Using Biochar in Coffee Agroforestry Management to Store Soil Carbon and Produce Biomass Energy in Puerto Rico

By

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Introduction

Anthropogenic climate change is disrupting ecological and human systems worldwide, particularly across the tropics. A complete transformation of our energy and food systems is necessary. We must aggressively phase out fossil fuels and dramatically reduce the current levels of atmospheric CO_2 to avoid disaster. The 2018 IPCC Report acknowledges that to stay under the 1.5 degrees of warming target, carbon dioxide removal (CDR) must be employed. Unfortunately, most proposed CDR projects center around expensive and energy-intensive industrial-chemical processes. Instead, we hope that this research can contribute to the growing amount of scholarly research of biological carbon sequestration through smallholding agricultural management and energy microgrids.

The motivation behind this research is to understand the potential between coffee agroecosystems, smallholder farming, and climate change mitigation. Current research shows evidence that smallholder management of coffee agroecosystems is linked to increased biodiversity (Richard & Mendez, 2013; Perfecto et al., 2014; Goodall et al., 2015). However, the results are mixed for its potential for carbon sequestration and climate change mitigation (Schmitt-Harsh et al., 2012; Richard & Mendez, 2013; Goodall et al., 2015; Tumwebaze & Byakagaba, 2016). This study explores the sustainable management of coffee agroforests using biochar and biomass energy to store soil carbon and provide decentralized energy in rural and farming communities in Puerto Rico.

This work is divided in two chapters. In Chapter 1, we examine the relationship between shade management in coffee agroforestry, and the availability of downed woody material (DWM), and its potential as feedstock for energy production. We estimate total biomass of DWM from sampling twenty coffee farms across a shade gradient in the central mountains of Puerto Rico using line transects. We then compare the average amount of DWM found in each farm and the amount of shade measured at two levels (at breast height and above the highest coffee bush). Using the data obtained in the field survey, we estimate the potential for electricity generation per year using DWM from coffee agroforests in Puerto Rico and the potential for reduction in carbon emissions from the production of biochar.

In Chapter 2, we study a greenhouse experiment using biochar to understand its effects on plant growth of coffee (*Coffea arabica*). Using coffee seedlings grown in different mediums consisting of compost, soil, and biochar mixtures, we track height, number of leaves, and length of the longest leaf of each seedling for three consecutive months to understand the potential effect of biochar as a soil amendment. This study was the first part of a broader project with our local partner Casa Pueblo. This self-management organization owns a small coffee farm where the seedlings were transplanted for the next phase of this project.

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I. Chapter 1: Estimating Woody Debris Biomass Availability across a Shade Gradient in Puerto Rican Coffee Agro-Ecosystems for small scale Biochar and Bioenergy Production

Abstract

Many agroforestry systems exist along a shade gradient depending on management practices. Shade trees are thought to be responsible for multiple ecosystem functions such as nitrogen fixation, nutrient cycling, moisture retention, and carbon storage, among others. Recently there has been growing interest in an additional potential function of shade and the provisioning of biomass as feedstock in small-scale biochar and other bioenergy production. The goal of this study is to examine the relationship between shade management in coffee agroforestry and the consequent availability of woody debris for its potential as feedstock for energy production. We estimated total biomass of woody debris from surveys of twenty coffee farms across a shade gradient in the central mountains of Puerto Rico, using line transects. We compared amount of woody debris biomass with upper (above coffee plants) and lower (at approximately 1.3 meters above ground) canopy cover in each farm. We found that the average amount of down woody material (DWM) biomass was 1.5 Mg/ha with a standard deviation of 1.76 Mg/ha, ranging from 0.25 Mg/ha to 6.67 Mg/ha. There is a statistically significant difference between the average biomass available in shade farms (1.91 Mg/ha) vs. sun farms (0.88 Mg/ha) ($p < 0.05$). After performing a linear regression, we can observe that lower canopy and biomass are positively related showing the influence of planting density and biomass. However, upper canopy and biomass are negatively related and sharply so for sun coffee farms. Using our results and data from the Caribbean Climate Hub, we estimate a potential for 5.79 GWh/year producible from DWM in coffee agroforests in the entire island of Puerto Rico through biomass gasification. Biochar, co-produced in the gasification process and returned to farm soil, could potentially reduce 8110 tons of CO_2e/year. Our study shows evidence linking shade management practices with increased biomass. Additionally, it provides base line estimates for a circular economy model linking agroforestry coffee production and decentralized renewable energy production in rural Puerto Rico. Through co-production of biomass energy and biochar, coffee farmers can reduce carbon emissions associated with decomposition of DWM within their farms while supplying part of their own energy needs through syngas.

1. Background

Anthropogenic climate change is disrupting ecological and human systems worldwide. At 450 ppm, current CO_2 levels in the atmosphere have locked the planet into a future of extreme climatic events with dire consequences, particularly across the tropics (Masson-Delmotte et al., 2018). Since our current CO_2 levels are well above the limit that serious scientific studies have established is necessary to avoid catastrophic planetary consequences, a rapid coordinated response to this issue is imperative. Climate change mitigation requires a complete transformation of our energy systems by phasing out fossil fuels and reducing the current levels of atmospheric CO_2. Although a host of expensive, controversial, and technologically heavy proposals have been floated, especially in the grey and popular literature, the potential for carbon sequestration and reduced emissions of smallholder agriculture has not received the attention it deserves.

In particular, the role and function of agroforests has not been studied as much as other types of forests, yet they are critical repositories of carbon. For example, Zomer et al. (2016) report that more than 43% of agricultural land globally has more than 10% tree cover, containing an estimated 45 billion tons of carbon. While there is obviously a great deal of carbon in trunks, roots, and leaves of the trees in agroforestry systems, they are also quite dynamic ecologically. Agroforests, much like other forests, have an internal cycling mechanism that also includes respiration from both plants and the microorganisms decomposing the debris they shed. Thus, photosynthesis removes CO_2 from the air, but decomposition, under normal circumstances, releases that CO_2 back to the atmosphere.

It is feasible, however, to interfere with that basic ecological process of decomposition through pyrolysis, a thermal decomposition of materials at high temperatures under low oxygen. This process produced recalcitrant carbon molecules along with syngas, a high nitrogen content gas. The syngas can be used for energy with low carbon emissions, while the recalcitrant carbon can be returned to the soil for both local improvement in soil characteristics as well as long-term carbon sequestration in the soil. In much of the literature there is an emphasis on the potential of agroforestry systems to mitigate greenhouse gases through carbon storage in plant biomass and soil organic material, certainly an important issue, since in the tropics, the carbon sequestration potential of this land management system is estimated to be between 12 and 228 Mg per hectare (Albercht & Kandji, 2003). However, very little attention has been paid to the potential of reducing emissions by collecting some of the biomass that would normally decompose and turning it into energy and biochar.

Decentralized biomass energy production has the potential to provide renewable energy and carbon sequestration through co-production of biochar, a stable form of carbon and an agricultural soil amendment. This is particularly important for rural and agricultural communities which face structural challenges accessing renewable energy and already rely on local biomass or fossil fuels for their cooking and heating needs (Iiyama et. al., 2014; Bailis et al., 2015). However, it is important to note that the sustainability of biomass energy systems relies on using agricultural waste as feedstock. Industrial biomass energy using tree plantations and other live woody material has been discredited for its inaccurate carbon accounting, land use change (Haberl et al., 2012; Ter-Mikaelian et al., 2015), and its impact on other ecosystem services such as biodiversity conservation (Pedroli et al., 2013).

In Puerto Rico, agroforestry systems, for example shaded coffee farms, present a unique opportunity to link renewable energy and sustainable agriculture. Woody debris or downed woody material (DWM) from coffee shrubs and the associated shade trees has the potential to be used as feedstock for local bioenergy and biochar production. In turn, biochar can be used as an amendment to improve soil quality and sequester soil carbon, simultaneously contributing both to agricultural sustainability and climate change mitigation. For coffee farmers, bioenergy and biochar systems can generate renewable energy, reduce reliance on fossil fuel-based fertilizers, and repurpose agricultural waste. Shade trees in tropical agroforestry systems refer to overstory trees under which crops (e.g., coffee and cocoa) are cultivated. They have been linked to multiple benefits and ecosystem services, including soil fertility through nitrogen fixation, erosion control, resistance to insect pests and pathogens, and increased biodiversity conservation (Vandermeer et al., 2010; Tscharntke et al., 2011; Tully et al., 2012; Perfecto et al., 2014).

Intensification practices have tended to eliminate or reduce shade trees in coffee farms so as to increase short-term gains in crop yield, but perhaps inadvertently depleting soil health in the long-term (Dollinger & Jose, 2018) creating a negative feedback loop that pressures farmers to increase deforestation in search of more fertile lands. Additionally, reducing shade trees reduce biodiversity (Perfecto et al., 1996; Moguel and Toledo, 1999; Jha et al., 2014) and can make these systems more vulnerable to extreme climatic events (Philpott at al. 2008; Lin 2008, 2011; Perfecto et al., 2019). The additional potential function of debris from shade trees providing a feedstock for energy production is obvious and suggests a need to understand the relationship between shade trees and that feedstock. Multiple studies have linked aboveground biomass availability with shade tree density in agroforestry systems (Vieilledent et al., 2012). Nevertheless, little attention has been accorded to the relationship between shade trees and downed woody materials (DWM). It is well-known that the litter layer is an important component of carbon stocks and nutrient cycling in forests and agroforestry systems (Pfeifer et al., 2015). Collecting DWM from coffee agroforestry systems for bioenergy and biochar production could provide local renewable energy and carbon sequestration while incentivizing reforestation with the use of shade trees. It can also reduce the amount of fuel loading and reduce the probability of wild fires spreading into coffee farms, especially during drought years (Brandeis and Woodall, 2008).

1.1 Research Questions

In this study, we explore the potential of a coupled agroforestry and biomass energy system in Puerto Rico as strategy for sustainable energy production, climate change mitigation, and sustainable agriculture. We seek to explore the extent to which management, especially with respect to shade tree coverage, contributes to the potential for DWM from coffee farms and provide a significant feedstock for local energy production. The specific goal of our study was to assess the quantity of down woody biomass available in coffee farms that could be used as a source for small-scale biochar and bioenergy production in the coffee-growing region of Puerto Rico. We posed four questions to evaluate the use of agricultural woody biomass and its environmental implications: (1) What is the amount of down woody materials available per hectare in coffee farms in the central mountains of Puerto Rico? (2) What is the relationship, if any, between the amount of down woody biomass and percent canopy cover? (3) How much energy can be derived from locally available down woody material in coffee farms through a gasification process? (4) How many tons of carbon per year could be sequestered by using farm-generated biochar? We hope the answers to these questions can further the understanding of biochar, agricultural management of coffee, and its energy generation and carbon sequestration potential.

