TOWARD THE RESILIENCE OF COUPLED FOOD AND ENERGY SYSTEMS: EFFECTS OF BIOCHAR AMENDMENTS ON PUERTO RICAN SOILS

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ABSTRACT

Agriculture in the tropics is challenging in large part because of low-fertility soils that are highly weathered, acidic, and have few nutrients which are prone to leaching during heavy rainfall. A potential solution to this dilemma is the use of biochar as a soil amendment to raise pH and increase nutrient availability for plants. To test the efficacy of biochar in enhancing soil fertility and plant growth, we built a gasifier to create biochar through pyrolization of wood from inga trees. Resulting biochar was used to create eight soil treatments in which bush bean plants were grown from seed in an outdoor greenhouse. Treatments consisted of four different amounts of biochar and the presence or absence of an organic calcium-containing fertilizer. After measuring the growth of individual plants over the course of 45 days, soil pH levels in pots were measured, beans were harvested, then plants were oven dried and weighed to determine biomass. Results showed that biochar amendments lead to significant increases in plant biomass and soil pH. A 4% amendment of biochar to soil without fertilizer increased plant biomass by 73% on average while the same 4% amendment of biochar in combination with fertilizer increased plant biomass by 173%. Unamended soil had an average pH of 5.1, soil amended with only the calcium containing fertilizer had a pH of 5.7, and soil amended only with 4% biochar a pH of 5.75.

INTRODUCTION

Puerto Rico

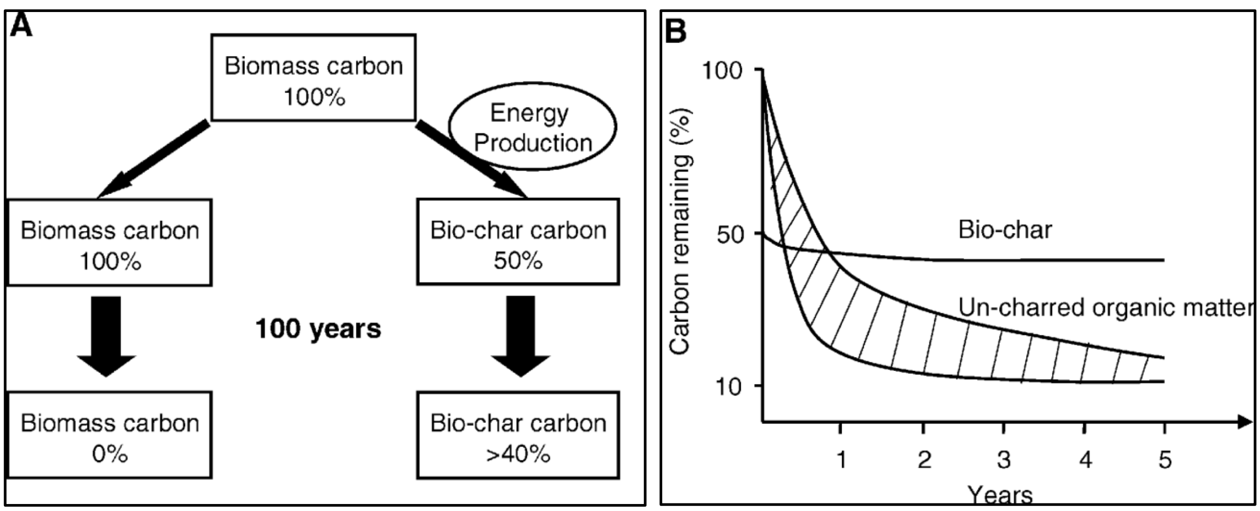
When recalling the impacts of Hurricane Maria making landfall on the island of Puerto Rico on September 20, 2017, what typically springs to mind is the record breaking eleven month blackout, the physical destruction to homes and buildings, and the nearly 3,000 lives lost in the aftermath. One of the lesser known impacts was the hit taken by Puerto Rico's agricultural sector which lost 80% of its crop value in the wake of the storm. Before Maria, 85% of all food consumed in Puerto Rico was imported. After Maria, food imports rose to 95%, further heightening food insecurity on the island (Bascomb 2018, Garcia-Navarro, 2017). As the effects of climate change continue to mount, the likelihood of storms forming with intensities matching Hurricane Maria will increase.

