (0.8)
(4)2N albizia	18.8 (2.4)	429.2 (13.5)	2.3 (1.1)	7.5 (2.2)	3.2 (0.6)
(5)1N combo	20.7 (3.3)	432.0 (13.6)	2.5 (1.2)	7.6 (1.2)	2.4 (0.9)
(6)2N combo	23.1 (3.2)	432.9 (13.7)	2.8 (1.2)	8.2 (1.1)	2.0 (0.6)
F stat	1.703			0.313	2.481
Chi-sq		3.389	0.98		
df	5,18	5	5	5,18	5,18
p-value	0.185	0.64	0.964	0.899	0.071
transformed	no	no	no	no	no

Treatment	leaf P (g kg^{-1})	leaf Fe (mg kg^{-1})	leaf Cu (mg kg^{-1})	leaf Mn (mg kg^{-1})	leaf Zn (mg kg^{-1})
(1)control	3.7 (1.0)	93 (29)	4.4 (1.2)	17 (5)	26 (6)
(2)1N fert	2.9 (0.7)	81 (10)	6.8 (3.1)	16 (4)	23 (5)
(3)1N albizia	4.0 (0.6)	71 (14)	4.5 (1.3)	16 (6)	26 (9)
(4)2N albizia	4.5 (1.0)	63 (6)	5.0 (1.0)	15 (5)	49 (35)
(5)1N combo	3.4 (0.4)	72 (16)	5.5 (2.3)	16 (7)	32 (13)
(6)2N combo	3.1 (0.4)	88 (23)	6.6 (3.2)	15 (6)	32 (13)
F stat	2.712	1.604		0.114	
Chi-sq			3.1179		3.524
df	5,18	5,18	5	5,18	5
p-value	0.054	0.209	0.682	0.988	0.62
transformed	no	log	no	no	no

Appendix A.9. Corn nutrient level means (with standard deviation in parentheses), and results of ANOVA (F stat) or Kruskal-Wallis (Chi-sq) tests by location. Significant tests have bold p-values. Letters were given to different means in significant comparisons. Soil resin values are in units of μg N-NO_3^-, N-NH_4^+, or P-PO_4^-/gram anion or cation resin/day.

Location	pH	soil P (mg kg^{-1})	soil Ca (mg kg^{-1})	soil K (mg kg^{-1})	soil Mg (mg kg^{-1})	soil NO_3 (mg kg^{-1})	soil NH_4 (mg kg^{-1})
Pepe‘ekeo	5.6 (0.1) ^{a}	33 (8) ^{a}	324 (103) ^{a}	65 (13)	108 (21) ^{a}	3.3 (1.7) ^{a}	2.9 (0.9)
Kolekole	5.8 (0.2) ^{a}	32 (8) ^{a}	350 (80) ^{a}	72 (22)	121 (26) ^{a}	1.3 (1.2) ^{a}	4.8 (1.5)
Honomū	5.8 (0.2) ^{a}	46 (11) ^{a}	824 (189) ^{b}	60 (14)	190 (69) ^{a}	6.7 (2.4) ^{b}	5.6 (2.3)
Kapa‘au	6.6 (0.1) ^{b}	72 (21) ^{b}	3129 (428) ^{c}	1122 (180)	1240 (69) ^{b}	9.2 (1.7) ^{b}	1.0 (0.4)
F stat		12.29	180.9			22.59	11.94
Chi-sq	16.159			13.887	16.287		
df	3	3,20	3,20	3	3	3,20	3,20
p-value	**0.001**	**< 0.001**	**< 0.001**	0.003	**< 0.001**	**< 0.001**	**< 0.001**
transformed	no	log	no	no	no	no	no

Location	**soil N ($g\ kg^{-1}$)**	**soil C ($g\ kg^{-1}$)**	**soil DOC ($mg\ kg^{-1}$)**	**soil resin PO_4**	**soil resin NO_3**	**soil resin NH_4**
Pepe‘ekeo	7.0 (0.2) ^{a}	104.8 (6.2) ^{a}	6.5 (6.0) ^{a}	70 (43) ^{ab}	190 (155)	158 (165)
Kolekole	5.5 (0.5) ^{b}	80.0 (3.2) ^{b}	-4.2 (6.0) ^{b}	20 (16) ^{a}	1835 (1493)	473 (364)
Honomū	6.6 (0.4) ^{a}	86.3 (4.5) ^{b}	13 (10) ^{a}	91 (75) ^{ab}	2080 (2266)	437 (530)
Kapa‘au	4.1 (0.5) ^{c}	42.9 (7.4) ^{c}	51 (17) ^{c}	205 (80) ^{b}	2448 (4058)	854 (1286)
F stat		130.4	24.01		1.857	0.302
Chi-sq	19.887			14.8		
df	3	3,20	3,20	3	3,18	3,18
p-value	**<0.001**	**< 0.001**	**< 0.001**	**0.002**	0.173	0.823
transformed	no	no	log	no	log	log