2. Methods

2.1 Study Area and Survey Sites

This study was conducted in the *Cordillera Central* or central mountains of Puerto Rico (Fig. 1) in twenty coffee farms distributed among the municipalities of Utuado, Adjuntas, Yauco, Las Marias, Juana Diaz, Ponce, and Orocovis. The U.S. Forest Service classifies this climatic area as subtropical moist forest with 2300 – 4500 mm of rainfall per year (Ewel et al., 1973). According to the USDA, soils in the area belong to the oxisol and ultisol orders, which are highly weathered and acidic soils. Historically, agricultural activity in this area has centered around coffee farming (Bergad, 1978). Agricultural management intensity of the surveyed farms ranged widely from coffee monocultures grown under full sun to coffee grown under the canopy of shade trees intercropped with other fruit trees and root vegetables. For exact coordinates and locations of each farm, see Table S1 in supplementary materials.

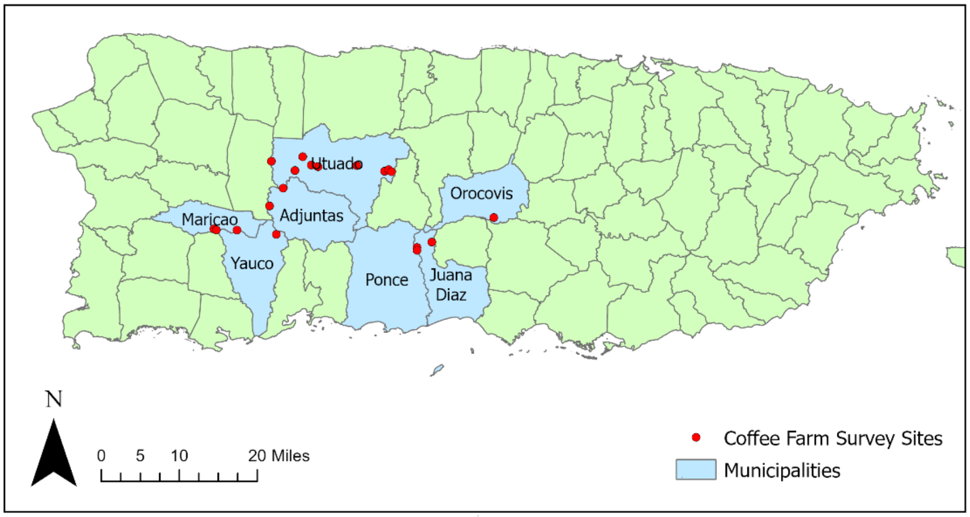


Figure 1. Map of Puerto Rico divided highlighting the municipalities and locations of the farms surveyed.

2.2 Down Woody Material Survey

To estimate the amount of down woody material in each farm, we used a line transect method (Van Wagner, 1968) with a few modifications. We drew a 10-meter line using a meter tape in an area representative of the rest of the farm. We, then, collected up to one hundred DWM samples that intersected with our line. For each sample, we measured its diameter and length using caliper and measuring tape, respectively. If the number of samples found within 10-meter transect were less than one hundred, we increased the transect by another five meters until one hundred samples were measured. The final length of the transect was the distance from the start of the line to where the one hundredth sample was found. Likewise, if we encountered 100 samples before reaching the 10 meter mark, we noted the length of the transect as the distance between the beginning of the transect and where we encounter the one hundredth sample.

2.3 Biomass Availability

The volume of individual pieces was estimated by approximating the shape of each piece to a cylinder and using the sampled lengths and diameters of each piece. Total volume of all sampled DWM was calculated by adding the volume of all individual pieces. To find volume per area, we used the following process. (1) All pieces were tallied and binned according to their lengths to create frequency distribution graphs of each farm. (2) To estimate the mass of each piece, we multiplied their individual volumes by 0.62 g/cm3, which is the wood density of coffee (Goldsmith & Carter, 1981), since most of the twigs and branches encountered were from coffee. Afterwards, we calculated the frequency per area using the following equation:

$$= \frac{f}{L * 2 * b}$$

Where f is the frequency of pieces, L is the length of the transect in cm, and b represents the bin size also in cm. This equation assumes that the width used to sample DWM is at most twice the size of the largest piece (bin size). (3) Finally, we multiply this frequency/area with the average mass per bin to obtain mass/area.

Our estimates assume that all DWM pieces were sound and freshly fallen or decay class = 1 (Woodall et all, 2013). For the purposes of feedstock collection for gasification and biochar, woody material can be obtained on a yearly basis during the pruning of coffee trees after the harvest.

2.4 Canopy Cover

Percent canopy cover was estimated using CanopyApp, an image processing application from the University of New Hampshire. Measurements of canopy cover were taken at two different heights: low and high. In each farm, a 10 x 10 meter plot representative of the management of the rest of the farm was selected. For the low canopy cover estimates, we took measurements in 5 point of the plot (the four corners and the center) at approximately 1.3 meters from the ground and used the average percent canopy cover. For the high canopy estimate we took 5 measurements in approximately the same positions (four in each corner and one in the center) but the measurements were taken at a height determined by the highest coffee plants in the plot. Our two different measurements of canopy cover reflect, indirectly, the basic origin of the woody debris. The measurements at the 1.3m level reflect the canopy cover resulting from the coffee bushes themselves and is referred as lower canopy cover. The measurements above the coffee bushes reflect the canopy cover resulting from the shade trees above the coffee and is referred to as upper canopy cover.

In order to take these measurements, the camera was placed in an extendable pole and connected to a remote shooter that allowed for a picture to be taken at height higher than a meter. CanopyApp uses the smart phone gyroscope so that each picture is level with the ground. After pictures are taken, the user selects leaf colors to allow the application to estimate a percent of canopy cover.

2.5 Statistical Analysis

Data analysis was carried out in Microsoft Excel. The DWM biomass dataset was not normally distributed, so we used a non-parametric test (Mann-Whitney test) to compare the means between shade farms and sun farms and our two canopy measurements. A linear regression was performed on the natural logarithm of the data to understand the relationship between ln(biomass) and percent of shade cover at both levels (upper and lower).

2.6 Electricity Generation

We estimated electricity generation using the following equation:

$$Electricity\ generation\ \left(\frac{kWh}{year}\right) = A(ha) * Y\ \left(\frac{ton}{ha * year}\right) * 1000\ \left(\frac{kg}{ton}\right) * LHV\left(\frac{MJ}{kg}\right) *\ \eta * 0.28\ (\frac{kWh}{MJ})$$

Where, A represents the area of a farm dedicated to coffee cultivation in hectares. Y is the yield or weight in tons of our DWM per hectare per year. The Lower Heating Value (LHV) for woody biomass has been reported between 17.4 and 18.37 MJ/Kg (Torres et. al, 2018). . We use a conservative figure of 17 MJ/kg. η is the electrical efficiency of the gasifier which has been reported for small units from 8.13 to 15.21% (Zainal et al, 2002; Roesch, 2011). We assumed an average value of 12%.

This equation assumes an estimated moisture content of feedstock or yield not greater than 15 to 25%. In our down woody material availability survey, we encountered DWM with a moisture content of 7 to 14%. Since this study was conducted in less than a year, we do not have survey data of availability per year. However, based on semi-structured interviews, we assume that the estimated amount of DWM is available on a yearly basis from pruning after the coffee harvest also known as *poda de mejoramiento*. It is also important to note that while the biomass may be available at one specific time during the year, storage for woody biomass would allow the electricity production to be carried out throughout the year.

2.7 Carbon Sequestration Potential

To calculate the amount of biochar produced we used the following equation:

$$Biochar\ production\ \left(\frac{tonnes}{year}\right) = Total\ Area\ (ha) * Average\ DWM\ biomass\ \left(\frac{tonnes}{ha*year}\right) * biochar\ yield\ efficiency\ (\%)$$

We have two important assumptions to estimate the amount of biochar produced annually that can be returned to the soil as an agricultural condition. 1) We assumed a lifecycle yield of 0.9 tons of CO_2e per ton of feedstock for woody biomass and gasification (Cowie et al., 2015). The total amount of agricultural land dedicated to coffee in Puerto Rico is 6747 ha (USDA, 2016)

3. Results

3.1 DWM and Shade Tree Management

The amount of down woody material available varied between farms (Fig. 2). The smallest amount found in any farm was 0.25Mg/ha. The largest amount was 6.67 Mg/ha. The mean available DWM in all farms was 1.5 Mg/ha with a large standard deviation of 1.76 Mg/ha.

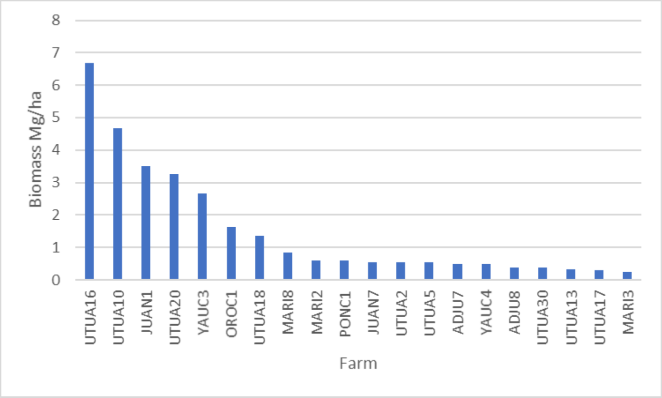


Figure 2. Estimated biomass available in every farm surveyed from highest (6.67 Mg/ha) to lowest (0.25 Mg/ha).

Using two canopy cover estimates (upper and lower), we noted that there was a large range of measurements, from zero canopy to almost 50% cover. The twenty farms sampled fell into two distinguishable groups, sun coffee and shade coffee, based on shade measurements of the upper canopy (Fig. 3). The exact amount that constitutes sun or shade coffee is somewhat arbitrary and depends on multiple management practices. The maximum shade recorded was less than 50% and we classified anything above 5% as shade coffee. The average DWM biomass in sun farms was 0.88 Mg/ha and in shade farms 1.91 Mg/ha. These results are statistically significant ($p < 0.05$) using a Mann-Whiney test to compare the means of shade farm and sun farms.