Puerto Rico needs to rebuild its food and energy infrastructure to be more resilient in the face of future storms. Our experiment is one half of a larger, combined project that offers a potential pathway to advance the goal of more resilient food and energy systems in Puerto Rico. The other half entails the analysis of electricity production by rooftop solar panels and the potential for installation of a microgrid for a rural community in the Puerto Rican municipality of Utuado. Linking the two projects is a gasifier which pyrolyzes biomass to produce a combustible gas with biochar as a byproduct. Coupling solar panels with the gasifier as a backup generator for nighttime or overcast skies would create a system of 100% renewable electricity generation. That system would be fed with biomass from local farms, and farmers would then take the biochar produced by the gasifier and apply it their soils as an amendment to improve fertility and in turn improve crop yields. This dual system would function as a closed loop with the additional benefit of being carbon neutral, as biochar sequesters carbon in the soil as part of the stable organic matter fraction (Lehman et al 2006).

Soil Fertility

Despite plentiful rainfall and temperatures that permit a year-round growing season, tropical agriculture can be extremely challenging. One of the greatest problems farmers in the tropics face is low soil fertility, both in terms of nutrients and organic matter. Large amounts of rainfall can lead to elevated leaching of critical plant nutrients such as nitrate and phosphate while high temperatures promote rapid decomposition of organic matter that has little chance to accumulate in the soil (Brady and Weil, 2014).

One solution to the problem of soil fertility in the tropics is the use of biochar as a soil amendment. Indigenous peoples of the Brazilian Amazon rainforest created biochar by charring or partially burning wood in kilns or pits. The fire would be smothered while allowing limited air in so that it could continue to smolder (Coomes and Mitler 2006). Examinations of their settlements found that sites where biochar had been added retained their productivity long after the communities who created them left (Cheng et al., 2008). Termed *terra preta* or 'dark earth' for their distinctive black coloration, these anthrosols that had received additions of biochar were found to be more fertile than adjacent oxisols with which they shared the same base properties but had not received biochar (Cheng et al., 2008, Lehmann et al., 2006).



Figures 1-2: Graphical representations of the persistence of carbon biomass in biochar compared to non-charred organic matter (Lehmann et al., 2006)

Just as the addition of biochar by indigenous farmers in the Amazon basin created fertile *terra preta* centuries ago, it could also be used to enhance the fertility of tropical soils elsewhere in the world today. We use gasifiers to control the combustion conditions for syngas and biochar production. In pyrolysis where organic matter is burned at low temperatures and oxygen levels, hydrogen and carbon atoms are separated from the hydrocarbons that compose many organic molecules. This process creates syngas, a mixture of gases such as hydrogen, methane, carbon dioxide, and carbon monoxide, and concomitantly makes biochar. During pyrolysis, much of the carbon in biomass is stripped away like in normal combustion, but the remaining carbon is structurally rearranged into a recalcitrant form that is highly stable and resistant to decomposition. The majority of this will persist in soil for decades up to millennia, while the equivalent amount of initial biomass would have long since decayed had it been added directly (Figures 1-2).

Biochar particles contain numerous negatively charged sites that positively charged cations can bind to, preventing them from leaching into the soil solution and making them more readily available for plant uptake. Biochar has also been shown to raise pH which has implications for a multitude of processes such as microbially-facilitated nutrient cycling, cation exchange capacity (CEC), and plant uptake of essential nutrients, many of which are cations (Laird et al., 2010, Major et al., 2010, Jeffery et al., 2011).

