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The potential contribution of biochar to sustainable fertility of lowland rainforests' soils
Literature overview and experimental application in Peruvian Amazonia

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The Potential Contribution of Biochar to Sustainable Fertility of Lowland Rainforest's Soils

LITERATURE OVERVIEW AND EXPERIMENTAL APPLICATION IN PERUVIAN AMAZONIA

Summary

Abstract

In the Amazonian rainforest, farmers rely on slash-and-burn technique to cope with low fertility soils (Kumar and Nair, 2006; Takasaki, 2013; Lehmann et al., 2002). However, this technique result in forest degradation (Glaser et al., 2002) and is considered not sustainable for it does not allow more than three to five years of cultivation in the same parcel (Kumar and Nair, 2006).

Biochar is a carbon-rich material produced from any kind of dry biomass using high temperature combustion combined with low oxygen input (phenomenon known as pyrolysis) that aims at alleviating the rapid fertility loss of tropical soils (Lehmann et al., 2006). Used as a field amendment it has shown to reduce nutrients leeching (Lehmann Johannes, 2007a; Zheng et al., 2010), increase water retention (Glaser et al., 2002), enhance soil biota (Lehmann et al., 2011) and increase crop yield (Crane-Droesch et al., 2013).

Moreover, due to its great residence time in soil (Abiven Samuel, 2015), and its positive effect on greenhouse gas flux in soils (Rogovska et al., 2011; Scholz et al., 2014), biochar have been suggested as a solution to reduce the atmospheric CO_2 concentration (Beverly D. McIntyre et al., 2009; Zheng et al., 2010; Weisberg et al., 2014).

However, biochar properties and effects varies considerably according to the pyrolysis temperature (Fuchs et al., 2014), biomass used (Clay and Malo, 2012; Demirbas, 2004), type of soil amended, crop used and climatic conditions (Van Zwieten et al., 2010; Crane-Droesch et al., 2013; Abiven Samuel, 2015). Moreover, although biochar making technologies are affordable and easy to build, they are still not widespread and are therefore absent of most small-scale farms.

In this paper, we firstly present a prototype design of a small-scale and affordable biochar-making oven that uses the heat of pyrolysis for cooking. This oven uses local material and tools and is designed for family farms of the village of Pilcopata- Peru. Although the biochar yield results did not achieved the reported amount of other small-scale biochar oven, this prototype can be used as a good starting point for further research.

Secondly, we present the preliminary results of an experimental program aimed at measuring the effects of Paca-bamboo biochar on plantain and pineapple yield when mixed with lombricompost on a soil of Pilcopata-Peru.

Key words: biochar, climate change, soil fertility, rainforest, small-scale farmers

Table of Acronyms

CEC	Cation exchange capacity
PAH	Polycyclic aromatic hydrocarbons
Mg	Megagram
Pg	Petagram
CO_2-C_e	Carbon dioxide - carbon equivalent
CDM	Clean development mechanism
SSA	Specific surface area
ANOVA	Analysis of variance
T	Tons
ha	Hectares

Table of elements

CO_2	Carbon dioxide
CH_4	Methane
P	Phosphorus
N	Nitrogen
C	Carbon
N_2O	Nitrous oxide

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1 Introduction

Food production concerns population all around the globe. But while in some cases, production takes place where the weather, soils, technologies and techniques allow high yield and sedentary lifestyle, others cope with poor soils, destructive rainfalls or harsh sunlight. It is the case for farmers in the Amazon rainforest where a vast majority relies on slash-and-burn technique and family labor to survive.

The slash-and-burn technique consists on the clearing of a parcel of secondary or primary forest, cultivating this parcel for three to five years until the soil becomes too poor and weed pressure too important, then moving to another parcel and start the process over again, resulting in increased work load, distance between field and homes and forest degradation. Moreover, as a response to environmentalists and conservationists, policy makers put additional pressure on farmers by regulating where to cut or where not to cut, sometimes forcing farmers to rely on an easy growing crop, able to grow when the soils go poor, but already abundant on the market and therefore hard to sell, increasing the precariousness of their situation.

In view of those constraints, the need for new sustainable techniques is of critical importance. This is where the biochar may prove of interest. Biochar is basically charcoal produced with the aim of using it as a soil amendment. Biochar has proven its ability to increase soil fertility and crop yield. At the same time, it stores carbon in the soil for centuries, reducing greenhouse gas emissions induced by agriculture. The process of producing biochar is simple and cheap, available even for the most remote households and, therefore, likely to be adopted by the population.

This paper provides, firstly, an overview of literature about biochar: what it is, what it does and what are its prospects. Secondly, it presents the experimental design, building and use of an affordable oven for rural dwellers and the test of its ability to increase yields on plantain and pineapple fields in Pilcopata, Peru.

Overview of the literature

In the following chapters we briefly present the rainforest environment with an emphasis on the types of soil found in the Amazonia and the state of agriculture in this particular region. We then introduce the biochar and focus on its effect on soil fertility, crop yield and its capacity to mitigate climate change.

2 Sustainability of agriculture in lowland tropical rainforest

2.1 Tropical rainforests: a fragile asset that deserves protection

Rainforests are typically found in equatorial zones between the Tropic of Cancer and Tropic of Capricorn. This refers to latitudes with warm temperatures and relatively constant year-round sunlight and heavy rainfall (Butler, n.d.)