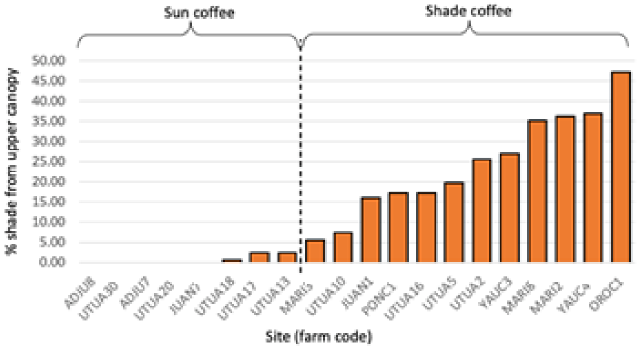


Figure 3. Bar chart of the shade measurements on all 20 farms in the study, showing the arbitrary division between sun farms and shade farms set at <5%.

Based on the expectation that more shade would generally translate into more down woody material, we examined the relationship between upper and lower canopy cover and DWM, as shown in Figure 4. For upper canopy, the relationship is negative. Interestingly, for sun coffee alone, the relationship is sharply negative (Fig. 4a). For lower canopy, the relationship is, as expected, positive.

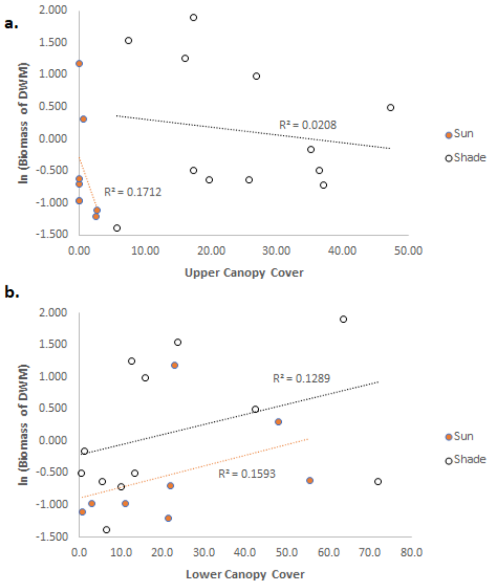


Figure 4. Scattergrams of percent canopy cover related to the log of biomass of downed woody material. Shade coffee in open circles, sun coffee in red solid circles. a. relationship between biomass and high shade cover (i.e., percent canopy cover above the highest coffee bush). b. relationship between biomass and percent canopy cover measured at 1.3 m above ground level, reflecting both high cover from shade trees plus the shade cast by the coffee itself.

Dividing the farms into shade categories, the mean biomass for shade coffee is 1.92 while that of sun farms is 0.88, a marginally significant difference ($p < 0.05$ by a simple bootstrap resampling, $p < .082$ with a standard one-tailed t-test). This difference is represented graphically with a rank order plot of both shade and sun farms in figure 5.

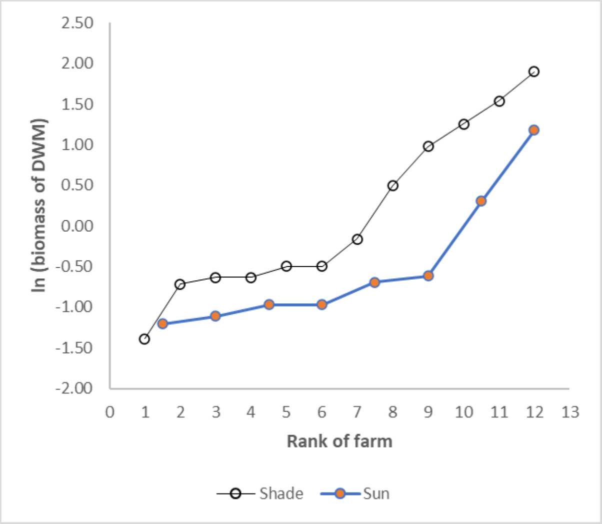


Figure 5. Ranked farms production of biomass of woody debris, based on status as sun or shade farms. Ranks are displayed in two ranges for the sun farms since there are fewer of them than the shade farms.

The canopy density of coffee bushes, as estimated with the “lower” canopy cover at 1.3 m, varied enormously from farm to farm, as shown in figure 6. No distinct separation of shade and sun coffee is evident in these data. However, the six most “dense” farms and the six least “dense” farms seem to be distinguishable from the intermediate farms. The woody debris figures for these two subgroups in isolation show a significant difference with the dense coffee farms producing an average of 1.87 and that of the low-density farms producing 0.49mg/ha of woody debris ($p < 0.05$).

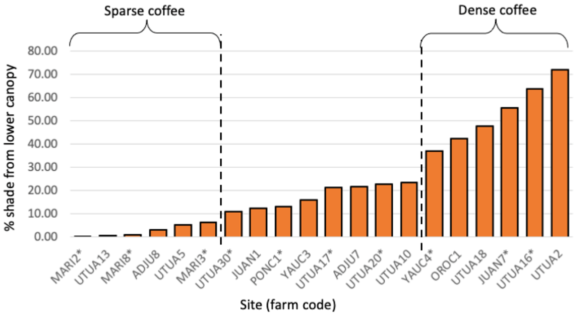


Figure 6. Sparce versus dense coffee bush plantings, as estimated from the lower canopy measurements. A simple dual division, as clear for the upper canopy cover measures, is not evident in these data. A division of the six lowest and the six highest is, however, clearly possible.

3.3 Energy and Emissions Reduction

Total electricity generation was estimated using our average yearly DWM biomass availability in conjunction with data for land size used for coffee farming from the Caribbean Climate Hub (USDA, 2016). We obtained three electricity generation results using different areas and three different average waste biomass stock: all coffee farms regardless of shade type; shade coffee farms; and sun coffee farm (Table 1).

Management style	Total Area of coffee cultivation (ha)	Average yearly DWM biomass (Mg/ha*year)	Electricity generation (GWh/year)
All types	6747.71	1.50	5.79
Shade	1184.22	1.91	1.29
Sun	5563.49	0.88	2.80

Table 1. Total electricity generation from total hectares of sun and shade coffee planted in Puerto Rico using the average DWM biomass availability estimated from our survey.

Production of biochar was estimated using a lifecycle assessment of 0.8 CO2e yield per ton of feedstock (Cowie et al., 2015). We used the data from electricity generation scenario where woody debris is obtained from all coffee farms in Puerto Rico regardless of management style. Our results in metric tons can be found in Table 2.

Area of coffee cultivation (ha)	DWM biomass stock (Mg/ha)	Total Biomass (metric ton)	CO_2e (metric ton)
6747.71	1.50	10138.43	8110.74

Table 2. Total metric tons of CO2e that can be sequestered using down woody debris on a yearly basis.

4. Discussion

4.1 Biomass Availability and Shade Management

These results collectively suggest that sun coffee farms produce fewer woody debris than shade coffee farms and that farms with densely planted coffee bushes produce more DWM than sparsely planted ones. However, it is important to note that it is generally the case that coffee bushes are planted less densely when under shade (Perfecto et al. 1996; Moguel and Toledo, 1999; Avelino et al., 2004). This explains why we did not find a strong positive relationship between shade level and the amount of DWM, since farms that have low shade, have higher density of coffee plants that contribute to the DWM. In other words, the management of shade is related to DWM in two ways. First, it is generally expected that the proportion of the DWM will be proportional to the amount of shade in the system, with coffee bushes and shade trees both contributing to the amount of DWM. Yet the expected lowered production of coffee bushes- as overstory shade becomes more prominent- suggests that the amount of DWM contributed by coffee bushes will decrease as the level of shade increases. Our two different measures of canopy cover, one at 1.3m above ground, the other above the coffee canopy, reflect these two inputs. With low upper canopy shade, we expect most of the DWM to be a product of the coffee bushes and with high upper canopy we expect a higher proportion of the DWM to be a product of the shade trees. Furthermore, we expect that the range of coffee management systems will produce not only a distinct set of origins for the DWM, but a particular pattern of variability, from low to high to low, as the management system proceeds from full sun to full shade (Fig. 6).

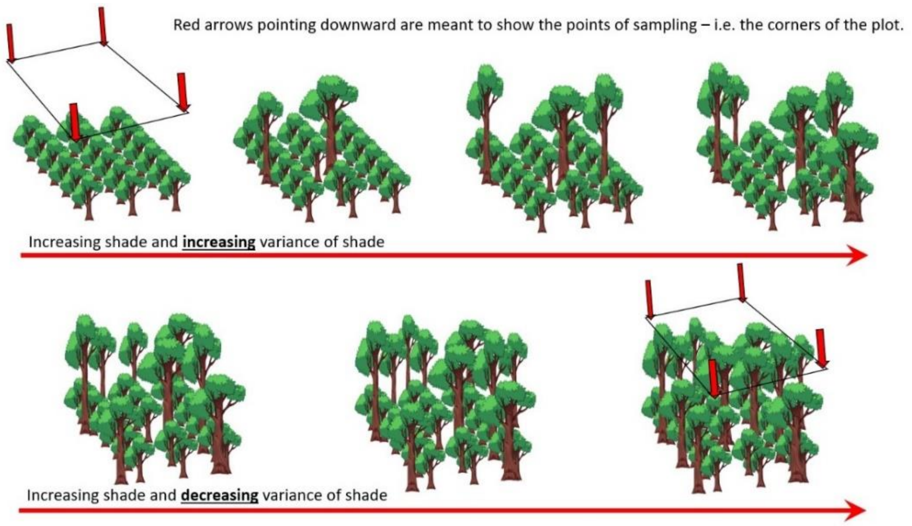


Figure 6. Increasing shade trees increases the variance of shade until canopy cover starts becoming more homogenous and variances decreases back to zero.

Our results show a statistical difference in the average DWM biomass between sun and shade coffee with the latter producing more biomass. Additionally, there is stronger evidence that the availability of DWM biomass is influenced by the amount of lower and upper canopy shade cover when we take planting density into account. This indicates that DWM biomass in dense sun coffee farms could increase by planting shade trees up to a point where further increases in shade do not yield significantly more DWM. This result could be explained by the relationship between upper canopy shade and its variance (Fig 6).

Our estimates of DWM biomass stocks in Puerto Rico are in line with other estimations of coffee agroforests in other parts of the world. In Mexico, DWM biomass has been estimated from 0.02 to 1.4 Mg/ha for coffee agroforests (Soto-Pinto & Aguirre-Davila, 2014). In Indonesia, biomass at the litter layer was found to be 1.8Mg/ha for polyculture coffee, 1.2 Mg/ha for shade coffee, and 1.2 Mg/ha for sun coffee (Hairiah et al., 2006). For comparison, secondary forests in Puerto Rico are estimated to hold about 9.4 Mg/ha of DWM biomass (Brandeis & Woodall, 2008)-. This can possibly be explained by current agricultural practices and economic conditions in Puerto Rico. Agricultural labor in coffee farms is very limited due to wage competitions with other sectors. Most farmers only hire workers during the harvest season. This has created a very limited active management of shade trees. When overgrown shade tree branches do fall, they are collected over many years in separate piles in certain parts of the farm. We chose not to include those piles in our survey, which represent a large amount of DWM biomass, as part of our sampling because we could not assess their availability on a yearly basis. Higher DWM from sun coffee farms can be explained by higher amounts of debris from coffee trees which are left in place in the soil and which we likely encountered at a much higher rate than debris from shade trees.