In this experiment we examined the effects of biochar on plant growth with and without fertilizer. Based on a literature review of previous biochar studies, we expect biochar to improve soil fertility and consequently plant growth. The mechanism at here would be increased availability of plant nutrients due to reduced leaching and soil pH being raised to levels more suitable for uptake of those nutrients. We also expect the effect of biochar on plant growth to be greater with the application of fertilizer as an additional nutrient source. Plant growth was assessed by measuring height of individual plants at five day intervals and removing plants from soil to obtain an oven dry mass at the end of the 45 day growing period.

METHODS

The biochar for this experiment was made by pyrolyzing wood in a homemade gasifier based on a downdraft design model provided by a FEMA manual (FEMA 1989). All wood used was from trees in the genus *Inga* and collected on the University of Puerto Rico Utuado campus where we conducted our experiment. Some wood was from trees that had been toppled by hurricane Maria the previous year and the rest was cut from live trees. Branches were run through a wood chipper and wood chips were dried in a solar kiln for several days before undergoing pyrolysis in the gasifier and being converted to biochar.

Concentrations (g)				
Treatment	Soil	Fertilizer	Biochar	Total
Soil (S)	600			600
Soil + Biochar 1% (SB1%)	600		6	606
Soil + Biochar 2% (SB2%)	600		12	612
Soil + Biochar 4% (SB4%)	600		24	624
Fertilizer (F)	600	13		613
Fertilizer + Biochar 1% (FB1%)	600	13	6	619
Fertilizer + Biochar 2% (FB2%)	600	13	12	625
Fertilizer + Biochar 2% (FB2%)	600	13	24	637

Table 1: Experimental Soil Treatments

Eight soil treatments (Table 1) were used in this experiment to determine how biochar and fertilizer, separately and in combination, would affect plant growth. Native topsoil was collected on the University of Puerto Rico Utuado campus, sieved through a 0.5 sq. inch mesh, and placed into a five inch pot. There were two sets of treatments concerning fertilizer, one with, and one without. Fertilizer used was Bioflora Crumbles, a 6-6-5+8% N-P-K+Ca organic blend. For treatments containing fertilizer, the amount was kept constant at 13 g per the manufacturer's recommendation based on the amount of soil used.

There were four treatments for additions of biochar to soil, as a percentage of soil mass. Soil mass for all treatments was held constant at 600 g per pot, and levels of biochar were 0%, 1%, 2%, and 4% of soil mass (see Table 1). The amounts of biochar added were determined based on the most commonly occurring rates in a review of relevant scientific literature (Deal et al., 2012, Laird et al., 2010). The proportions used in our experiment are the same, only expressed as a percentage of soil mass; 10g/kg then becomes 1% of soil mass. We also Biochar and fertilizer amendments were incorporated by placing the soil in a plastic bag, adding the necessary amendments for the treatment, sealing the bag, and mixing by hand.

Each of the eight treatments consisted of ten replications, giving us a total of 80 pots of soil. Each pot was seeded with five bean seeds (Organic Bean Garden Bush Blue Lake 274 Seed, *Phaseolus vulgaris*) on August 3rd (day 1) and allowed to grow until September 16th (day 45). Seeds which failed to germinate were removed from the pot. In pots with multiple germinating seeds, the largest plant after five days of growth was kept, while the rest were removed. Plants were grown outdoors in a greenhouse open to ambient temperature and some precipitation. The walls of the greenhouse were made of a metal frame covered in mesh and the roof consisted of both solid panel and mesh sections. Parts of the greenhouse were also shaded by nearby trees and the surrounding hills at various points in the day. To ensure relatively uniform exposure to light, pots were rotated throughout the greenhouse on a five-day basis coinciding with recording growth measurements.

Plants were checked daily for insect infestation and dry soil conditions. Insects were controlled with applications of neem oil mixed with water, and plants were given water periodically as needed. The height of each growing plant, measured from the top of the soil surface to the topmost portion of the stem, was recorded every five days. As plants grew, they were tied to stakes that were inserted into the pots to keep them upright. After 45 days of growth, beans from each plant were harvested and number and mass were recorded. The entire plant was then removed from the soil and then air dried in an oven overnight. A pH test was conducted on the soils from all of the treatment pots using a glass electrode. Dry mass of the remaining plant tissues, separated into above and below ground sections, was then weighed and recorded.