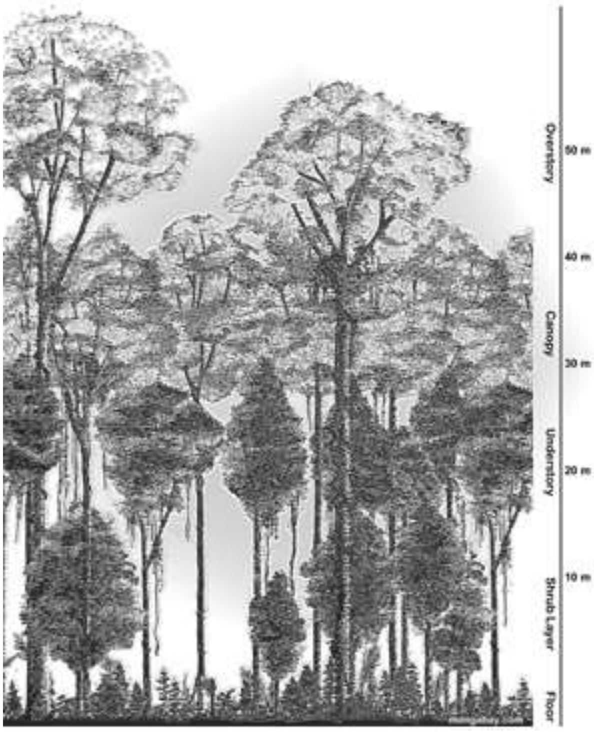

Figure 1: Rainforest structure (Butler, 2012)

The world’s largest rainforest is the Amazon rainforest (South America). However tropical rainforest can also be found in the Congo Basin (and surroundings), the South East Asia, in the Caribbean island, Central America and Mexico, India, on the island of the South Pacific, and in Madagascar as shown in Figure 2 (Butler, n.d.).

Although each rainforest is unique, scientists agree on certain features common to all tropical rainforests:

- Rainforests lie in the tropics
- Precipitations are at least 200 cm per year
- Rainforests have a canopy (refers to the dense ceiling of leaves and tree branches formed by closely spaced forest trees) inhabited by a large proportion of plants and animals
- Rainforests have extraordinarily highs level of biological diversity (estimated to 50% of Earth’s biodiversity)(Butler, n.d.)

Figure 2: Tropical forest repartition (Butler, n.d.)

Although climate in the tropics is said to have two well-defined seasons (a dry and a rainy season) the lowland rainforest does not share this characteristic. Indeed, it rains all year round with longer sunny period between each rain in the so-called "dry season".

The mean temperature oscillates between 25°C and 28°C and precipitation between 1,500 and 3,000 mm annually, depending on the location (Vera, 2006). In some cases, however, much higher temperatures, up to 33°C, have been recorded, for instance, in the Brazilian rainforest ("Climate of the Amazon Rainforest," n.d.).

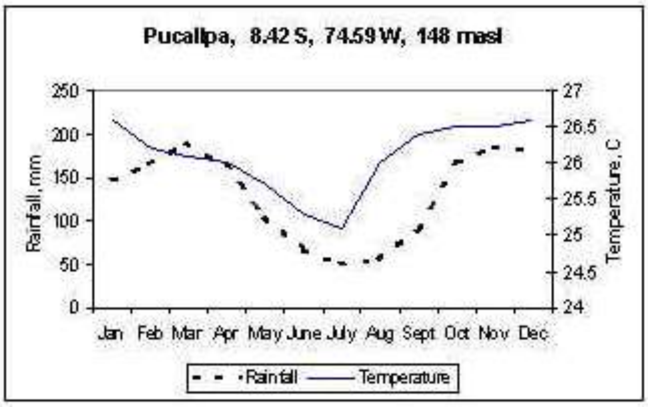

Figure 3: Mean monthly temperature and rainfall at Pucallpa, amazon lowlands of Peru (Vera, 2006)

The Amazonian rainforest is considered as an incredible biodiversity hot spot. Nevertheless, in Peru only, the deforestation rate of the past few years has reach 260,000 ha/year (Piu and Menton, 2014), which is a source of concern for environmentalists and scientists, afraid of the loss of the irreplaceable. Moreover, because of the large scale of Amazonia, land conversion, exploitation and logging have the potential to strongly affect global greenhouse gas burden creating, under some scenarios, catastrophic events ("Global Ecosystem Monitoring network", 2015).

2.2 The soils of tropical lowland Amazonian rainforest

Biochar being a soil amendment, it is essential to understand the quality of the soil it is used on before discussing its potential effect on it.

Various types of soils are identified under tropical climate. Focusing on the lowland Amazon, the most representative of them are Ferralsols, Acrisols and Alisols.

2.2.1 Ferralsols

Ferralsols are generally found on flat, well-drained areas of tropical regions where the hot temperature and heavy rainfall promote strong weathering. They are chemically poor, acidic, present a poor cation exchange capacity (CEC)[1] and have low carbon content (Quesada et al., 2011; Wick, n.d.)