5.2 Energy and Carbon Sequestration Potential

The total amount of energy generated using coffee biomass is around 5 GW-hours per year. This is a very small amount compared to the total energy use in Puerto Rico estimated at 17,000 GW-hours per year (CCS, 2014). However, it could account for 19% of all energy use in the agricultural sector of Puerto Rico which is estimated at 26 GW-hours in 2016 (CCS, 2014). Biomass energy alone, even when accounting for other agricultural biomass apart from coffee, cannot supply all the energy consumed in Puerto Rico. However, energy systems in the island face challenges that could make biomass energy a viable and sustainable addition to its energy mix. Puerto Rico has a complex topography that includes the coastal plains and mountains among. Its power grid relies on 2,400 miles of transmission and 30,000 miles of distribution lines (EIA). In 2017, Hurricane Maria badly damaged this infrastructure leaving residents without power for months. In response, the Puerto Rico Electric Power Authority has proposed the creation of microgrids and minigrids that can increase the resilience of power systems and reduce reliance in the central grid (EIA). In this context, biomass energy from coffee can be a viable option for supplying electricity in rural areas of Puerto Rico. Some studies have shown that biomass energy can effectively supplement solar and wind energy microgrids in rural areas (Mazzola et al., 2016; Li et al., 2019).

In terms of carbon sequestration, total biochar production from coffee agriculture ranges from 500 to 3900 Mt per year. Production of biochar will be dependent on gasifier efficiency and whether the system is tuned for syngas production or biochar production (Yao et al., 2018). Even for the higher range of production, this amount is insignificant compared to the island’s total carbon footprint in 2017 which was 18 $MMtCO_2e$. However, there is potential to offset emissions for electricity consumption in the agricultural sector which produced 19 000 MtCO2e in 2015. Our data indicates that it is possible to offset between 2% and 20% of GHG emission from electricity used for agriculture using biochar from coffee production. Based on the Caribbean Climate Hub data, the total area of coffee cultivation in Puerto Rico amounts to 6.7k hectares which could benefit from soil quality improvement by using biochar. In Puerto Rico, agriculture itself produces very few GHG emissions. In 2013, agriculture was responsible for a net sink of 0.3 MMtCO2e due to perennial crops, like coffee, offsetting emissions associated with local livestock and crop production (CCS, 2014). However, this does not take into account agrochemicals.

6. Conclusions

In Puerto Rico, coffee is an important crop for small holder farmers and for rural livelihoods. While it is outside of the scope of this paper, it is necessary to state that industrial biomass energy produced from tree plantations is not compatible with sustainable energy and food systems. For that reason, our study focuses on biological carbon sequestration that can help support tropical farmers. We link shade management to energy provisioning and carbon sequestration as ecosystem services derived from what is traditionally considered waste material in coffee agroforests. Our findings support the addition of pyrolysis of coffee agro-residues in microgrids in Puerto Rico to achieve an agricultural circular economy. Our analysis estimates that island-wide biomass energy from DWM in coffee fields can produce almost 20% of the energy used in the whole agricultural sector of Puerto Rico. Further research and analysis are needed to estimate the contributions of other agricultural biomass residues. Additionally, woody debris in forest ecosystems, including agroforests, has multiple roles including water retention, erosion prevention, nutrient cycling, and habitat and food for decomposers. In the future, we must also understand the trade-offs between decomposition of DWM and its use for energy generation and carbon sequestration to truly understand its implication in sustainable management of resources in these agroforestry systems.

II. Chapter 2:

Plant Response to Biochar Soil Enrichment in Coffee(Coffea arabica) Seedlings

Abstract

Amending soils with biochar is an increasingly popular agricultural management technique to enhance crop productivity. However, the relationship between plant growth rate and the rate of biochar addition in soil is not fully understood. Using biochar during the seedling establishment process of coffee (*Coffea arabica*) offers an opportunity for addition to soil and to test its effects in a perennial agroecosystem. The objective of this experiment was to understand plant performance of coffee seedlings when biochar-amended tropical oxisols were used as a growing medium. A greenhouse experiment was set up in the central mountains of Puerto Rico where we grew seventy-two coffee seedlings using six different treatments. The growing mediums were a mixture of biochar, compost, and local soil. All treatments consisted of 50% compost and 50% of a soil/biochar mixture. The soil/biochar mixture contained the following proportions of biochar: 0%, 25%, 50%, 75%, and 100%. Additionally, we had a control treatment of soil with the addition of calcium carbonate. The seedling's height, number of leaves, and length of its longest leaf were tracked every fourteen days for three consecutive months. The pH of the soil was measured at the end of the experiment. We found that soil pH increased linearly with the proportion of biochar added to the growing medium. Treatments with a 100% biochar mixture resulted in coffee plants with the lowest mean height and lowest mean length of its longest leaf ($P<0.01$, by a one-way ANOVA and Tukey post-hoc test), while the number of leaves showed no statistical differences. A second-degree polynomial fit between the proportion of biochar and plant height produced an R-squared of 30%. These results possibly show a saturation effect of biochar as a soil amendment in the establishment of coffee seedlings. They also suggest that seedling growth rate in pots can be optimized based on the proportion of biochar present in the growing medium and its effects on soil pH.

1. Introduction

Agricultural intensification around the world has led to an increase in greenhouse gas(GHG) emissions because of management practices that focus on crop productivity while depleting soil organic carbon(SOC) and relying on inorganic fertilizers (Smith, 2008). Emissions from agriculture, forestry, and land use change are a major contributor to global climate change accounting for approximately 24% of all emissions (IPCC, 2014). Current concentrations of CO_2 (410 ppm) in the atmosphere have locked us into dangerous climatic patterns that will impact human and agricultural systems at a global scale (IPCC, 2018). Furthermore, this model of industrial agriculture has been exported to the Global South leading to a decreasing biodiversity and disrupting the livelihoods of farmers and peasants (Perfecto et al., 2009).

An effective and just response to climate change in agriculture will require innovative management techniques, for example biochar, that can support farmer livelihoods and help reduce GHG emissions. Biochar is a stable form of carbon obtained after pyrolysis of biomass such as wood, leaves, or agricultural waste (Lehmann, 2007). Charcoal and biochar are differentiated by their applications: the former is used as a source of energy while the latter is used for soil enhancement. There is evidence that application of biochar can increase soil organic carbon sequestration (Lehmann, 2007) and improve fertility in agricultural soils, further increasing carbon dioxide absorption (Biederman and Harpole, 2013). The use of charred organic material as a soil amendment can be traced back to pre-Columbian practices in the Amazon basin. These anthropogenic soils, known as *Terra Preta do Indio,* have a high content of organic material and higher fertility than the surrounding soils. Multiple studies have established a positive relationship between biochar addition to soil and several key functions of agricultural productivity, such as plant biomass, cation exchange capacity, water retention, and nutrient retention (Lehmann & Joseph, 2009; Jeffery et al., 2011; Karhu et al., 2011; Chintala et al., 2014). This is particularly important in the tropics where agriculture is frequently limited by low nutrient availability due to the highly weathered soils.

In Puerto Rico, coffee has been an important commercial crop since the 1800s when it surpassed sugar cane as an export crop (Borkhataria, 2012). Despite multiple devastating hurricanes and trade policies that opened the island to coffee imports, coffee farming has remained a part of the Puerto Rican economy and culture. In the municipality of Utuado, where this research took place, coffee agro-ecosystems are highly heterogenous and range from sun-grown coffee monocultures to shade-grown coffee in the understory of native forests. Farmers have found themselves reliant on industrial inputs to offset the nutrient-poor soils (ultisols and oxisols) found in the “Cordillera Central” or the central mountains of Puerto Rico. In such agro-climatic conditions, inorganic fertilizer applications are leached quickly, and few nutrients remain available for plant absorption. Organic fertilizers are mineralized quickly and the products similarly leached quickly. The effectiveness of biochar as a soil amendment has mostly been tested with annual crops, but there is little research on its effects in a perennial system like coffee. In a system with little to no tilling, an appropriate place to introduce biochar may at the seedling planting stage. Coffee seedlings are grown in nurseries until they reach an appropriate height to be planted in fields. This presents an opportunity to test the use of biochar as a growing medium for seedlings. Coffee farms are routinely renovated, and part of that renovation is planting new coffee, usually in the form of seedlings. If seedlings can be grown in a biochar-rich soil, the normal (usually yearly) replanting of seedlings could offer a process whereby biochar would be introduced naturally into the soil. Motivation for doing so would be aided by farmers realizing immediate benefits from the process. Thus, the research reported herein interrogates the possibility that seedlings grown in a biochar-rich soil will display characteristics that will be seen as beneficial to the agricultural process.

The general goal of our research is to further the understanding of sustainable management techniques like biochar and assess its potential to support farmer livelihoods in the tropics by increasing crop yields and soil carbon storage. To achieve our goal, we seek to understand the effect of using biochar as a soil amendment in the growth and establishment of coffee seedlings. Particularly, we were interested in measuring the effects (if any) of different rates of biochar addition on seedling growth in a perennial crop like coffee. We posed three questions: (1) Does biochar have a positive effect on the growth of coffee seedlings? (2) Can different amounts of biochar produce different outcomes in coffee seedling establishment? (3) Is there an ideal amount of biochar that can increase biomass productivity in coffee seedlings? The answers to these research questions can help inform farmers of management practices that increase coffee production and support soil carbon sequestration.

2. Methods

2.1 Experimental Setup

A greenhouse experiment was set up to grow coffee seedlings using five different growing mediums as treatments and one control with twelve replicates each. A total of seventy-two coffee (*Coffea arabica*) seedlings (Caturra Amerillo variety), in their cotyledon stage, were obtained from the nursery at the Universidad de Puerto Rico, Utuado campus, in Utuado, Puerto Rico. Each seedling was grown in compostable bags of 15cm in height with a volume of 500ml. Treatments consisted of different mixtures of biochar, vermicompost (VC), and local soil by volume in order to differentiate the effects of multiple rates of biochar addition. All treatments contained 50% compost to account for the lack of nutrients (particularly N and P) in biochar. The other 50% was a mixture of soil and biochar. This soil/biochar mixture contained the following proportions of biochar: 0% (T1), 25% (T2), 50% (T3), 75% (T4), and 100% (T5). Since Biochar usually increases the pH of the soil, in addition to the control treatment (T1= 50% VC, 50% soil, 0% biochar) we added a second control treatment (T6) consisting of 50% VC , 50% soil, 0% biochar, plus 5g of calcium carbonate (limestone). Calcium carbonate (CaCO3) is applied in coffee agroecosystems to raise the pH of highly acidic soils. When considering the entire volume of substrate in the bags, the treatments translate into: 50%VC, 50% soil (T1); 50% VC, 12.5% biochar, 62.5% soil (T2); 50% VC, 25% biochar, 25% soil (T3); 50% VC, 62.5% biochar, 12.5% soil (T4); 50% VC, 50% biochar (T5); 50% VC, 50% soil, plus 5 ml of calcium carbonate (T6) (Fig. 1). Coffee farmers regularly apply inorganic fertilizer to supply the necessary nutrients for their plants. However, we chose to use compost to more closely mimic the conditions of *Terra Preta*.