Location	**leaf N ($g\ kg^{-1}$)**	**leaf C ($g\ kg^{-1}$)**	**leaf Ca ($g\ kg^{-1}$)**	**leaf K ($g\ kg^{-1}$)**	**leaf Mg ($g\ kg^{-1}$)**
Pepe‘ekeo	19.2 (2.2) ^{a}	434.3 (3.7)	1.7 (0.3) ^{a}	9.4 (0.7) ^{a}	2.7 (0.5) ^{ab}
Kolekole	18.1 (3.5) ^{a}	436.7 (5.0)	1.5 (0.4) ^{a}	7.7 (1.1) ^{bc}	3.2 (0.8) ^{a}
Honomū	24.1 (2.6) ^{b}	435.6 (13.1)	4.1 (0.5) ^{b}	8.1 (0.9) ^{ab}	2.2 (0.3) ^{b}
Kapa‘au	18.1 (2.0) ^{a}	407.9 (9.1)	2.8 (0.3) ^{c}	6.4 (1.3) ^{c}	2.1 (0.8) ^{b}
F stat	6.986			8.282	4.42
Chi-sq		12.452	19.607		
df	3,20	3	3	3,20	3,20
p-value	**0.002**	0.006	**< 0.001**	**< 0.001**	0.015
transformed	no	no	no	no	no

Location	**leaf P (g kg^{-1})**	**leaf Fe (mg kg^{-1})**	**leaf Cu (mg kg^{-1})**	**leaf Mn (mg kg^{-1})**	**leaf Zn (mg kg^{-1})**
Pepe‘ekeo	3.7 (0.9)	86 (12)	6.6 (2.1)	22 (3) ^{a}	22 (2) ^{a}
Kolekole	2.8 (0.5)	76 (22)	5.2 (1.7)	15 (2) ^{bc}	20 (1) ^{a}
Honomū	4.1 (0.5)	70 (9)	7.1 (1.2)	11 (2) ^{b}	45 (27) ^{b}
Kapa‘au	3.8 (1.0)	81 (28)	2.9 (0.8)	16 (4) ^{c}	39 (10) ^{b}
F stat	3.247	0.732		16.57	
Chi-sq			15.123		17.239
df	3,20	3,20	3	3,20	3
p-value	0.044	0.545	**0.002**	**< 0.001**	**< 0.001**
transformed	no	log	no	no	no

Appendix A.10. Corn aboveground biomass yields correlated with soil and plant nutrient variables. Significant tests have bold p-values.

Variable 1	Variable 2	r (Pearson)	ρ (Spearman)	S	t	df	p value	95% CI
log biomass	pH		-0.345	3093			0.099	
log biomass	**log soil P (mg kg^{-1})**	-0.228		2614	-1.100	22	0.283	-0.578, 0.193
log biomass	**soil Ca (mg kg^{-1})**		-0.013	2330			0.953	
log biomass	**soil K (mg kg^{-1})**		-0.092	2512			0.667	
log biomass	**soil Mg (mg kg^{-1})**		0.034	2222			0.876	
log biomass	**soil NO_3 (mg kg^{-1})**	0.219			1.051	22	0.305	-0.203, 0.572
log biomass	**soil NH_4 (mg kg^{-1})**	0.436			2.274	22	0.033	0.040, 0.714
log biomass	**soil N (g kg^{-1})**		0.281	1654			0.183	
log biomass	**soil C (g kg^{-1})**	0.232			1.117	22	0.276	-0.190, 0.581
log biomass	**log soil DOC (mg kg^{-1})**	-0.185			-0.884	22	0.386	-0.548, 0.236
log biomass	**soil resin PO_4**		-0.285	2956			0.176	
log biomass	**log soil resin NO_3**	0.492			2.528	20	0.02	0.089, 0.757
log biomass	**log soil resin NH_4**	0.383			1.853	20	0.079	-0.046, 0.693
log biomass	**leaf N (g kg^{-1})**	0.675			4.288	22	**< 0.001**	
log biomass	**leaf C (g kg^{-1})**		0.439	1290			0.032	
log biomass	**leaf Ca (g kg^{-1})**		0.445	1276			0.03	
log biomass	**leaf K (g kg^{-1})**	0.343			1.712	22	0.101	-0.070, 0.656
log biomass	**leaf Mg (g kg^{-1})**	-0.472			-2.510	22	0.02	-0.735, -0.085
log biomass	**leaf P (g kg^{-1})**	-0.425			-2.204	22	0.038	-0.707, -0.027
log biomass	**log leaf Fe (mg kg^{-1})**	0.031			0.146	22	0.886	-0.377, 0.429
log biomass	**leaf Cu (mg kg^{-1})**		0.629	863			**0.001**	
log biomass	**leaf Mn (mg kg^{-1})**	-0.273			-1.333	22	0.196	-0.610, 0.146
log biomass	**leaf Zn (mg kg^{-1})**		-0.001	2303			0.995	

Appendix A.11. Corn ear yields correlated with soil and plant nutrient variables. Significant tests have bold p-values.