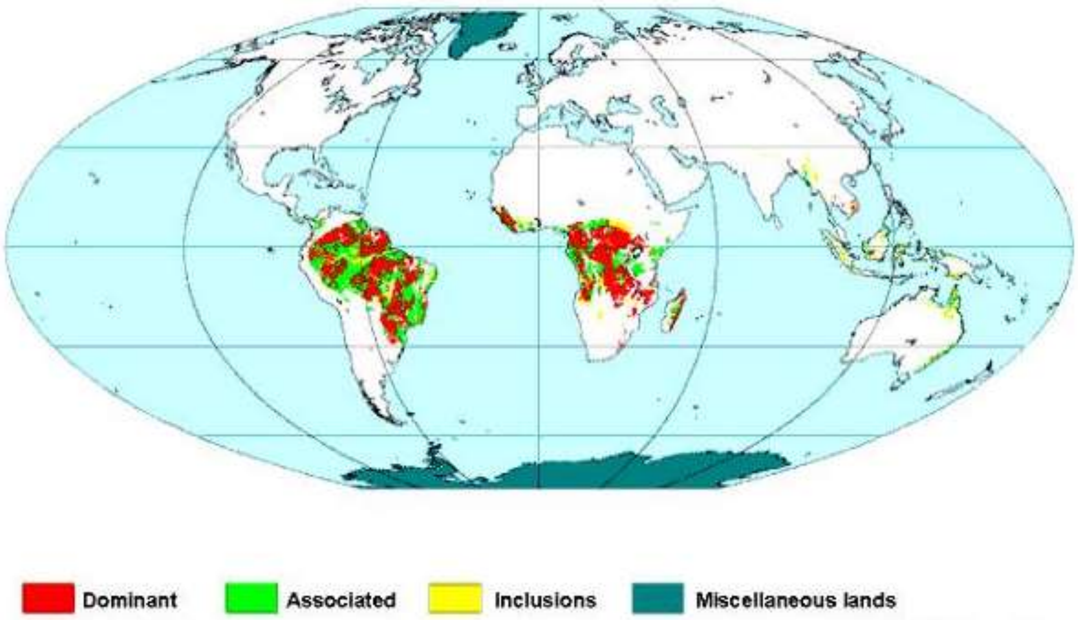

Figure 4: Worldwide repartition of ferralsols (Driessen and Deckers, 2001)

The well-aerated structure of ferralsols allows a free circulation of air and water thus tolerates fast rainfall acceptance, helpful in rainforest climate to avoid erosion. On the downside, most of the useful elements for the plants leach rapidly to deeper layers, out of reach of crops' roots, leaving only the less leachable elements such as iron and aluminum, creating the typical yellow to red colors of ferralsols (Quesada et al., 2011).

Because the retention fraction of useful elements by the clay (mainly kaolinite, Wick, n.d.) is not very active, the quantity of nutrients available for the plants is entirely dependent on the quantity and quality of the organic matter. Moreover, studies show that the presence of non-humified organic matter (especially the fraction that is produced by the early decomposition of fresh produces) is very important for the stability of the clay. The removal of organic substances induces the breakdown of the aggregate thus the loss of the well-aerated structure leading to the release of important amount of clay (van Wambeke, 1974; Driessen and Deckers, 2001).

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[1] The CEC is the ability of a material to hold cations (Edmunds, 2012). It is the measure of how well cations are bounded to the material and therefore accessible to plant nutrition and less susceptible to leaching (Verheijen et al., 2010).

Therefore, if the stability of the structure of ferralsols is to be preserved, the permanent intensive biological activity needs to be preserved either by a constant supply of fresh organic matter or by the natural decomposition of the roots and the litter. Indeed, organic matter binds the soils particles together, improving the structure and granulation. It also lightens and expands the soil making it more porous, thus increasing its water retention ability (Vickery and Vickery, 1982).

Intensive agriculture methods, exporting the biomass and interrupting the nutrient cycle, are therefore not recommended in these types of soil.

2.2.2 Acrisols

Acrisols occupy younger geomorphic positions than ferralsols and are considered the second most common soil in Amazonia (Quesada et al., 2011).

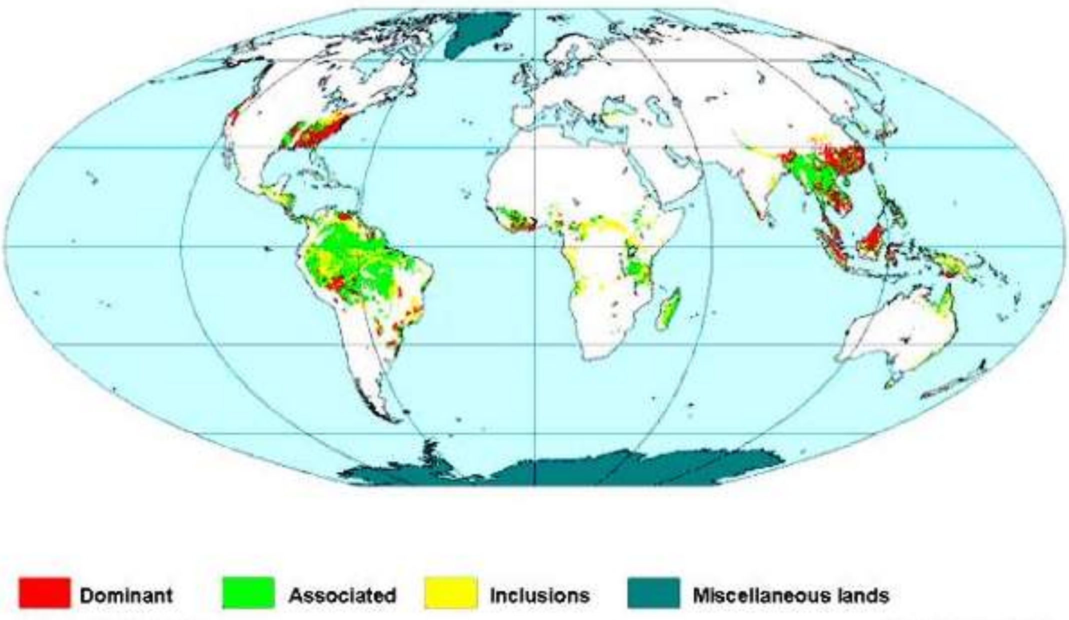


Figure 5: Worldwide repartition of acrisols (Driessen and Deckers, 2001)

Acrisols are strongly weathered acid soils with low base saturation and low activity clay, resulting in a low CEC. They are not very productive soils due to their overall poverty of plant nutrients (pH≈ 4.5 (Vickery and Vickery, 1982)) and to aluminum toxicity (Driessen and Deckers, 2001; Vera, n.d.).

Moreover, acrisols' physical properties are often a major limitation to plant growth. Indeed, the textural variation within the profile and the weak structure of the loamy/sandy upper layer, is often reported to reduce infiltration, hence increasing runoff and favoring compaction. When protected by forest cover, acrisols have a porous surface but as soon as the forest is cleared, the upper layer starts to degrade and forms a hard surface crust. The crust prevents sufficient water infiltration during heavy rain and creates surface erosion (Driessen and Deckers, 2001). Preservation of the surface soil, including its organic matter, is therefore a necessity for farming on acrisols.