The vermicompost used for the experiment was made at the university campus using house manure, plant residues and kitchen scraps (for nutrient content see Table S-T1 in Appendices). The soil was taken from a small coffee farm within the university campus and was classified as an Ultisol (fine, kaolinitic, isohyperthermic Typic Hapludults; (for information about nutrient content see table S-T2 in Appendices). The biochar used for this experiment was obtained from Wakefield Biochar, a commercial provider in Michigan. It is made exclusively from pine wood and it has a pH of 7.4. (its detailed composition can be found in Table S-T3 in Appendices).

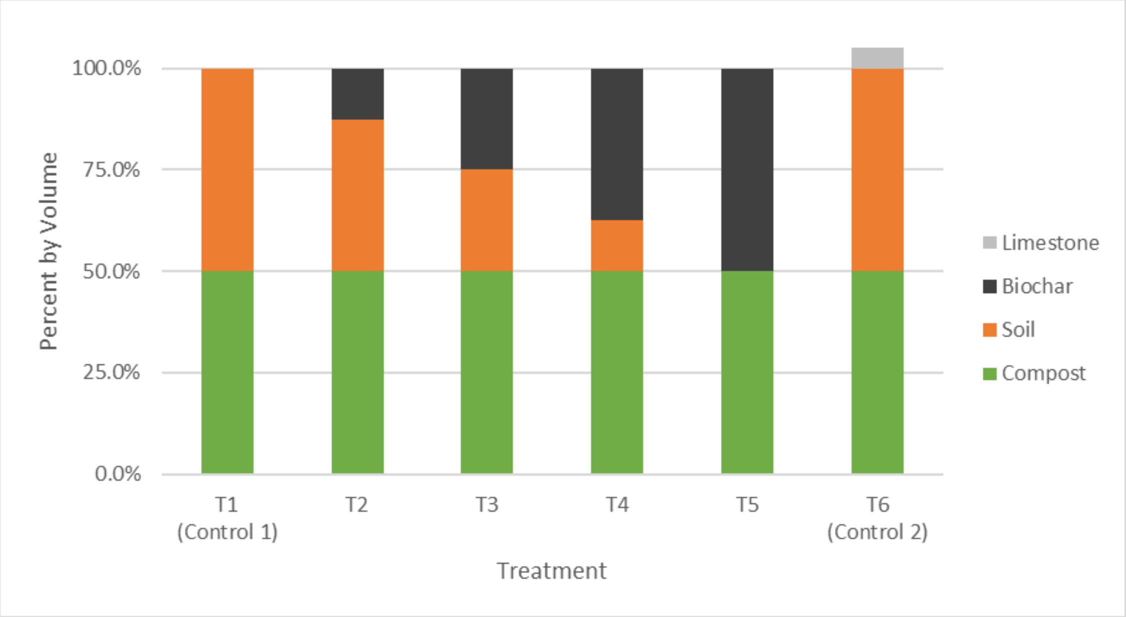


Fig. 1 Composition of growing medium by treatment (T1-T6) showing percent of biochar, soil, and compost of total volume

Each bag with coffee seedlings was housed in a greenhouse and arranged in a tray containing six bags of all six treatments. An automatic sprinkler system watered the coffee seedlings twice a day. All blocks were rotated clockwise every two weeks to control for light and watering differences within the greenhouse.

2.2 Measurements

Sampling non-destructively, we assessed plant response to different biochar addition rates using three traits for dependent variables: seedling height, number of leaves, and the length of the longest leaf. These measurements were taken every two weeks for three consecutive months. The height was measured from the base of the seedling and the growing medium to its apical bud (tip of stem). The length of its longest leaf was measured from the base of the node to the tip of the leaf blade. Only leaves that were fully opened were counted.

At the end of the experiment, we measured the pH of the growing medium for each bag. Soil samples were collected using a tube of 10 cm in length. For each replicate, 2.5gr of soil were mixed with 20 mL of a 1 mol solution of KCL and allowed to sit for 5 minutes. Afterwards, a pH strip was submerged in the solution and the result measured colorimetrically.

2.3 Statistical Analysis

Data analysis was carried out in R version 3.5.2. Each dependent variable was analyzed using a one-way ANOVA test to determine if any treatments were significantly different from each other. Dataset passed all the assumptions of the ANOVA test (normal distribution, independence, and homoscedasticity). This was followed by a Tukey HSD post-hoc test to establish which treatments were different from each other. Additionally, we applied a linear and a polynomial fit to each dependent variable to describe the dependence between physiological traits and the amount of biochar in the growing medium. More specifically, we used a linear equation and quadratic equation in R by applying the 'lm' function to the forms: (y ~ x) and (y ~ x)+ I (x2) respectively.

3. Results

3.1 Coffee plant height

At the end of the experiment (three months), the mean height of coffee seedling varied considerably among treatments. Treatment 3 which contained 50% VC, 25% biochar and 25% soil had the highest mean height at 19.13 cm, representing a 12% increase over the control (T1= 50% VC, 50% soil) (Fig. 2). Treatment 5, which contained 50% VC and 50% biochar had the lowest mean height at 13.68 cm. The two control treatments did not differ significantly from each other and had the most similar heights with T6 = 16.94 cm and T1 = 17.11 cm. Neither of the control treatments had any biochar additions. Some differences in mean height were statistically significant ($p < 0.01$ by a one-way ANOVA test). Specifically, treatment 5, which had the lowest mean height, was statistically different from treatments 2 and 3, which had the highest mean heights after performing a TukeyHSD post-hoc test. We used a polynomial fit to understand the relationship between proportion of biochar and height of coffee seedlings. In this analysis we excluded treatment 6 since it represented the same proportion of biochar as treatment 1. A 'hump-shaped' or quadratic curve had an $R^2 = 34.37\%$ (Fig. 2).

When examining the growth of the plants' heights over time, we see that all treatments follow each other closely until week 5. After that, T5 with the highest amount of biochar shows a visibly lower seedling height. T3 shows the highest seedling height beginning on week 6 until the end of the experiment. The rest of the treatments trail T3 and follow each other closely from beginning to end of the experiment (Fig. 3).

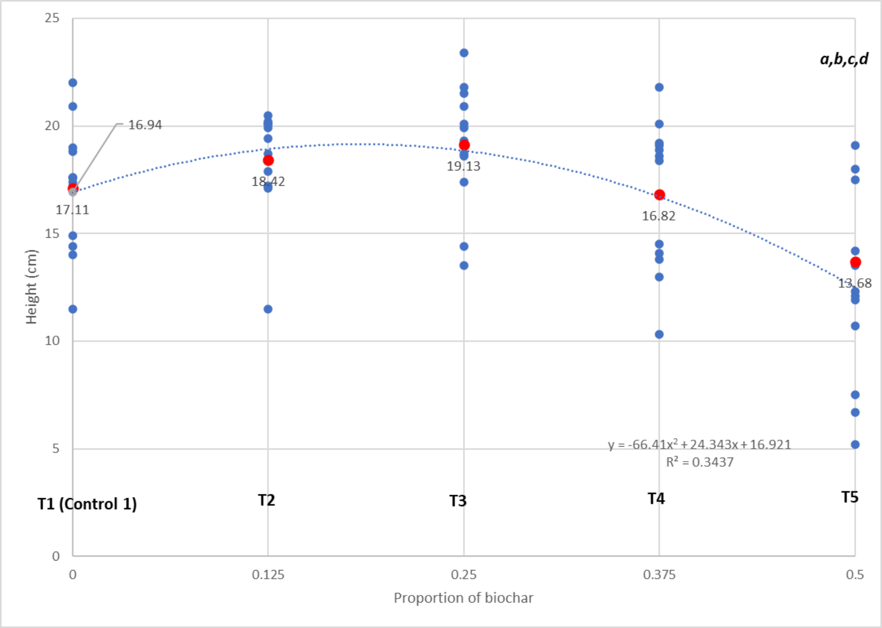


Fig. 2 In red, mean height per treatment. T1: 17.11 cm, T2: 18.42 cm, T3: 19.13 cm, T4: 16.82 cm, T5: 13.68 cm. In grey, mean height for T6: 16.94 cm. In blue, quadratic fit of relationship between proportion of biochar and height of seedlings with $R^2 = 34.37\%$. Statistical difference is shown in letter as follows: a, significantly different from T2 ($p < 0.05$); b, significantly different from T3 ($p < 0.05$); and c, moderately different from T1(Control 1) ($p < 0.1$). d: moderately different from T6(Control 2) ($p < 0.1$).

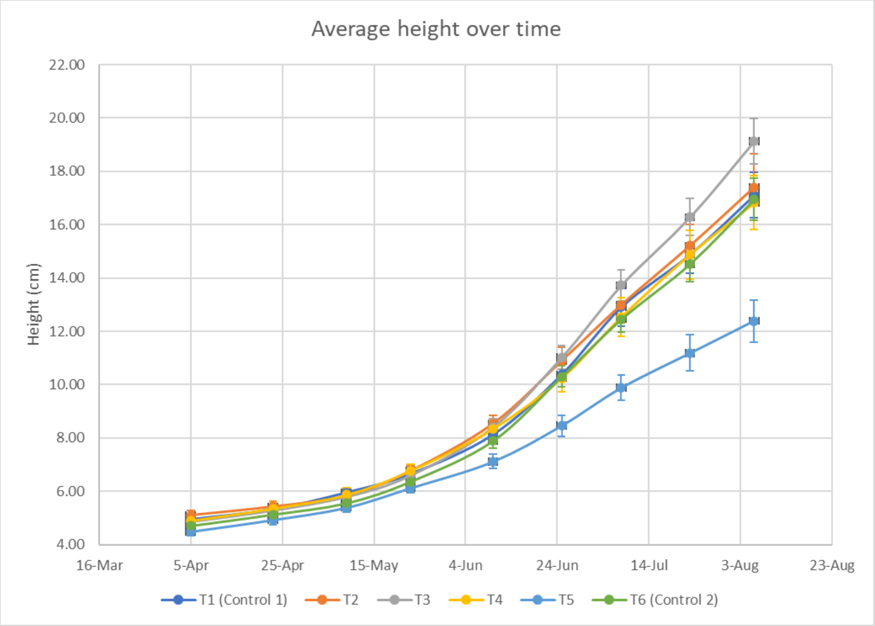


Fig. 3 Average height of every treatment and control over the duration of the experiment with standard error bars.