Variable 1	**Variable 2**	**r (Pearson)**	**ρ (Spearman)**	**S**	**t**	**df**	**p value**	**95% CI**
log corn ears	pH		-0.3349	3070			0.11	
log corn ears	**log soil P (mg kg^{-1})**	-0.1571			-0.746	22	0.464	-0.527, 0.263
log corn ears	**soil Ca (mg kg^{-1})**		0.07391	2130			0.731	
log corn ears	**soil K (mg kg^{-1})**		-0.02957	2368			0.892	
log corn ears	**soil Mg (mg kg^{-1})**		0.08696	2100			0.685	
log corn ears	**soil NO_3 (mg kg^{-1})**	0.3389			1.689	22	0.105	-0.075, 0.653
log corn ears	**soil NH_4 (mg kg^{-1})**	0.3904			1.989	22	0.059	-0.015, 0.686
log corn ears	**soil N (g kg^{-1})**		0.2878	1638			0.172	
log corn ears	**soil C (g kg^{-1})**	0.2296			1.107	22	0.281	-0.192, 0.579
log corn ears	**log soil DOC (mg kg^{-1})**	-0.1262			-0.597	22	0.557	-0.504, 0.292
log corn ears	**soil resin PO_4**		-0.06348	2446			0.768	
log corn ears	**log soil resin NO_3**	0.4525			2.269	20	0.034	0.038, 0.734
log corn ears	**log soil resin NH_4**	0.3879			1.882	20	0.074	-0.040, 0.696
log corn ears	**leaf N (g kg^{-1})**	0.7673			5.613	22	**< 0.001**	0.527, 0.894
log corn ears	**leaf C (g kg^{-1})**		0.3853	1414			0.063	
log corn ears	**leaf Ca (g kg^{-1})**		0.5348	1070			0.008	
log corn ears	**leaf K (g kg^{-1})**	0.2826			1.382	22	0.181	-0.136, 0.616
log corn ears	**leaf Mg (g kg^{-1})**	-0.5554			-3.133	22	0.005	-0.783, -0.196
log corn ears	**leaf P (g kg^{-1})**	-0.3034			-1.493	22	0.15	-0.630, 0.114
log corn ears	**log leaf Fe (mg kg^{-1})**	0.1212			0.573	22	0.573	-0.297, 0.500
log corn ears	**leaf Cu (mg kg^{-1})**		0.6636	774			**< 0.001**	
log corn ears	**leaf Mn (mg kg^{-1})**	-0.2919			-1.432	22	0.166	-0.622, 0.126
log corn ears	**leaf Zn (mg kg^{-1})**		0.07131	2136			0.741	

Appendix A.12. Cassava total biomass means, cassava root biomass means (with standard deviation in parentheses), and percent difference from control of these variables, with results of ANOVA or Kruskal-Wallis tests by treatment.

Treatment	**mean cassava total biomass (Mg ha^{-1})**	**mean cassava biomass diff from control (%)**	**mean cassava roots (Mg ha^{-1})**	**mean cassava roots diff from control (%)**	**soil aggregation (%)**
(1)control	19.1 (16.5)	0 (0)	6.67 (4.10)	0 (0)	52 (8.0)
(2)1N fert	23.9 (14.6)	52 (80)	9.01 (5.04)	61 (88)	50 (9.0)
(3)1N albizia	21.0 (12.8)	30 (53)	7.58 (3.67)	33 (54)	55 (15)
(4)2N albizia	22.4 (16.1)	41 (65)	8.84 (5.82)	48 (80)	56 (6.0)
(5)1N combo	22.2 (8.80)	85 (99)	8.41 (3.73)	88 (128)	56 (7.0)
(6)2N combo	24.0 (12.1)	83 (88)	8.80 (5.08)	75 (109)	68 (11)
F stat	0.072	no test	0.2072	no test	1.6
df	5,18		5,18		5,18
p-value	0.996		0.955		0.211
transformed	no		no		no

Appendix A.13. Cassava total biomass means and cassava root means (with standard deviation in parentheses), with results of ANOVA tests by location. Letters are given to different means in significant comparisons.