RESULTS

Growth Rate

We used changes in height as a proxy for biomass in our experiment for its convenience. Plants from soil treatments with fertilizer and biochar amendments had both greater overall average height and faster rates of growth than treatments without fertilizer (Figures 3-4). The average height of plants after 45 days of growth for treatments without fertilizer with no biochar, 1%, 2%, and 4% biochar additions were 36.06 cm, 30.40 cm, 47.85 cm, and 41.33 cm. The average heights for plants grown at the same levels of biochar additions plus fertilizer over the same period were

98.41 cm, 63.89 cm, 112.65 cm, and 98.00 cm. However, there was no significant difference in plant height at the end of the growth period deeming effects of soil treatments on plant growth were inconclusive.

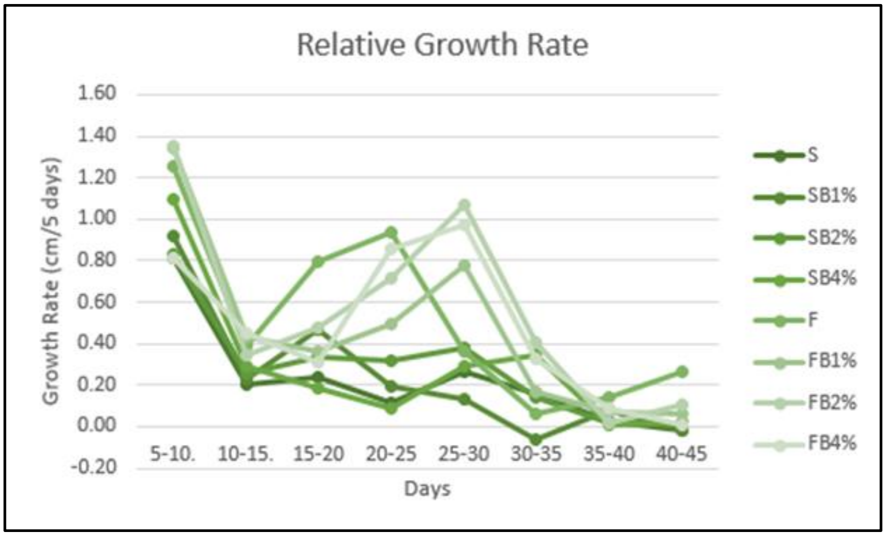


Figure 3: Relative growth rate over time (average of replicates, N=10)

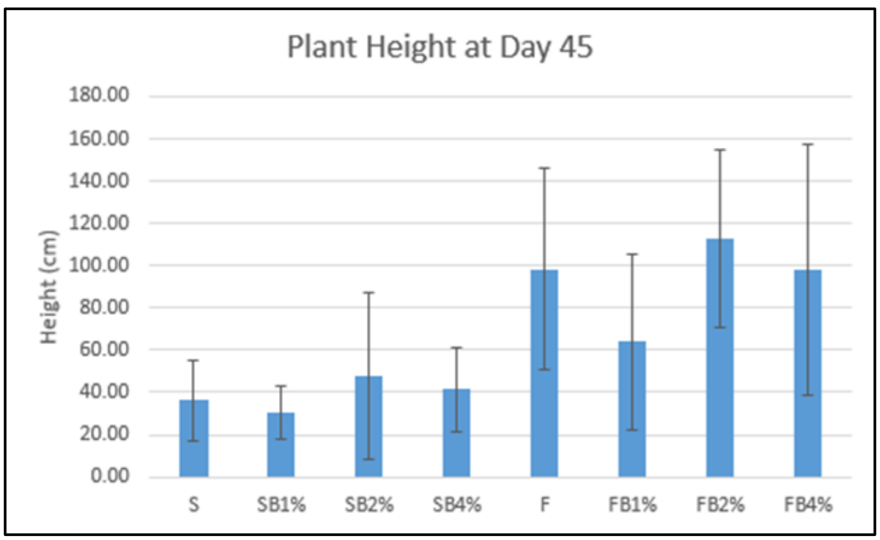


Figure 4: Plant height at day 45 (average of replicates, N=10)