2.2.3 Alisols

Alisols usually occur on old land surface with hilly or undulating topography. They are known to be strongly acidic soil (pH≈ 4.5 (Vickery and Vickery, 1982)) and, unlike acrisols, present a high activity clay which allows an intermediate CEC and are therefore considered of limited fertility (Quesada et al., 2011).

The limited fertility is due, first of all, to the occupation of more than a half of the exchangeable site by aluminum which results from the oxidation of the aluminum rich parental material (Wick, n.d.).

Secondly, alisols present a rather weak structure in the surface layer due the low biological activity prevented by the strong acidity and the high aluminum concentration. This weak structure of the surface layer reduces the permeability thus delays internal drainage and intensifies erosion (Driessen and Deckers, 2001).

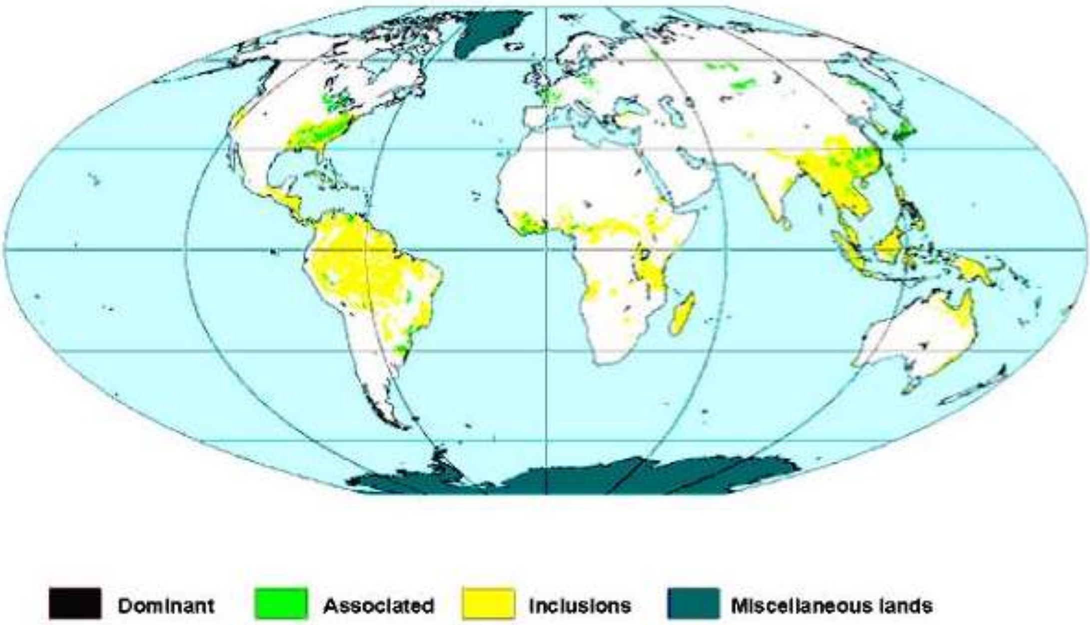


Figure 6: Worldwide repartition of alisols (Driessen and Deckers, 2001)

The high activity clays, characteristic of alisols, provide favorable cation exchange properties, which enable them to have a relatively good nutrient availability. However, their propensity to erosion due to weak surface structure and undulating topography, their toxic level of aluminum as well as the acidic pH makes alisols unproductive.

Management to reduce the toxic effect of aluminum includes the application of organic matter. Indeed, soils organic matter complexes the aluminum in non-exchangeable form. Another technique to eliminate the exchangeable aluminum is to raise the pH to a certain level. This could be achieved by liming although the amount of lime necessary is elevated and usually unaffordable for small-scale farmers (Driessen and Deckers, 2001).

2.3 Agriculture in lowland tropical rainforest

In lowland rainforests, the main agricultural practice is swidden cultivation (also known as slash-and-burn or shifting cultivation) (Kumar and Nair, 2006; Takasaki, 2013; Lehmann et al., 2002). This practice consists on the clearing then burning of a field site situated in primary or secondary forest, followed by plantation of crops. Generally, after two or three years the cropping stops due to decreasing yields and an increasing weed pressure. Farmers then need to change site and start burning another patch of forest while a secondary forest starts to grow on the fallowed field. While this practice used to be sustainable, population increase has led to shorter fallow periods resulting in irreversible soil damage and increased forest degradation (Glaser et al., 2002).

Additionally, the use of crop residues for or by livestock and of cow dung as a source of energy has an adverse impact on soil carbon content. Indeed, it directly conflicts with the use of crop residues, cover crops and manure for soil enhancement. The exportation of most of the crop residue along with the high temperature, humidity level and fauna activity (typical of tropical climate) inducing a rapid turnover of organic matter, creates an important depletion of organic content in tropical soils inducing compaction and accelerated erosion, as discussed in chapter 2.2 above leading to unproductive land.

Conventional agriculture techniques are not applicable in the rainforest because they rely on a preparation of the soil to implement the culture. This soil preparation modifies the dynamic of the soil's organic matter eventually leading to a net loss of organic matter. Moreover, it exposes the bare ground making it more susceptible to erosion. The loss of organic material in the soil induces a loss of biological activity increasing the leaching of clay material along with nutritional elements and the decrease of soil structure. This loss of structure leads to a superficial rooting thus a misuse of water and nutritional content. As a consequence, the plants grow weak, more land preparation is required to improve soil structure, and a chemical approach is needed to compensate the decrease of soil fertility.

This method can lead to important yields in temperate climate where the chemicals and agricultural machinery are accessible and reliable, the climate allows a slow mineralization, precipitations are moderate, and soil is originally fertile. However, transferred to tropical climate, this technique leads to intense erosion, massive loss of organic matter, quick degradation of soils and ultimately poor yields. Moreover, chemicals and machinery are usually too expensive and inaccessible for small-scale farmers (Seguy et al., 2009).