Location	**mean cassava total biomass (Mg ha^{-1})**	**mean cassava roots (Mg ha^{-1})**	**soil aggregation (%)**
Pepe‘ekeo	6.04 (2.69) ^{a}	3.10 (1.59) ^{a}	46 (10) ^{a}
Kolekole	21.5 (6.50) ^{b}	11.9 (3.86) ^{b}	60 (6.0) ^{c}
Honomū	38.2 (4.40) ^{c}	10.8 (2.20) ^{bc}	64 (11) ^{bc}
Kapa‘au	22.7 (1.95) ^{b}	6.69 (.59) ^{ac}	53 (5.0) ^{b}
F stat	56.956	15.36	5.798
df	3,20	3,20	3,20
p-value	**<0.001**	**<0.001**	**0.005**
transformed	no	no	no

Appendix A.14. Eigenvector values for PCA of cassava nutrients.

Variable	PC1	PC2	PC3	PC4	PC5
pH	-0.277	-0.284	0.049	0.123	0.060
soil K (mg kg^{-1})	-0.275	-0.254	-0.165	0.067	-0.033
soil Mg (mg kg^{-1})	-0.290	-0.250	-0.122	0.076	-0.079
log soil NO_3 (mg kg^{-1})	-0.301	-0.104	0.096	0.038	-0.020
log soil NH_4 (mg kg^{-1})	-0.159	0.276	0.209	-0.224	0.574
soil C (g kg^{-1})	0.231	0.345	0.113	0.086	-0.068
log soil DOC (mg kg^{-1})	-0.289	-0.089	-0.006	0.280	-0.030
log soil resin PO_4	-0.240	0.115	0.243	-0.256	0.153
log soil resin NO_3	-0.276	0.109	0.158	0.274	0.000
log soil resin NH_4	-0.139	0.316	0.081	0.533	0.278
leaf N (g kg^{-1})	-0.290	0.160	-0.166	-0.165	-0.230
leaf C (g kg^{-1})	0.135	-0.350	0.286	-0.261	-0.019
leaf Ca (g kg^{-1})	0.231	-0.008	0.265	0.359	-0.249
leaf K (g kg^{-1})	-0.208	0.242	0.290	-0.163	-0.065
leaf Mg (g kg^{-1})	0.113	-0.389	-0.026	-0.062	0.541
leaf P (g kg^{-1})	-0.249	0.216	-0.277	-0.234	-0.007
leaf Mn (mg kg^{-1})	0.145	0.220	-0.448	-0.165	-0.017
leaf Zn (mg kg^{-1})	-0.249	0.004	0.018	-0.165	-0.281
soil aggregation	-0.008	-0.018	0.507	-0.221	-0.248

Appendix A.15. Eigenvalues and % variation for top five principal component vectors for cassava PCA.

PC	Eigenvalues	%Variation	Cum.%Variation
1	8.54	44.9	44.9
2	3.02	15.9	60.9
3	2.76	14.5	75.4
4	1.16	6.1	81.5
5	0.785	4.1	85.6

Appendix A.16. Cassava nutrient level means (with standard deviation in parentheses), and results of ANOVA (F stat) or Kruskal-Wallis (Chi-sq) tests by treatment. Significant tests have bold p-values. Letters are given to different means in significant comparisons. Soil resin values are in units of µg N-NO_3^-, N-NH_4^+, or P-PO_4^-/gram anion or cation resin/day.

Treatment	**pH**	**soil P (mg kg^{-1})**	**soil Ca (mg kg^{-1})**	**soil K (mg kg^{-1})**	**soil Mg (mg kg^{-1})**	**soil NO_3 (mg kg^{-1})**	**soil NH_4 (mg kg^{-1})**
(1)control	5.6 (0.2)	18 (0.7)	841 (1192)	225 (343	360 (594)	3.6 (4.0)	2.0 (0.2)
(2)1N fert	5.6 (0.3)	18 (0.8)	645 (636)	202 (288)	272 (364)	4.7 (2.9)	2.4 (0.3)
(3)1N albizia	5.6 (0.3)	18 (0.8)	601 (674)	149 (203)	242 (354)	4.3 (3.2)	2.3 (0.3)
(4)2N albizia	5.7 (0.2)	18 (0.6)	654 (639)	125 (186)	259 (363)	5.3 (5.1)	2.7 (0.7)
(5)1N combo	5.7 (0.2)	18 (0.7)	580 (568)	186 (293)	248 (355)	4.4 (4.1)	2.5 (0.6)
(6)2N combo	5.7 (0.2)	19 (0.7)	716 (529)	161 (211)	260 (335)	5.1 (2.4)	2.5 (1.0)
F stat		1.266	0.096			0.32	0.616
Chi-sq	1.785			2.02	1.04		
df	5	5,18	5,18	5	5	5,18	5,18
p-value	0.878	0.321	0.992	0.846	0.959	0.895	0.689
transformed	no	log	log	no	no	log	log