Plant Biomass

Plants grown in soil treatments containing fertilizer had an average biomass 4-6 times greater than the treatments without, and, of those plants, treatments containing biochar and fertilizer had greater biomass than with fertilizer alone (Figure 5). Average total biomass of plants of treatments without fertilizer from no biochar to 1%, 2%, and 4% additions were 1.00 g, 1.25 g, 1.07 g, and 1.73 g. Average total biomass of plants for treatments with fertilizer from no biochar to 1%, 2%, and 4% additions were 8.69 g, 11.43 g, 10.25 g, and 11.89 g. Although average total biomass of plants with fertilizer was much greater than plants grown without, presence or absence of biochar in treatments also had a significant difference on total plant biomass. For treatments without fertilizer, going from no biochar to 4% resulted in a 73% increase in total biomass (1.00 g to 1.73 g). For treatments with fertilizer, going from no biochar to 4% resulted in a 173% increase in total plant biomass (8.69 g to 11.89 g). The below figure below shows the effect of treatments on root, stalk, leaf, and bean biomass separately. However, there were no statistically significant differences in total biomass between treatments, nor were there significant differences in above or below ground biomass between treatments (between treatments referring to additions of biochar to as compared to either soil alone or fertilizer alone).

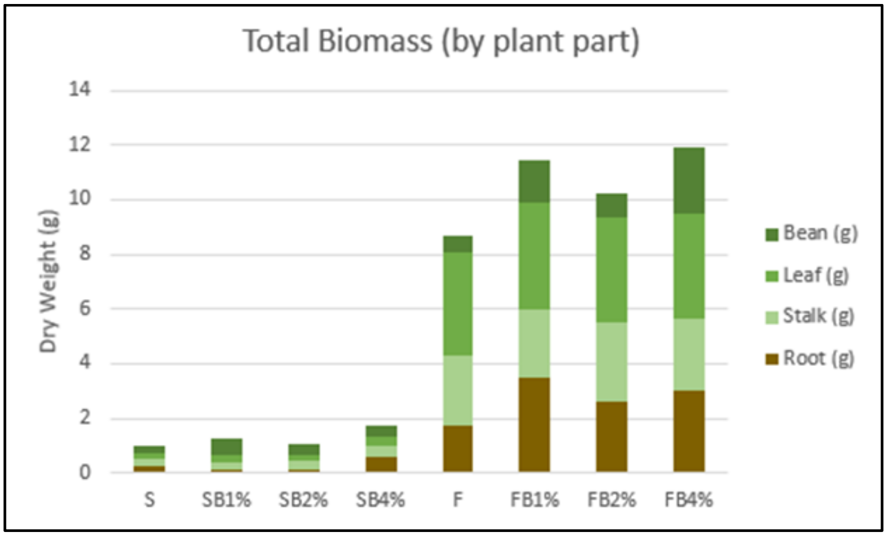


Figure 5: Plant biomass by treatment (average of replicates, N=10)

The presence or absence of biochar in soil treatments did have significant effect on bean yield (Figure 6). Plants with soil alone produced an average of 0.29 g of bean biomass per plant while an addition of 4% biochar resulted in an average of 0.40 g per plant, a 138% increase. With fertilizer alone, average bean biomass production was 0.63 g per plant while an addition of 4% biochar resulted in an average of 2.43 per plant, 386% increase. A one-way anova and tukey test was run in R to compare bean yield across treatments. Without fertilizer, the 1% biochar treatment was significantly different from the soil only treatment ($P < 0.01$). With fertilizer, the 1% biochar as well as the 2% biochar were significantly different from the fertilizer only treatment ($P < 0.01$ for 1% and 2% biochar treatments).