3.2 Number of leaves

The number of leaves in coffee seedlings also varied per treatment. Again, treatment 3, contained the highest mean number of leaves at 15.45, representing an 11% increase in the number of leaves over the control (Treatment 1) (Fig. 4). Treatment 6, the control treatment (no biochar) with limestone, had the lowest mean number of leaves at 13.16 followed by treatment 5 at 13.40. The variation between treatments was small. Treatment 3 was significantly different ($p < 0.05$) from treatments 1, 5, and 6 after running a one-way ANOVA and TukeyHSD post-hoc test. Once again to understand the relationship between biochar dosage and physiological response (number of leaves), we tried to fit a polynomial curve. A 'hump-shaped' or quadratic curve had an $R^2 = 23.76\%$ for the data (Fig. 4). Figure 7 shows average number of leaves over time for each treatment.

When examining the number of leaves over the duration of the entire experiment, we see some variability in all treatments (Fig. 5). However, starting at week 4, T3 shows the highest number of leaves until the end of the experiment. During the first 4 weeks, T6 (Control 2) with no biochar and with limestone, showed the lowest number of leaves. Starting at week 5, the average number of leaves for T6 seedlings surpasses that of T5 seedlings.

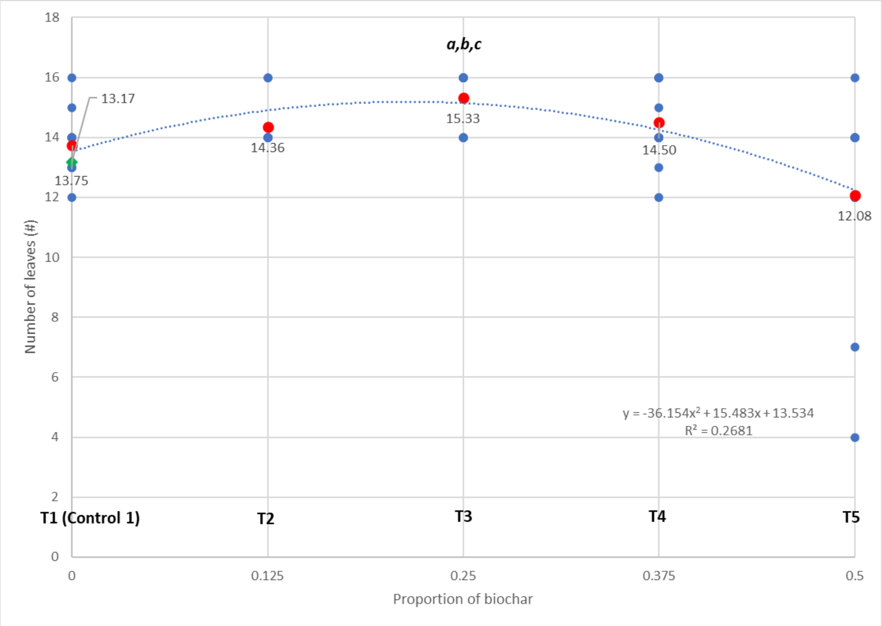


Fig. 4 In red, mean number of leaves per treatment. T1: 13.75, T2: 14.40, T3: 15.45 , T4: 14.5, T5: 13.40. In green, mean number of leaves per treatment for T6: 13.16. In blue, quadratic fit of relationship between proportion of biochar and number of leaves $R^2 = 26.81\%$. Statistical difference is shown in letter as follows: a, significantly different from T1 ($p < 0.05$); b, significantly different from T5 ($p <0.05$); and c, significantly different from T6(Control 2) ($p < 0.05$).

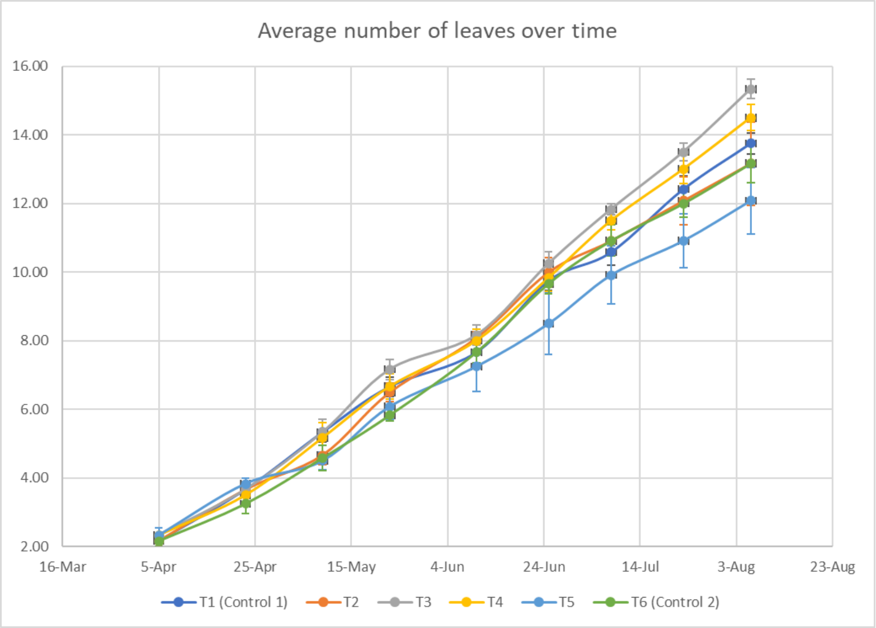


Fig. 5 Average number of leaves per treatment over the duration of the experiment with standard error bars.

3.3 Length of longest leaf

Mean length of the longest leaf of a coffee seedling also varied between different treatments. Here again, treatment 3 had the highest mean for the length of its longest leaf at 14.42 cm, representing a 9.6% increase over the control (T1) (Fig. 6). Treatment 5, which contained 50% CV, and 50% biochar, had the lowest mean length of its longest leaf at 13.68 cm. The control treatment scored at 13.50 cm and was closest to treatment 1 and treatment 4. Treatment 5, which had the lowest mean for the length of its longest leaf, was statistically different from treatments 2 and 3 ($p < 0.05$). Treatment 5 was also marginally different from treatment 6 ($p = 0.054$). All values come from performing a one-way ANOVA and TukeyHSD post-hoc test. A quadratic curve with an $R^2 = 31.43\%$ explained the relationship between biochar addition and the length of a coffee seedling's longest leaf (Fig. 6).

Throughout the experiment, the average length of the longest leaf, followed a different pattern than that of the average height or average number of leaves (Fig. 7). For the first 3 weeks, T5, the treatment with the highest amount of biochar, shows the highest length of its longest leaf while T2, the treatment with 50% VC, 35.5% soil, and 12.5% biochar, showed the lowest length of its longest leaf. until the end of the experiment. After that, T3 showed the highest average for the length of its longest leaf, and T5 showed the lowest.

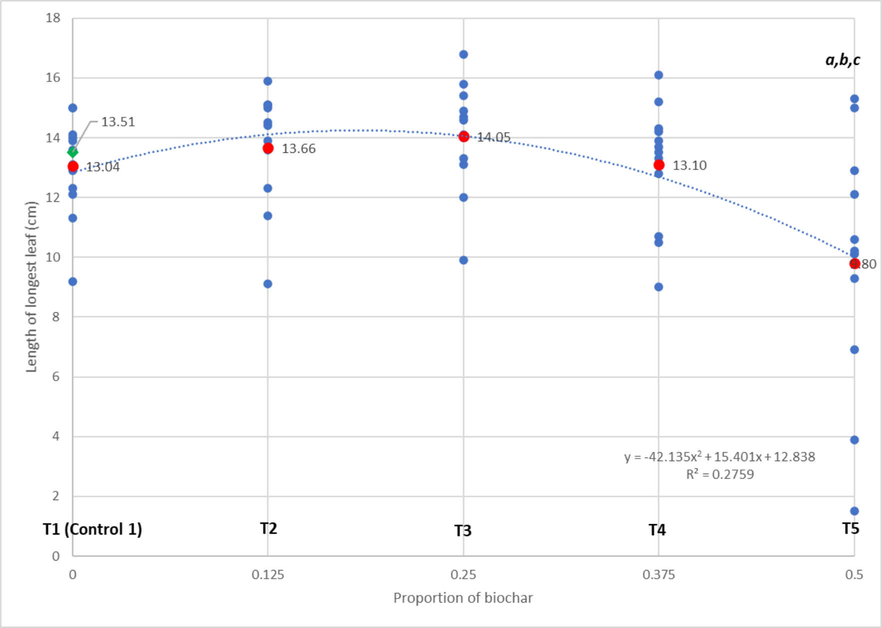


Fig. 6 In red, mean length of longest leaf per treatment. T1: 13.04 cm, T2: 14.12 cm, T3: 14.42 cm, T4: 13.10 cm, T5: 9.80 cm. In green, mean length of longest leaf for T6: 13.51 cm. In blue, quadratic fit of relationship between proportion of biochar and length of the longest leaf. R = 27.59%. Statistical difference is shown in letter as follows: a, significantly different from T2 ($p < 0.05$); b, significantly different from T3 ($p < 0.05$); and c, significantly different from T6(Control 2) ($p < 0.05$).

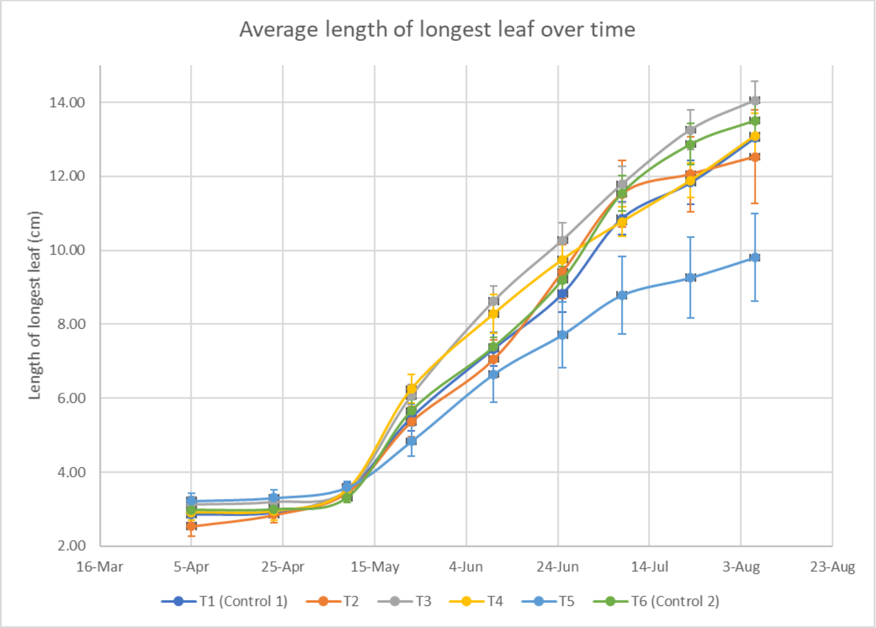


Fig. 7 Average length of the longest leaf per treatment over the duration of the experiment.