3 Biochar: A solution to counter rapid fertility loss

3.1 Biochar: Definition

Biochar (also termed as charcoal, agrichar or black carbon) is a carbon-rich material produced from biomass using high temperature combustion combined with low oxygen input, a phenomenon known as pyrolysis. Pyrolysis is a well-known, simple and inexpensive process. Populations have been using it for centuries for charcoal production. The only difference between charcoal and biochar rely in its use. Indeed the latter is intended to be used as a soil amendment and can exploit dust or small particles where charcoal uses dense pieces for energy production.

The process of pyrolysis induces a series of by-products: biochar, bio-oil, and syngas (synthetic gases consisting of hydrogen, carbon monoxide and methane) the two latter can be captured for further combustion and energy production (see Figure 7) (Lehmann Johannes, 2007a).

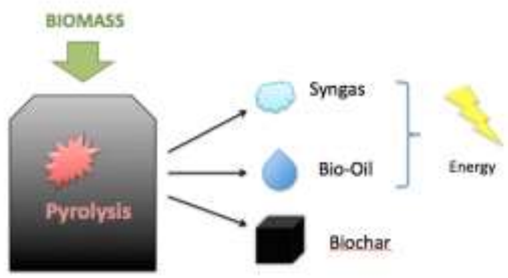


Figure 7: Representation of Pyrolysis (Lefebvre David)

Pyrolysis systems can be classified as slow, fast and flash pyrolysis. The fast pyrolysis producing more oils, the slow one more syngas and the flash pyrolysis yielding more biochar (Scholz et al., 2014).

Only the slow pyrolysis process will be discussed here for it is the most common and affordable system for small-scale farming in developing countries.

The pyrolysis process influences three aspects of the biomass: chemical composition, chemical structure and physical structure.

1. Chemical composition: The loss of water content, carbon dioxide (CO_2), methane (CH_4), and other gases concentrates some elements such as carbon (C), nitrogen (N) and phosphorus (P). However, the N and P found in the biochar are confined in a complex structure and therefore not easily available for plant nutrition
2. Chemical structure: The pyrolysis process induces 2 to 3 evolution phases of the structure due to the increase of the temperature. The first one leads to the creation of aromatic structures resulting of the loss of oxygen and hydrogen compound, the second one is a phase of organization of those aromatic structures in piles or mass and happens between 400°C to 500°C. The last phase is the organization in layers of the mass or piles structures. The third phenomenon occurs at high temperature and, depending on the pyrolysis technique, does not appear in every biochar making process.
3. Physical structure: The high temperature in the pyrolysis process sort of “cleans” the vessels of the wood and results in a spongy like structure, as seen on Figure 8, which has a high specific surface area (SSA) and porosity.

The consequences of theses chemical and physical changes is a structure stable, very difficult for microorganisms to break (Abiven Samuel, 2015).

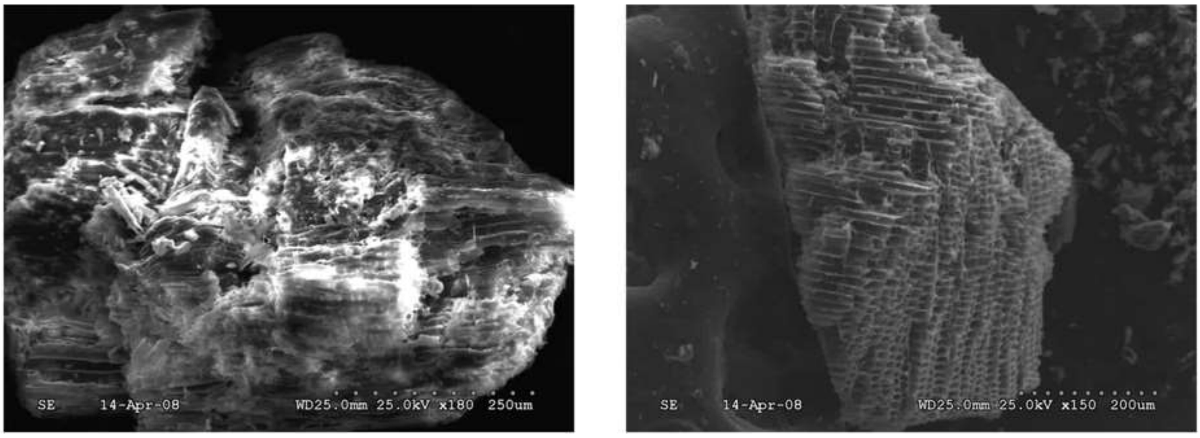


Figure 8: Microscopic view of the same piece of wood before (left) and after (right) pyrolysis process (Abiven Samuel, 2015)

The biochar can be produced using all sources of biomass such as crop residues, manure, wood chops and green waste. Only the water-saturated type of biomass will need pre-treatment to evaporate a maximum of water before being placed in a pyrolyser. The heat produced by the pyrolysis process can be used for the pre-treatment. (Scholz et al., 2014; Abiven Samuel, 2015).

3.2 Origin of biochar

The application of biochar on land is not a new concept. Certain dark earths (“Terra pretas” in Portuguese) are found in the Amazon basin; those patches of land are so fertile that a market of Terra pretas was created, allowing farmers to buy it to increase the fertility of their soil.

Although scientists still do not know how those soils were formed, they agree on an anthropogenic origin, either intentionally or as a result of habitation activities. Carbon dating estimates their age to around 7,000 years old. (Lehmann et al., 2006).

Terra pretas soils typically contain 70% more charcoal on average than surrounding soil. They have remained fertile over thousands of years and present, still today, a high amount of organic matter. Indeed, Terra pretas soils have a carbon content of up to 150g/kg while surrounding soils shows a content of only 20-30g/kg (Ricigliano, 2011).