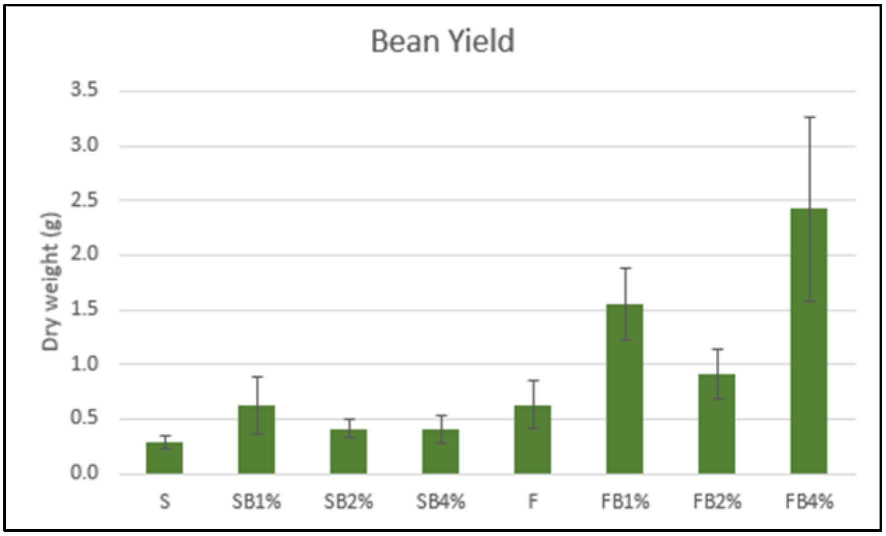


Figure 6: Bean yield by treatment (average of replicates, N=10)

Soil pH

Both the addition of biochar and fertilizer raised soil pH (Figure 7). Without either amendment, average soil pH was 5.10. Adding biochar at rates of 1%, 2%, and 4% of soil mass raised average soil pH to 5.34, 5.57, and 5.70. Soil treated with only fertilizer had a pH of 5.75. Adding biochar at 1%, 2%, and 4% of soil mass to soil treatments including fertilizer resulted in pH of 5.93, 6.08, and 6.38. A one-way anova and tukey test was run in R to compare soil pH across treatments. Without fertilizer, the additions of 1%, 2% and 4% biochar were all significantly different from the soil only treatment ($P < 0.01$ for all treatments), and the same was true for treatments with fertilizer where additions of 1%, 2%, and 4% biochar were significantly different from the fertilizer only treatment ($P < 0.01$ for all treatments).

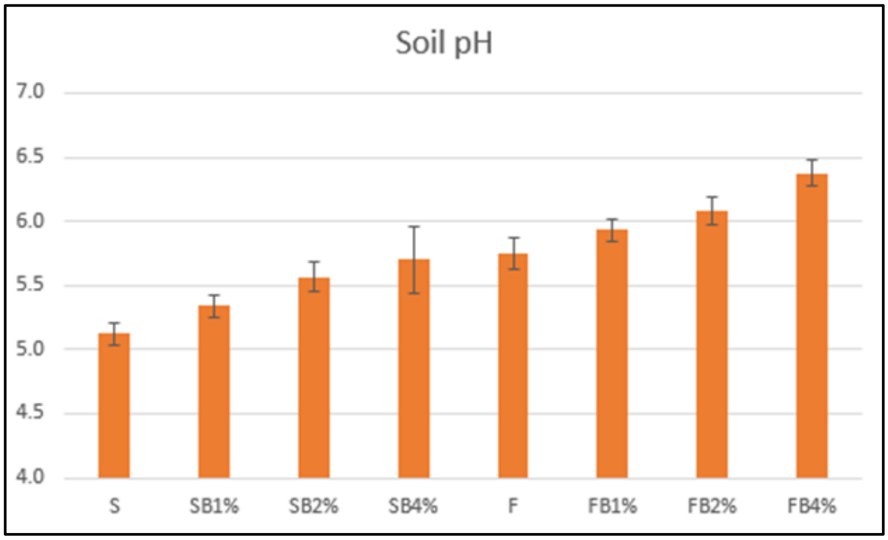


Figure 7: Soil pH by treatment (average of replicates, N=10)