Treatment	**soil N (g kg^{-1})**	**soil C (g kg^{-1})**	**soil DOC (mg kg^{-1})**	**soil resin PO_4**	**soil resin NO_3**	**soil resin NH_4**
(1)control	4.9 (1.5)	62.0 (21.4)	119 (207)	30 (19)	434 (487)	113 (101)
(2)1N fert	5.9 (1.5)	76.8 (22.6)	82 (93)	20 (26)	406 (395)	186 (199)
(3)1N albizia	5.8 (1.0)	78.1 (23.5)	233 (412)	85 (148)	581 (695)	500 (662)
(4)2N albizia	5.7 (1.0)	76.4 (22.4)	41 (18)	28 (28)	400 (426)	172 (81)
(5)1N combo	5.7 (1.2)	76.8 (24.6)	28 (23)	72 (80)	1057 (1282)	113 (36)
(6)2N combo	5.9 (1.2)	79.0 (26.4)	39 (18)	201 (380)	664 (923)	323 (402)
F stat	0.384		0.411	0.147	0.126	0.328
Chi-sq		2.519				
df	5,18	5	5,18	5,18	5,18	5,18
p-value	0.853	0.774	0.835	0.978	0.985	0.89
transformed	no	no	log	log	log	log

Treatment	**leaf N (g kg^{-1})**	**leaf C (g kg^{-1})**	**leaf Ca (g kg^{-1})**	**leaf K (g kg^{-1})**	**leaf Mg (g kg^{-1})**
(1)control	35.7 (9.9)	46.0 (1.2)	13.1 (3.2)	10.3 (1.4)	3.6 (0.6)
(2)1N fert	33.4 (5.2)	46.2 (1.6)	12.7 (3.2)	8.5 (1.4)	3.4 (0.4)
(3)1N albizia	37.5 (7.5)	45.0 (2.5)	11.2 (2.7)	11.0 (1.9)	3.1 (0.2)
(4)2N albizia	35.4 (6.3)	46.2 (1.0)	12.2 (2.3)	9.0 (1.3)	3.6 (0.7)
(5)1N combo	36.8 (6.3)	46.5 (0.9)	11.3 (3.3)	10.7 (3.2)	3.3 (0.5)
(6)2N combo	36.4 (6.5)	46.2 (0.8)	13.5 (1.6)	9.8 (3.5)	3.6 (0.6)
F stat	0.164		0.46	0.68	0.51
Chi-sq		2.54			
df	5,18	5	5,18	5,18	5,18
p-value	0.973	0.77	0.801	0.644	0.769
transformed	no	no	no	no	no

Treatment	**leaf P (g kg^{-1})**	**leaf Fe (mg kg^{-1})**	**leaf Cu (mg kg^{-1})**	**leaf Mn (mg kg^{-1})**	**leaf Zn (mg kg^{-1})**
(1)control	2.8 (0.8)	410 (590)	6.0 (1.2)	190 (120)	46 (9.7)
(2)1N fert	2.6 (0.5)	150 (100)	4.9 (0.7)	160 (89)	39 (5.1)
(3)1N albizia	3.0 (0.7)	120 (48)	6.2 (1.4)	160 (94)	44 (10)
(4)2N albizia	2.9 (0.7)	110 (31)	5.2 (0.8)	160 (74)	49 (18)
(5)1N combo	2.9 (0.6)	110 (28)	5.8 (1.1)	140 (64)	44 (16)
(6)2N combo	2.8 (0.5)	110 (19)	5.5 (0.7)	160 (80)	48 (5.1)
F stat					0.439
Chi-sq	1.71	1.447	3.368	1.46	
df	5	5	5	5	5,18
p-value	0.888	0.919	0.644	0.918	0.815
transformed	no	no	no	no	no

Appendix A.17. Cassava nutrient level means (with standard deviation in parentheses), and results of ANOVA (F stat) or Kruskal-Wallis (Chi-sq) tests by location. Significant tests have bold p-values. Letters were given to different means in significant comparisons. Soil resin values are in units of μg N-NO_3^-, N-NH_4^+, or P-PO_4^-/gram anion or cation resin/day.