Although the Terra pretas are the most famous representation of the anthropogenic addition of pyrogenic organic matter, this technique was witnessed in every continent throughout the ages. In every case, leading to exceptionally fertile patches of land compared to the surrounding soils (Abiven Samuel, 2015).

3.3 The properties of biochar

The elemental composition and surface characteristics of biochar are strongly dependent on the pyrolysis conditions and of the types of biomass used (Fuchs et al., 2014).

A study made by Zheng and al. (2010) showed that the yields of bio-products created by corn cob, pine cone or wood chip under same pyrolysis condition vary as presented in the Table 1 below.

Table 1: Influence of biomass type on the yield of bio-products of pyrolysis (Zheng et al., 2010)

Feedstock	Biochar (%)	Bio-oil (%)	Syngas (%)
Corn cob	32.2	45.6	22.2
Pine cone	38.0	44.6	17.6
Wood chip	35.0	42.0	23.0

The same study showed that when increasing pyrolysis temperature from 250°C to 500°C, the yield of biochar decreases from 55% to 24% respectively, while the yields of syngas and bio-oil increase. The decreased yield of biochar is due to a larger amount of volatile released when the biomass is processed at a higher pyrolysis temperature.

More than influencing the yield, the type of biomass and the production conditions have an important effect on biochar composition and its properties as shown in the Table 2.

Table 2: Effect of production condition and biomass type on biochar properties and composition (Zheng et al., 2010)

Feedstock	Pyrolysis Temperature	SSA (m^2/g)	% C	% H	H/C
Corn cob	250°C	1.86	61.16	4.96	0.973
Corn cob	300°C	2.42	70.54	4.19	0.713
Corn cob	350°C	3.36	72.92	3.79	0.624
Corn cob	400°C	4.70	75.23	3.37	0.538
Corn cob	450°C	7.79	77.84	2.95	0.455
Corn cob	500°C	17.08	80.85	2.5	0.371
Corn cob	550°C	30.57	82.62	2.25	0.327
Wood chip	450°C	12.96	70.44	2.67	0.455
Pine cone	400°C	17.92	73.88	3.21	0.521

Indeed, at the same pyrolysis temperature, pine cone and corn cob show different results concerning the specific surface area. It is also acknowledged now that the physical characteristics of the biomass (particle size, shape, and structure) influence the properties and amount of biochar formed (Clay and Malo, 2012; Demirbas, 2004).

Table 2 also shows that, as the pyrolysis temperature increases, the percentage of carbon increases while the one of hydrogen decreases. Hydrogen being usually linked to plant organic matter, the decrease of H/C ratio means an increasing degree of carbonization. Therefore, although the increasing pyrolysis temperature reduces the yield of biochar, it increases the carbonization and with it its specific surface area (Zheng et al., 2010).

The temperature does not only influence SSA of the product but its chemical properties too. While the pH of biochar is usually higher than 8 some biochar can reach a pH of 10. Indeed, according to Abiven Samuel, (2015) and Nguyen et al., (2014) the higher the pyrolysis temperature used, the more alkaline the biochar produced will be. Moreover the temperature also has an effect on the CEC of biochar. One study shows that higher CEC have been obtained by using lower pyrolysis temperature (Gaskin et al., 2008).

In summary, the type of feedstock used and its physical characteristics but also the pyrolysis temperature determine the yield of biochar and its properties (Weisberg et al., 2014; Clay and Malo, 2012; Zheng et al., 2010; Lehmann Johannes, 2007a).

Knowing that the properties of biochar dictate its potential benefits, further research should be conducted to better understand those characteristics' changes (e.g. SSA, pH, CEC) in order to produce biochar that achieves the desired effect.

3.4 The benefits of Biochar

3.4.1 On soil biota

The microorganisms of the soil are known to contribute to numerous types of operations such as breaking down complex organic matter into absorbable material for the plants. Some microorganisms, known as nitrobacteria, change certain nitrogen materials of the soil into forms usable by the plants. Others store up the excessive nitrogen and release it slowly as the plant needs it. Some even attack and eat nematodes harmful to the plant's root (Vickery and Vickery, 1982).

Although investigations on the effects of biochar on soil biota are still at an early stage, researchers agree on an increased abundance of microorganisms after biochar addition (Lehmann et al., 2011). Indeed, its large specific surface area and complex pore structure appears to give an hospitable place for microorganisms to thrive (Zheng et al., 2010).

Moreover, investigating soil biota may serve as an indicator for environmental risk thus, the study of soil fauna could be important to assess the bio-safety risks of certain types of biochar, such examples are listed in chapter 3.5 below (Lehmann et al., 2011).

3.4.2 On fertility

Nutrients available to plants are linked to the mineral and organic matter of soil. While we are often incapable of changing the mineralogy of the soil, we can usually increase the organic matter present in the soil to increase the nutrient availability for the plants. Due to its greater negative surface charge and surface area than any other organic matter, biochar is known to have an important capacity to retain nutrients. Moreover, unlike most other organic materials, biochar has showed the ability to sorb phosphate even though it is an anion (Lehmann Johannes, 2007a; Zheng et al., 2010).

The capacity of biochar to retain nutrients is critical on highly weathered soils like the ones present in the lowland rainforests (see chapter 2.2) as it prevents the leaching of the nutrients and makes them available for plant nutrition. Moreover the affinity of plant nutrients for biochar can result in a slow release mechanism beneficial for the crops nutrition (Clay and Malo, 2012).

Biochar also increases the fertility of the soil by increasing its water holding capacity, making the crops more resistant to drought. Indeed, a study shows that a biochar-amended field increases its water holding capacity by 18% on a highly weathered tropical soil due to its great surface area (Glaser et al., 2002).