We performed linear regressions to determine the relationships between soil pH and total biomass as well as soil pH and bean yield. The relationships between soil pH and total biomass as well as soil pH and bean yield for treatments without fertilizer were very weak relationships. However, treatments with fertilizer had relatively strong relationships (Figures 8-9). The relationship between total biomass and soil pH with fertilizer had an R^2 value of 0.6 and the relationship between bean yield and soil pH had an R^2 value of 0.7, indicating that these models explain most of the variability of response data around the mean.

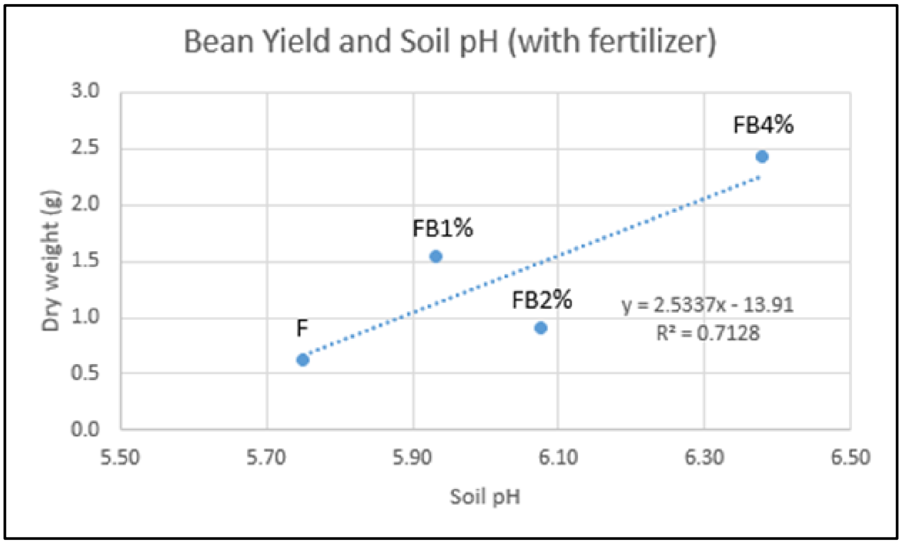


Figure 8: Relationship between soil pH and bean yield for fertilizer treatments

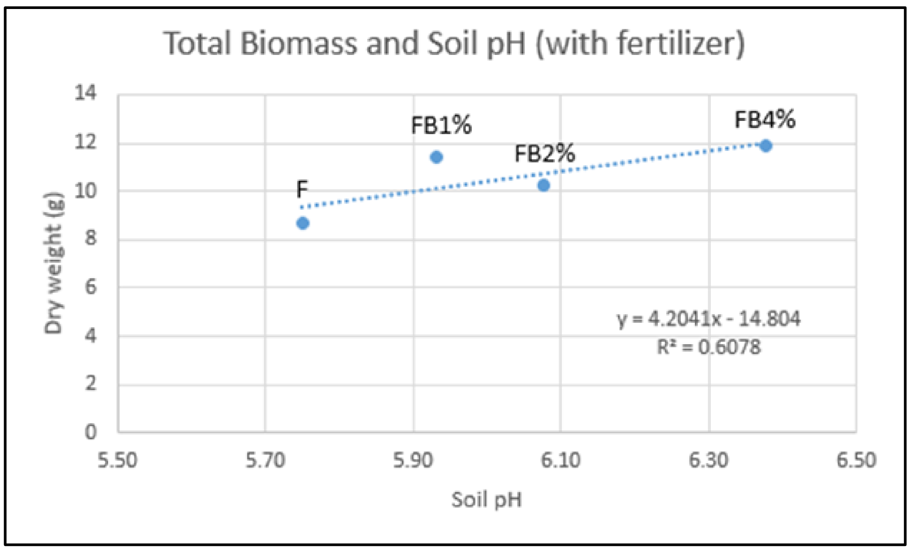


Figure 9: Relationship between soil pH and bean yield for fertilizer treatments

DISCUSSION

As expected, our results were in line with those of other studies regarding the effects biochar on soil. Adding biochar to tropical Puerto Rican soils increased soil pH and consequently total plant biomass and yield. Biochar additions presumably increased nutrient absorption by the plants as well, though we were unable to measure soil nutrient levels or nutrient absorption in this experiment. However, we believe increased nutrient absorption by the plants was implied given plants from combined biochar-fertilizer treatments had greater biomass compared to plants grown in the fertilizer-only treatment.

Biochar contains numerous negatively charged surfaces that increase the soil's ability to retain buffering cations such as Ca^{2+} and Mg^{2+} that in turn raise pH (Jeffery et al., 2014, Laird et al., 2010, Lehman et al., 2003, 2006). The soil-only 4% biochar treatment increased average pH almost as much the Ca-containing fertilizer-only treatment (5.70 and 5.75, respectively). Raising the pH of these acidic tropical soils allows plants to better absorb available nutrients as well as speed up microbially-mediated nitrogen mineralization, both of which are pH-sensitive processes. Positively charged cations such as Ca^{2+} and Mg^{2+}, along with K^+ and N in the form of ammonium (NH_4^+) are also vital plant nutrients in and of themselves (Brady and Weil, 2014). Biochar therefore reduces leaching of soil nutrients by providing additional charged sites that cations can bind to and make them readily available for plant uptake (Coomes and Mitler, 2006, Lehmann et al., 2003).