3.4 Soil pH

Results from the pH analysis show that pH rises with the proportion of biochar added to the growing medium in a linear fashion (Fig. 8). Using a linear model to explain the relationship between proportion of biochar and pH, we obtained an R^2= 82.11%. The lowest mean pH value corresponded to treatment 1, which contained no biochar, at 5.9. The highest value corresponded to treatment 5, with a 50% soil, 50% biochar mixture, at 7.2. The control treatment, which contains limestone, had a mean pH of 6.67. Table S-T4 contains all the means and standard deviation per treatment.

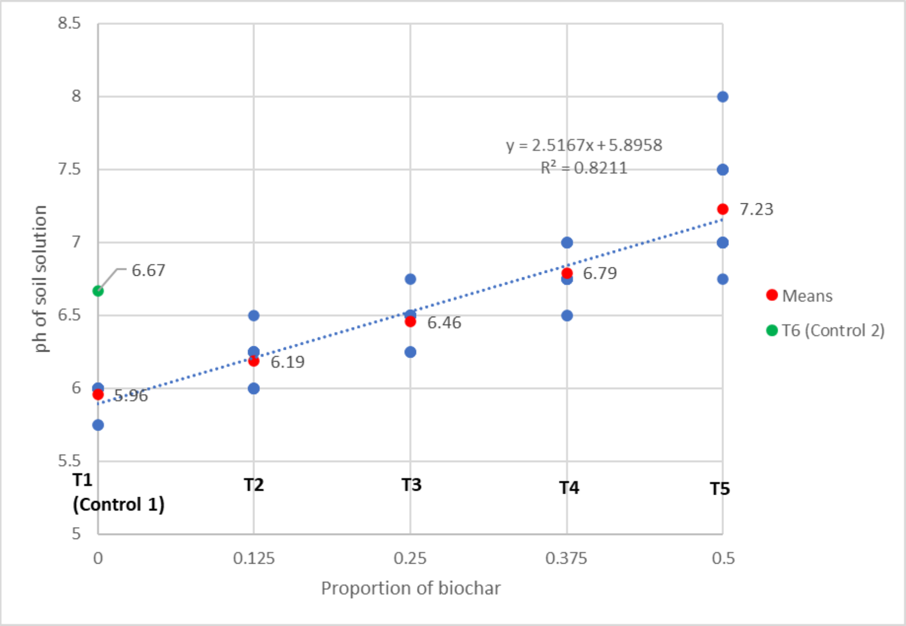


Fig. 8 In blue, proportion of biochar and pH have a strong linear relationship with an R^2 = 82.11%. In red, mean pH per treatment. In green, mean pH of T6 (Control 2) which contains limestone.

3.5 Carbon Sequestration Potential

To calculate the carbon sequestration potential of biochar as a growing medium in coffee nurseries, we used the total proportion of biochar per bag and the proportion of C in biochar on a mass basis (Table 1). In 2019, the U.S Department of Agriculture distributed 2 million coffee seedlings as an effort to aid farmers after Hurricane Maria. They estimated that between 9 to 18 million new coffee trees needed to be planted to replace what was lost. We estimated the carbon sequestration potential using the amount of biochar under the following assumptions: all seedlings bags weight 1 kg; weight of compostable bag is negligible; treatment with best performance (T3) is used for growing medium (25% biochar). Afterwards we created three scenarios based on the number of seedlings to be distributed (Table 1).

Treatment	Total % of biochar per bag	% C in biochar	Total weight of seedling bag (kg)	Number of seedlings (Millions)	Total Carbon (metric ton)
T3	0.25	0.88	1	2	440
T3	0.25	0.88	1	9	1980
T3	0.25	0.88	1	18	3960

Table 1. Total estimated carbon sequestration under three different scenarios

4. Discussion

The literature on the effects of biochar on annual cropping systems is extensive and growing (REF..). However, there are only a few studies that have examined the physiological responses of biochar amendments in agroforestry systems and perennial crops such as coffee (Stavi & Lal, 2013; Sanchez-Garcia et al., 2016; Miltner & Coomes, 2015; Gautam et al., 2017). Only one study investigated the effects of biochar added to coffee at the nursery stage (Ajema-Gebisa, 2019). Multiple studies in field and greenhouse experiments in annual crops report positive relationships between biochar application in tropical soils and crop growth (Schulz & Glasser, 2012; Wang et. al, 2012; Jeffrey et al., 2011). For example, different amounts of rice husk and corn stover biochars were used to grow eggplant with positive linear results on its height, number of leaves, and dry weight (Mohan et al., 2018). On the other hand, a few studies have found negative or no effects at all (Jeffrey et al., 2011; Laird et al., 2017).

In this study, we focus on biochar addition to the growing substrate for coffee seedlings in the nursery since this could be a potential way to add carbon to the soil in perennial and agroforestry systems. Perennial crops like coffee and cacao are renovated every few years when farmers remove old or diseased plants and replace them with new plants. If the seedlings are grown in a biochar rich substrate, the process of transplanting coffee seedlings into the soil can add carbon to the soil sequestering it for thousands of years (ref.)

We expected to find a positive linear relationship between rates of biochar addition and plant growth as measured in its height, number of leaves, and length of its longest leaf. Instead, we found a quadratic fit for all dependent variables. While surprising, this result shows the possibility of an ideal dosage of biochar when mixing growing medium for coffee seedlings. Other studies have established similar nonlinear relationships between the amount of biochar application and the physiological response in early successional forest plants in a greenhouse setting (Gale et al., 2017; Gale & Thomas, 2019). However, the rates of biochar applications were smaller than in our experiment.

For all three dependent variables, treatment 5, with the highest addition of biochar (50%), performed significantly worse than treatments 2 and 3 which contained 12.5% and 25% biochar respectively. One possible explanation for this could be the strong pH increasing effect of biochar. In our experiment and in other studies (Chintala et al., 2014; Hass et al., 2012), biochar was able to significantly raise the pH of the soil. Treatment 1, which had no biochar, had an average pH of 5.9, while treatment 5 with the highest addition of biochar had an average pH of 7.2. However, *Coffea arabica* is a plant adapted to the acidic soils of its native tropics. Its preferred pH range is between 5.2 to 6.2 (Clifford and Wilson, 1985). This could explain why Treatment 5, with a pH of 7.2, had the worst performance in our experiment. But it does not explain why Treatment 3, was the best performing treatment in terms of the response variables, since the average pH of this treatment was 6.5, which is above the preferred range for coffee. Some have argued that the increased basic effect is a chemical mechanism that enables the mobilization of N and P (Jeffrey et al., 2015), which are limiting nutrients for crops in tropical soils. It is possible that, while the substrate in Treatment 3 had a pH slightly above the preferred range for coffee, it also enabled the mobilization of essential nutrient for the plants, making it the best substrate to grow coffee seedlings.

Using biochar as a growing medium at the seedling stage offers a substantial and easy opportunity to increase carbon storage of tropical soils. According to our estimates, it is possible to sequester close to 4k metric tons of C in the process of replanting coffee trees lost during Hurricane Maria in Puerto Rico. This represents 220 metric tons of C per million trees planted. This number does not include all the sequestration of carbon dioxide by photosynthesis performed by the coffee plants and the shade trees that are frequently planted with coffee (Perfecto and Vandermeer 2015). However, 220 metric tons of C per million trees is a modest number relative to the carbon sequestration potential in annual agro-ecosystems were tilling allows for much higher additions of biochar on more frequent basis. A study of wheat farming in temperate areas found that applying biochar could result in 30 to 60 tons of carbon per hectare stored in agricultural soil (Vaccari et al., 2011). There are other options to consider in order to increase carbon storage. The International Biochar Initiative (IBI) has proposed surface application of biochar for perennial ecosystems despite possible higher losses by wind and water run-off (Major, 2010).

Although more research is needed, there is evidence from this experiment that biochar can have a positive effect on some physiological traits of coffee seedlings. Long term studies are needed to understand the effects of biochar in coffee bean yields which would have a more direct impact on farmers' livelihoods. There is also a need to understand the exact mechanism (chemical, physical, biological) by which biochar produces its positive effect on plant growth.

5. Conclusions

To summarize, using biochar as a growing medium for coffee has the potential to introduce recalcitrant carbon in the soils of perennial agroecosystems like coffee farms in Puerto Rico. The benefit of this management practice could be two-fold: improve plant growth and increase soil carbon sequestration. Based on this experiment, biochar used as soil amendment can benefit plant growth of coffee seedlings. Coffee nurseries could include the use of biochar amended growing mediums for their seedlings using a 12.5% to 25% dosage based on our results and expect on average higher plant growth than soil and compost alone.

Conclusion

In this thesis, I set out to understand the potential for integrating food and energy systems to mitigate climate change. Both food and energy production are significant emitters of greenhouse gases. Up to one-third of GHG emissions globally come from agriculture (Gilbert, 2012). A systems-thinking approach requires the study of both energy and agriculture. Climate change is creating more pressure on the management of energy, food, and water. These issues cannot be resolved in isolation but with a nexus approach (Finley & Seiber, 2014). Furthermore, agriculture in the tropics is particularly in danger due to changing weather patterns and increased intensity of climatic events. Degradation of forested ecosystems in tropical areas might also be a significant contributor of GHG (Pearson et al., 2017). Puerto Rico, the place where this research was conducted, was struck by Hurricane Maria in 2017 deepening its socioeconomic and racial inequalities (García-López, 2018). Puerto Rico's agricultural and energy sectors were affected. Certain parts of the island endured a blackout for almost a whole year (Smith-Nonini, 2020). Coffee agriculture in Puerto Rico was disrupted by damages and uprooted trees among other things (Mariño et al., 2018; Perfecto et al., 2019).