Location	**pH**	**soil P (mg kg^{-1})**	**soil Ca (mg kg^{-1})**	**soil K (mg kg^{-1})**	**soil Mg (mg kg^{-1})**	**soil NO_3 (mg kg^{-1})**	**soil NH_4 (mg kg^{-1})**
Pepe‘ekeo	5.4 (0.1) ^{a}	17 (0.4) ^{a}	181 (87) ^{a}	64 (18) ^{a}	59 (22) ^{a}	2.1 (1.1) ^{a}	2.2 (0.4)
Kolekole	5.6 (0.1) ^{ab}	18 (0.7) ^{a}	322 (182) ^{ab}	51 (15) ^{a}	79 (30) ^{a}	2.3 (0.8) ^{ab}	2.1 (0.3)
Honomū	5.6 (0.1) ^{b}	18 (0.4) ^{a}	484 (82) ^{b}	29 (9.6) ^{b}	92 (15) ^{a}	4.1 (1.2) ^{b}	2.9 (0.8)
Kapa‘au	6.0 (0.0) ^{c}	19 (0.3) ^{b}	1705 (452) ^{c}	555 (130) ^{c}	863 (191) ^{b}	9.7 (1.7) ^{c}	2.5 (0.4)
F stat		13.86	48.73	118.5		22.24	2.304
Chi-sq	18.029				16.82		
df	3	3,20	3,20	3,20	3	3,20	3,20
p-value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.108
transformed	no	log	log	log	no	log	log

Location	**soil N (g kg^{-1})**	**soil C (g kg^{-1})**	**soil DOC (mg kg^{-1})**	**soil resin PO_4**	**soil resin NO_3**	**soil resin NH_4**
Pepe‘ekeo	6.2 (1.5) ^{a}	90.3 (21.3) ^{ab}	21 (12) ^{a}	7.0 (2.8)	80 (120) ^{a}	328 (554)
Kolekole	5.5 (0.2) ^{a}	79.0 (2.5) ^{a}	22 (11) ^{a}	14 (16)	43 (31) ^{a}	70 (49)
Honomū	6.7 (0.2) ^{a}	86.9 (1.9) ^{b}	37 (11) ^{a}	174 (298)	1021 (854) ^{b}	346 (317)
Kapa‘au	4.2 (2.3) ^{b}	43.1 (2.0) ^{c}	281 (315) ^{b}	96 (109)	1216 (526) ^{b}	193 (130)
F stat	11.09		11.65	5.918	22.54	2.321
Chi-sq		18.008				
df	3,20	3	3,20	3,20	3,20	3,20
p-value	**< 0.001**	**< 0.001**	**< 0.001**	0.004	**<0.001**	0.106
transformed	no	no	log	log	log	log

Location	**leaf N (g kg^{-1})**	**leaf C (g kg^{-1})**	**leaf Ca (g kg^{-1})**	**leaf K (g kg^{-1})**	**leaf Mg (g kg^{-1})**
Pepe‘ekeo	36.8 (1.9) ^{a}	45.1 (1.9)	12.0 (2.1) ^{ab}	8.3 (1.1) ^{a}	3.35 (0.27) ^{a}
Kolekole	27.7 (2.0) ^{b}	47.7 (0.4)	13.8 (1.6) ^{a}	8.4 (1.2) ^{a}	4.00 (0.45) ^{b}
Honomū	36.2 (4.7) ^{a}	45.8 (0.5)	14.1 (2.6) ^{a}	12.2 (2.0) ^{b}	2.96 (0.20) ^{a}
Kapa‘au	42.8 (4.6) ^{c}	45.5 (0.6)	9.5 (1.4) ^{b}	10.6 (1.9) ^{ab}	3.46 (0.40) ^{a}
F stat	18.6		6.936	8.392	9.183
Chi-sq		13.734			
df	3,20	3	3,20	3,20	3,20
p-value	**<0.001**	0.003	**0.002**	**< 0.001**	**< 0.001**
transformed	no	no	no	no	no

Location	**leaf P (g kg^{-1})**	**leaf Fe (mg kg^{-1})**	**leaf Cu (mg kg^{-1})**	**leaf Mn (mg kg^{-1})**	**leaf Zn (mg kg^{-1})**
Pepe‘ekeo	3.1 (0.4) ^{a}	90 (0)	5.7 (0.3)	288 (46)	40 (6.0)
Kolekole	0.1 (0.1) ^{b}	105 (22)	4.4 (0.4)	122 (24)	37 (5.8)
Honomū	2.7 (0.5) ^{ab}	368 (461)	5.8 (0.6)	120 (15)	48 (6.1)
Kapa‘au	3.4 (0.4) ^{a}	102 (5.0)	6.5 (1.1)	111 (25)	55 (11)
F stat					6.667
Chi-sq	14.813	14.238	14.054	13.28	
df	3	3	3	3	3,20
p-value	**0.002**	0.003	0.003	0.004	0.003
transformed	no	no	no	no	no

Appendix A.18. Cassava total biomass yields correlated with soil and plant nutrient variables. Significant tests have bold p-values.