The ability of biochar to raise soil pH and plant nutrient availability is compounded by its recalcitrant properties. Pyrolysis alters the physical and chemical properties of carbon in organic matter, rendering the resulting biochar extremely resistant to decomposition when compared to other types of soil carbon (Lehmann, 2007, Lehmann et al., 2006). This allows carbon inputs from biochar into the soil to accumulate over time with repeated additions while repeated carbon inputs from green manure or compost must be continually reapplied as their carbon is rapidly decomposed and cycled. Biochar studies conducted on multi-year timescales show that increased levels of soil carbon, soil pH and CEC can persist even after biochar inputs cease. The *terra preta* soils located near indigenous settlements in the Amazon, even after centuries of abandonment, still show marked differences in physical, chemical, and biological properties compared to neighboring soils which received no inputs of biochar (Lehmann, 2007, Lehmann et al., 2006).

CONCLUSION

Our results show that the use of biochar as a soil amendment improves the fertility of otherwise weathered and acidic tropical soils. Our results reinforce the conclusions of previous studies that biochar enhances both overall plant growth and yields by improving soil pH and nutrient retention. The extent to which other benefits associated with biochar amendments impact soil fertility and plant growth, such as increased CEC, increased water holding capacity, and reduced nutrient leaching, should be included in future iterations of this study.

We utilized what is often thought of as a byproduct of pyrolysis to enhance soil fertility, yet the process of pyrolysis that creates biochar can simultaneously be used to fuel electricity production. While there are tradeoffs between generating electricity and making biochar, one could nevertheless obtain both products as a result of a single process from a single machine: a homemade gasifier.

For the purposes of our overall project, we deliberately designed a gasifier that could be built without specialized equipment or knowledge and act as a backup generator in conjunction with solar panels. Ideally, such gasifiers could provide both renewable and carbon neutral electricity for individual households or small communities while at the same time producing a valuable soil amendment for farmers to improve their crop yields. Crop residues and tree prunings from food systems then become a fuel source or input for energy systems, whose secondary output, biochar, in turn becomes an input for the food system as a soil amendment. The adoption and expansion of this circular economy would be especially beneficial to rural people in Puerto Rico as a means to put them on a path toward food sovereignty and energy independence.

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