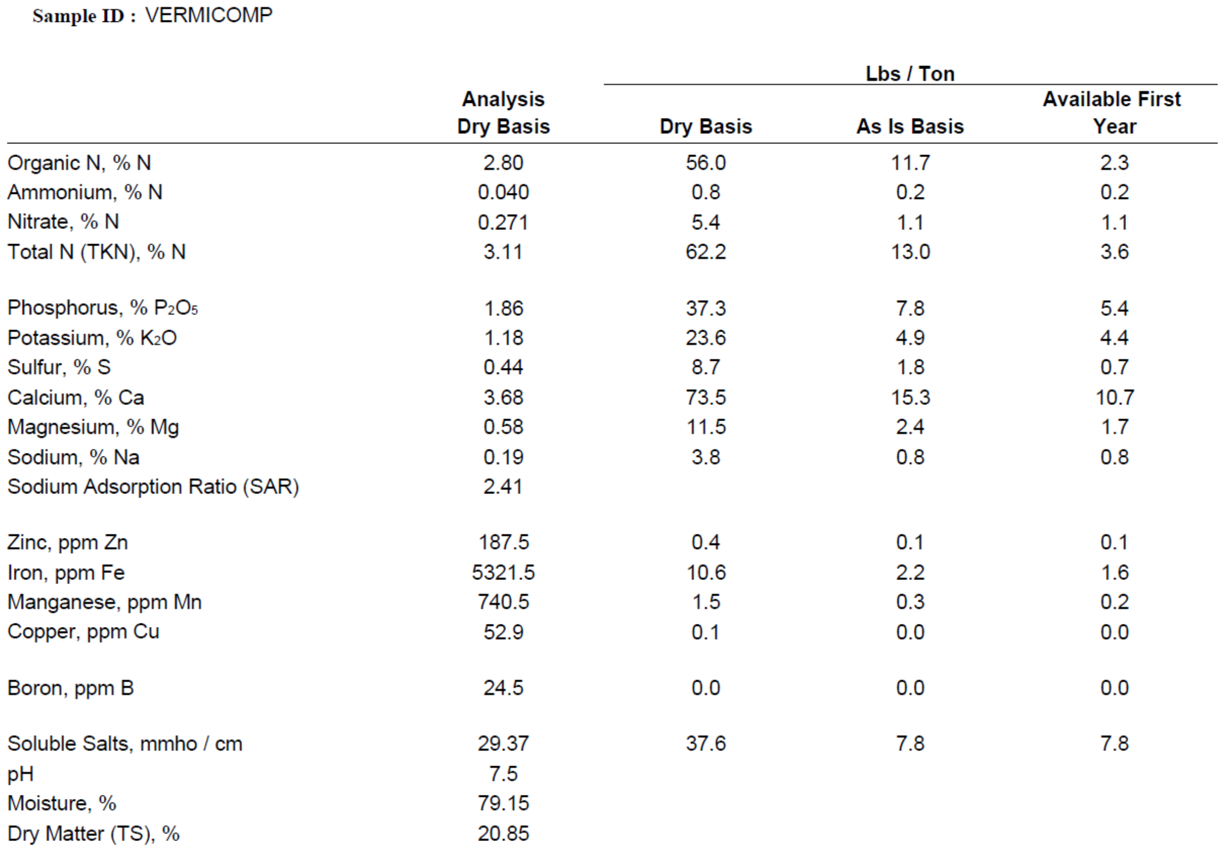
In the first part of this thesis, I conducted a survey to estimate the amount of down woody material biomass available in a gradient of sun to shade coffee agroecosystems. Based on those results, I calculated an approximate amount of energy generation that could be available through gasification, and the amount of carbon emissions reduction through biochar production. I began my study with four questions: (1) What is the amount of dead woody materials available per hectare in coffee farms in the central mountains of Puerto Rico? (2) What is the relationship, if any, between the amount of dead woody biomass and percent canopy cover? (3) How much energy can be derived from locally available dead woody material in coffee farms through a gasification process? (4) How many tons of carbon per year could be sequestered by using farm-generated biochar? Our results show some evidence that farms with densely planted coffee bushes produce more DWM than sparsely planted ones, and that sun coffee produces less DWM than shade coffee. Additionally, we estimated the potential to produce more than 5 GWh of energy per year using woody debris from coffee farms using our results for average down woody material found in our sampling locations. There is a potential to reduce emissions from agricultural activity and energy generation by using down woody material from coffee farms in biomass energy microgrids with biochar co-generation. About 8,000 tons of CO_2e per year could be reduced in this manner.

In the second part of this thesis, I conducted a greenhouse experiment to measure the effects of using biochar as a growing substrate for coffee seedlings. I measured plant response every fourteen days for three months tracking height, number of leaves, and the length of its longest leaf. At the end of the experiment, I measured the substrate pH. I began with three research questions: (1) Does biochar have a positive effect on the growth of coffee seedlings? (2) Can different amounts of biochar produce different outcomes in coffee seedling establishment? (3) Is there an ideal amount of biochar that can increase biomass productivity in coffee seedlings? The results show some evidence of positive effect of adding biochar in seedling growth of coffee plants. However, this effect seems to follow a quadratic relationship between seedling growth and amount of biochar. It is possible that there is a saturation effect or “too much” biochar added to the growing medium due to its highly alkaline nature. Additionally, I estimated the amount of carbon that could be sequestered by using a biochar and compost mixture as the growing substrate in coffee nurseries at a rate of 220 metric tons of C per million trees planted.

Finally, the results of this thesis show positive effects of integrating food and energy management by creating a circular economy of DWM in coffee agroecosystems and biochar soil conditioning. Most importantly, my thesis shows evidence that shade abundant coffee farms can produce more DWM as part of its management practices that can be used to generate biochar and energy through biomass gasification. Integrating small-scale biomass energy production and biochar co-generation in coffee agroforestry could be used as a technique to mitigate the effects of climate change. However, it is of utmost important to state that neither biochar nor emissions reductions nor biological carbon sequestration are silver bullets to fight climate change and its impact in tropical agriculture. The most important step to achieve a climate just future is to phase out all fossil and dirty fuels by 2030.

III. Appendices

Appendix A.



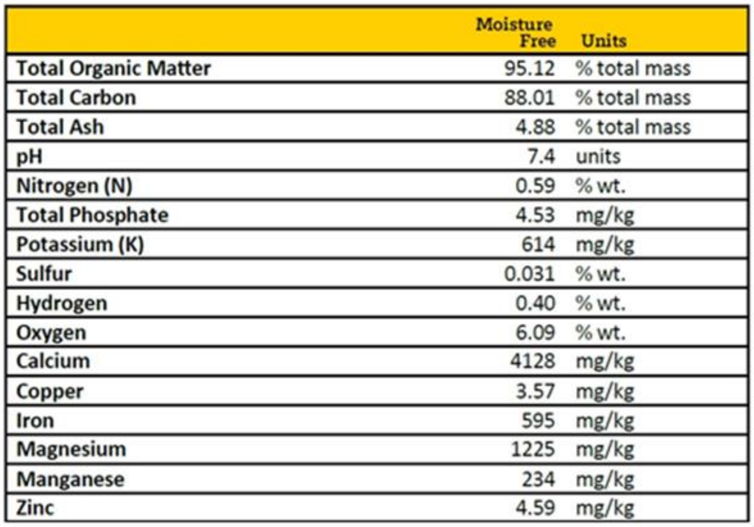
Sample ID : VERMICOMP

	Analysis Dry Basis	Lbs / Ton Dry Basis	Lbs / Ton As Is Basis	Lbs / Ton Available First Year
Organic N, % N	2.80	56.0	11.7	2.3
Ammonium, % N	0.040	0.8	0.2	0.2
Nitrate, % N	0.271	5.4	1.1	1.1
Total N (TKN), % N	3.11	62.2	13.0	3.6
Phosphorus, % P_2O_5	1.86	37.3	7.8	5.4
Potassium, % K_2O	1.18	23.6	4.9	4.4
Sulfur, % S	0.44	8.7	1.8	0.7
Calcium, % Ca	3.68	73.5	15.3	10.7
Magnesium, % Mg	0.58	11.5	2.4	1.7
Sodium, % Na	0.19	3.8	0.8	0.8
Sodium Adsorption Ratio (SAR)	2.41			
Zinc, ppm Zn	187.5	0.4	0.1	0.1
Iron, ppm Fe	5321.5	10.6	2.2	1.6
Manganese, ppm Mn	740.5	1.5	0.3	0.2
Copper, ppm Cu	52.9	0.1	0.0	0.0
Boron, ppm B	24.5	0.0	0.0	0.0
Soluble Salts, mmho / cm	29.37	37.6	7.8	7.8
pH	7.5			
Moisture, %	79.15			
Dry Matter (TS), %	20.85			

Table S1. Nutrient content analysis of vermicompost

2011												
Organic matter (%)	**K (%)**	**Mg (%)**	**Ca (%)**	**H (%)**	**Phosphorus (ppm)**	**Potassium (ppm)**	**Magnesium (ppm)**	**Calcium (ppm)**	**Nitrate (ppm)**	**Ammonia (ppm)**	**pH**	**CEC (meq/100g)**
2.65	5.39	11.59	50.96	32.34	28.00	154.88	102.75	813.38	5.00	7.09	5.30	7.65
2013												
Organic matter (%)	**K (%)**	**Mg (%)**	**Ca (%)**	**H (%)**	**Phosphorus (ppm)**	**Potassium (ppm)**	**Magnesium (ppm)**	**Calcium (ppm)**	**Nitrate (ppm)**	**Ammonia (ppm)**	**pH**	**CEC (meq/100g)**
3.49	4.91	10.93	53.66	30.43	19.75	130.25	89.75	755.75	6.38	3.63	5.35	6.93

Table S2. Soil analysis carried out by University of Puerto Rico Utuado in 2011 and 2013



	Moisture Free	Units
Total Organic Matter	95.12	% total mass
Total Carbon	88.01	% total mass
Total Ash	4.88	% total mass
pH	7.4	units
Nitrogen (N)	0.59	% wt.
Total Phosphate	4.53	mg/kg
Potassium (K)	614	mg/kg
Sulfur	0.031	% wt.
Hydrogen	0.40	% wt.
Oxygen	6.09	% wt.
Calcium	4128	mg/kg
Copper	3.57	mg/kg
Iron	595	mg/kg
Magnesium	1225	mg/kg
Manganese	234	mg/kg
Zinc	4.59	mg/kg

Table S3. Wakefield Biochar specification sheet

T1(Control 1)	5.9	0.097
T2	6.2	0.155
T3	6.5	0.144
T4	6.8	0.179
T5	7.2	0.361
T6(Control 2)	6.6	0.123

Table S4. pH values of soil solution per every treatment and standard deviation

IV. Bibliography

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