Variable 1	**Variable 2**	**r (Pearson)**	**ρ (Spearman)**	**S**	**t**	**df**	**p value**	**95% CI**
biomass	**pH**		0.407	1364			0.049	
biomass	**log soil P (mg kg^{-1})**	0.319			1.579	22	0.129	
biomass	**log soil Ca (mg kg^{-1})**	0.471			2.501	22	0.02	0.083, 0.735
biomass	**soil K (mg kg^{-1})**		-0.404	3228			0.052	
biomass	**soil Mg (mg kg^{-1})**		0.420	1264			0.028	
biomass	**log soil NO$_3$ (mg kg^{-1})**	0.408			2.094	22	0.048	0.005, 0.697
biomass	**log soil NH$_4$ (mg kg^{-1})**	0.327			1.622	22	0.119	-0.088, 0.645
biomass	**soil N (g kg^{-1})**	0.133			0.628	22	0.537	-0.286, 0.509
biomass	**soil C (g kg^{-1})**		-0.053	2423			0.804	
biomass	**log soil DOC (mg kg^{-1})**	0.288			1.412	22	0.172	-0.130, 0.620
biomass	**log soil resin PO$_4$**	0.387			1.966	22	0.062	-0.020, 0.683
biomass	**log soil resin NO$_3$**	0.594			3.465	22	**0.002**	0.251, 0.805
biomass	**log soil resin NH$_4$**	0.289			1.413	22	0.172	-0.130, 0.620
biomass	**leaf N (g kg^{-1})**	-0.031			-0.148	22	0.884	-0.429, 0.377
biomass	**leaf C (g kg^{-1})**		0.151	1952			0.481	
biomass	**leaf Ca (g kg^{-1})**	0.348			1.740	22	0.096	-0.065, 0.659
biomass	**leaf K (g kg^{-1})**	0.497			2.689	22	0.013	0.118, 0.750
biomass	**leaf Mg (g kg^{-1})**	-0.298			-1.463	22	0.158	-0.626, 0.120
biomass	**leaf P (g kg^{-1})**		-0.285	2955			0.177	
biomass	**leaf Fe (mg kg^{-1})**		0.697	696			**< 0.001**	
biomass	**leaf Cu (mg kg^{-1})**		-0.069	2459			0.748	
biomass	**leaf Mn (mg kg^{-1})**		-0.598	3676			**0.002**	
biomass	**leaf Zn (mg kg^{-1})**	0.260			1.263	22	0.22	-0.160, 0.601
biomass	**soil aggregation**	0.593			3.450	22	**0.002**	0.249, 0.804

Appendix A.19. Cassava root biomass yields correlated with soil and plant nutrient variables. Significant tests have bold p-values.

Variable 1	Variable 2	r (Pearson)	ρ (Spearman)	S	t	df	p value	95% CI
roots	**pH**		0.298	1615			0.157	
roots	**log soil P (mg kg^{-1})**	0.194			0.930	22	0.363	-0.227, 0.554
roots	**log soil Ca (mg kg^{-1})**	0.224			1.079	22	0.292	-0.197, 0.576
roots	**soil K (mg kg^{-1})**		-0.388	3192			0.062	
roots	**soil Mg (mg kg^{-1})**		0.266	1688			0.208	
roots	**log soil NO_3 (mg kg^{-1})**	0.097			0.455	22	0.654	-0.319, 0.481
roots	**log soil NH_4 (mg kg^{-1})**	0.056			0.264	22	0.794	-0.355, 0.449
roots	**soil N (g kg^{-1})**	0.080			0.375	22	0.711	'-0.334, 0.468
roots	**soil C (g kg^{-1})**		-0.070	2461			0.745	
roots	**log soil DOC (mg kg^{-1})**	0.092			0.434	22	0.669	-0.323, 0.478
roots	**log soil resin PO_4**	0.028			0.132	22	0.896	-0.380, 0.427
roots	**log soil resin NO_3**	0.157			0.744	22	0.465	-0.263, 0.527
roots	**log soil resin NH_4**	0.037			0.175	22	0.863	-0.372, 0.434
roots	**leaf N (g kg^{-1})**	-0.436			-2.272	22	0.033	-0.714, -0.039
roots	**leaf C (g kg^{-1})**		0.444	1280			0.03	
roots	**leaf Ca (g kg^{-1})**	0.472			2.508	22	0.02	0.084, 0.735
roots	**leaf K (g kg^{-1})**	0.046			0.216	22	0.831	-0.364, 0.441
roots	**leaf Mg (g kg^{-1})**	0.147			0.697	22	0.493	-0.273, 0.520
roots	**leaf P (g kg^{-1})**		-0.553	3572			0.005	
roots	**leaf Fe (mg kg^{-1})**		0.410	1357			0.047	
roots	**leaf Cu (mg kg^{-1})**		-0.450	3336			0.027	
roots	**leaf Mn (mg kg^{-1})**		-0.618	3722			**0.002**	
roots	**leaf Zn (mg kg^{-1})**	-0.102			-0.479	22	0.637	-0.485, 0.315
roots	**soil aggregation**	0.529			2.924	22	0.008	0.160, 0.768