When looking at soil fertility, the pH is particularly important for it dictates the availability of nutrients in the soil. As shown in Figure 9 below, the nutrient availability is best in slightly acidic to neutral soil, around pH 6.5-7. As the pH goes too acidic or too alkaline, the availability for the plant of certain nutrient decreases resulting in deficiencies (Vickery and Vickery, 1982).

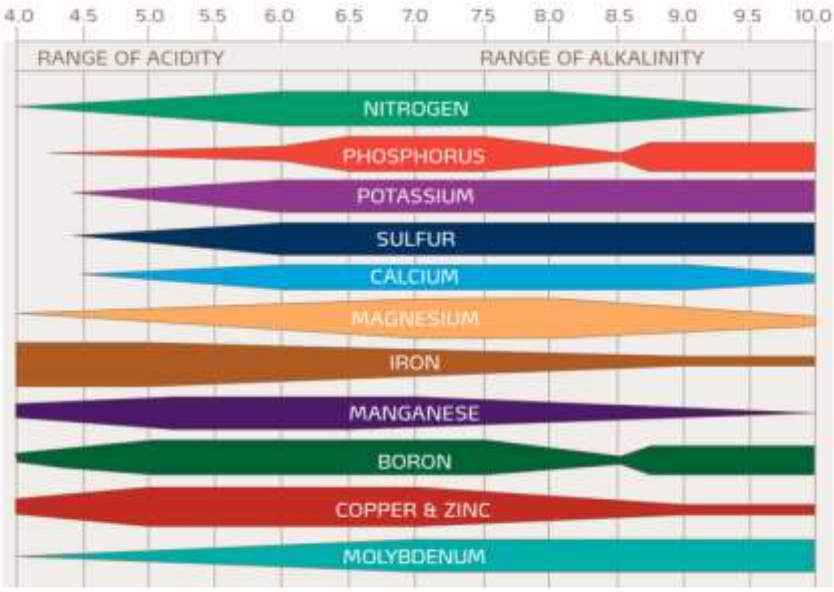


Figure 9: Influence of soil pH on nutrient availability ("Agronomic Principles | Soil & Water Requirements | Orchard Systems | Tree Manipulation | Yara," n.d.)

As discussed in chapter 3.3, biochar shows an alkaline pH and, when applied to highly acidic Amazonian soils (see chapter 2.2), it increases the nutrient availability and reduce the toxic effect of aluminum. Furthermore, biochar-amended soils show a greater CEC than surrounding non-amended soils (Liang et al., 2006; Zheng et al., 2010; Van Zwieten et al., 2010).

3.4.3 On yields

Biochar is a natural host for soil material such as fertilizers, nutrients and microorganisms. It is not consumed directly by the plant but enhance beneficial soils reactions (Herbert et al., 2012).

Some Terra pretas show a yield increase of 400% compared to surrounding land while some studies show a decrease up to 30% in yield (Abiven Samuel, 2015).

This wide dispersion between yields responses to biochar use is still under research. So far, it is explained by various factors such as:

- Quantity of biochar applied: research by Lehmann et al. (2006) shows the existence of a maximum quantity of biochar for different crops, leading to decreases in yield if this amount is exceeded.
- Properties of the biochar: the properties of biochar are dictated by the type of biomass and the pyrolysis temperature used (see chapter 3.3 above). A study by Zheng et al. (2010) showed an increase yield of corn ranging from 18 to 23% depending on the type of biochar used.
- Type of soil: the poorer the soil quality (low organic matter content, pH, and nutrient availability) the greater the positive yield response (Van Zwieten et al., 2010; Crane-Droesch et al., 2013).
- The number of successive years of culture: the beneficial effect of biochar increases as the years pass (Abiven Samuel, 2015). A study by Crane-Droesch et al. (2013) shows an increase

of 7% and 12.3% compared to the first yield response on the second and seventh cultural season respectively.

- Type of culture: the type of crops tested influences the yield response (Abiven Samuel, 2015)

A review of 781 papers on yield effect of biochar shows an average increase of 10% in crop yield against zero biochar control for a 3 Mg/ha application during the first cropping season (Crane-Droesch et al., 2013), confirming the overall yield benefit associated with biochar amendment.

Besides the effect on yield, biochar shows a better predictability in yields, a shorter germination time, allows a longer cropping season and an increased resilience to drought (Scholz et al., 2014).

3.4.4 On chemicals application

Biochar is said to be a good sorbent of organic compounds because of its great surface area. Therefore, it can reduce the mobility of chemicals in soil and consequently avoid pollution to ground water and lower the amount of chemical needed to grow a crop (Zheng et al., 2010; Lehmann Johannes, 2007a; Lehmann et al., 2006; Lehmann et al., 2003).

Organic molecules are sorbed by biochar through two mechanisms: surface adsorption on the carbonized surface and via electro-statically bounds to the non-carbonized remaining organic matter (Verheijen et al., 2010).

A study from Li et al. (2013) shows that the sorbed organic molecules of low temperature biochar (200°C – 500°C) may be released with a concentration difference force due to the remaining presence of organic compound on the surface, while the high temperature biochar (>500°C) blocks the organic molecule in a surface adsorption mechanism. Biochar obtained at a temperature below 200°C cannot retain much organic compound; indeed it does not show the typical porous spongy-like structure because most the woody component only decomposes at more than 200°C.

The biochar obtained at low temperature (between 200°C and 500°C) has the potential to control the release of soil-applied chemical compound. And if the rate of liberation suits the efficacy of the product, biochar can extend its availability preventing leaching, hence reducing the cost of application and protecting areas surrounding the zone of application from chemical exposition.