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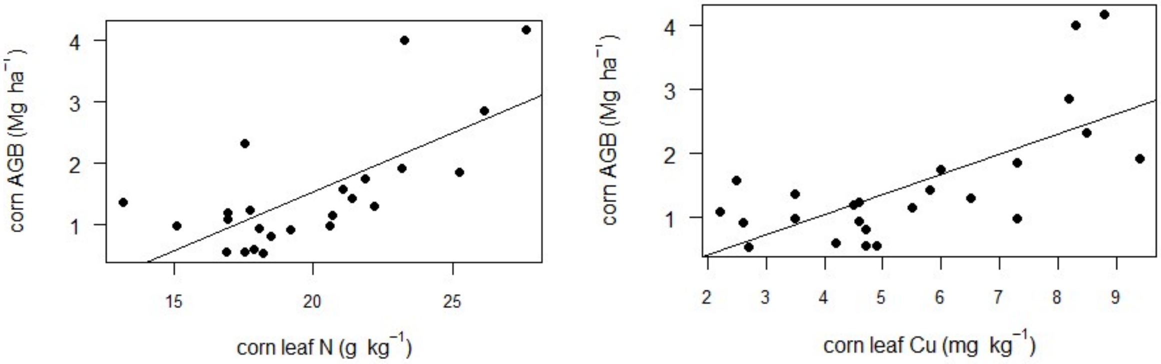
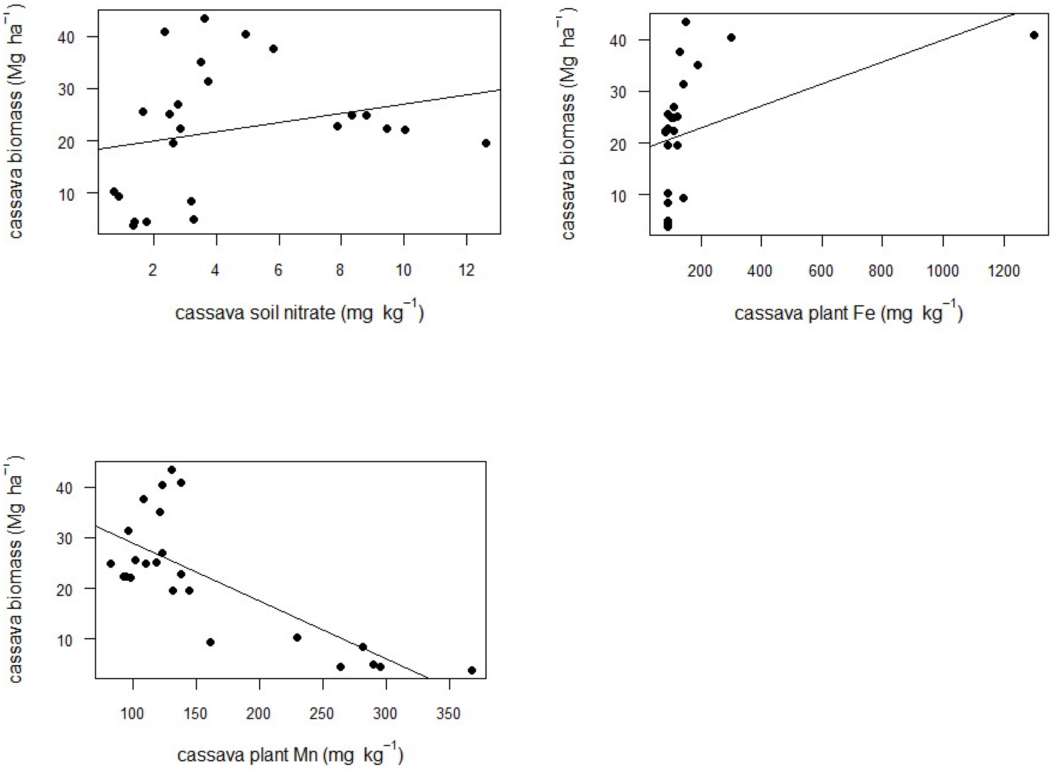
Appendix B. Figures



Appendix B.1a and 1b. Scatterplots of corn aboveground biomass (AGB) versus corn leaf N and Cu, two nutrients showing correlation with corn aboveground biomass yield.



Appendix B.2a, 2b, 2c. Scatterplots of cassava total biomass versus soil NO_3, leaf Fe, and leaf Mn, the 3 nutrients showing correlation with cassava biomass.

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