The release rate of an organic compound linked to biochar depends on many factors such as:

- Properties of the biochar: the sorption ability of a biochar depends on its organic content and surface area, which are dictated from the pyrolysis temperature and type of biomass used in the process (Lehmann Johannes, 2007a; Clay and Malo, 2012)
- The wetting and drying cycle of the soil (Li et al., 2013)
- The composition of the soil (Li et al., 2013)
- The soil pH: the pollutant retention effect of biochar seems to be stronger on slightly acid soil (Abiven Samuel, 2015).
- The temperature of the soil (Clay and Malo, 2012)
- The age of the biochar: although the mechanisms are still unclear, it is accepted that the CEC is higher in aged biochar than in freshly produced ones (Lehmann Johannes, 2007a).

In-depth field research is still required to determine the ideal dosage of biochar and chemicals for a specific type of soil under a specific climate if the usefulness of both biochar and chemicals is to be ensured.

3.5 The negative effects of biochar

3.5.1 Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAH) are carcinogenic and persistent pollutants present in the environment, and are likely to be formed during biochar production (Weisberg et al., 2014; Fabbri et al., 2013).

During the pyrolysis process, organic compound contained in the biomass are broken into smaller pieces containing highly reactive free radicals that associate to form stable PAHs.

When measuring the amount of PAH in biochar, a distinction must be made between the total amount and the bioavailable amount. Bioavailability is defined as *"the degree to which a contaminant in a potential source is free for uptake (movement into or onto an organism)"* (Kenneth L. Dickson et al., 1994). Put simply, a bioavailable compound is free to pass cellular membrane at any given time. More than being able to pass cell membrane to contaminate organisms, these bioavailable compounds are more unstable and able to leak to the surrounding environment (Hale et al., 2012), making biochar a source of contamination for its environment.

Although the production of contaminants and their deliberate application in soil is a source of concern, Hale et al. (2012) studied 59 types of biochar from various biomass, at different pyrolysis temperature, in industrial and traditional kiln and showed that neither total nor bioavailable PAH amount in the biochar tested poses concern, even at a dose equaling the amount of soil, according to existing environmental quality standard.

Still, attention should be paid and tests made before any amendment to ensure the safety of the technique.

3.5.2 Drawbacks of the sorption ability

In chapter 3.4.4, we discussed the ability of biochar to sorbs chemicals. However, if the sorption is too important, it could also impair the efficacy of a soil-applied chemical, and create competition between the biochar and the plant nutrition. (Clay and Malo, 2012)

Indeed, the adsorption of nitrogen (N) by biochar may lead to a low N availability for crops (Lehmann et al., 2003). A way to cope with nitrogen scarcity after biochar amendment is to use leguminous plants. These plants biologically fix atmospheric nitrogen with the help of certain bacteria and this nitrogen fixation process is improved on biochar-amended soils, due to its effect on soil biota (see chapter 3.4.1) (Lehmann et al., 2006).

To overcome this issue for non-leguminous plant, three solution are proposed by Lehmann et al., 2006:

- Apply biochar only to leguminous plants until a sufficient amount of N is built up in the soil
- Fortify the biochar with N using compost or during the char production using an energy demanding process
- Adjust the amount of biochar applied to ensure a sufficient amount N available while still increasing productivity

3.5.3 Uncertainties

In chapter 3.4.2 we described the importance of the liming effect of biochar on soil and its positive consequence on soil fertility when amended on acidic soil. Yet, according to Nguyen and Lehmann (2009), the pH of biochar itself will change over time. The magnitude of this change will depend on the biomass used and the production conditions. Moreover, with time, some biochar will show an increase of pH while others will show a decrease. Additional research should be conducted to confirm this assessment and find long-term potential changes on pH depending on specific biochar.

Another source of concern regards the sorption of heavy metal or toxic substances by biochar. While its sorption capacity is proved, scientists are still uncertain about the consequences of such an immobilization; some fear a time bomb effect. Moreover, if the biomass used contains heavy metals, the biochar process could concentrate theses heavy metals and afterward contaminate food and habitat (Weisberg et al., 2014).

3.6 Biochar as a solution to alleviate climate change

3.6.1 Biochar effects on greenhouse gases flux in the soil

Although it has been shown that all organic soils amendments promote higher CO_2 emissions compared to un-amended soils, these emissions are directly related to the proportion of decomposable organic carbon specific to each organic amendment. The stable carbon content of biochar and the decreased bioavailability of soluble organic substrate due to sorption on its surface leads to significant reduction of CO_2 emission compared to other organic amendments (Woolf et al., 2010).

Studies indicate that the addition of biochar increases soil respiration thus CO_2 emission, which offsets the carbon credit associated to C sequestration (discussed in chapter 3.6.2 below). The increase of CO_2 emission can be explained by the decrease in bulk density following the application of biochar. Increased porosity would enhance the amount of oxygen available to aerobic microorganism. Moreover, the internal porosity of biochar increases the habitat for such organisms, increasing their number hence the respiration process and along with it, the decomposition and mineralization rate (Rogovska et al., 2011; Scholz et al., 2014).

Meanwhile, this increasing rate of respiration also increases the global microbial activity, which enhances the nutrient cycling therefore decreasing nutrient leaching. As a consequence, crop production increase and carbon fixation (through photosynthesis) is improved (Rogovska et al., 2011). The carbon fixation reduction due to enhance respiration is somehow balanced by an increased production.

The nitrous oxide (N_2O) is a greenhouse gas with an estimated effect of 298 times that of CO_2. Nitrous oxide is emitted from the soil during the nitrification and denitrification process driven by microorganisms. These processes are governed by oxygen supply. Any treatment affecting the oxygen activity has a direct impact on the nitrification/denitrification process, thus influencing the N_2O fluxes.

Soils amended by biochar have shown a reduction of N_2O emissions. A study by Lehmann et al. (2006) shows that the addition of 20g of biochar by Kg of soil completely suppresses the emission of methane and reduces the emission of nitrous oxide by 50%. This could be explained by the enhanced soil aeration leading to fewer anaerobic sites which reduces the denitrification rate (Prommer et al., 2014; Lehmann et al., 2006). Moreover, the increased C/N ratio created by the biochar amendment reduces the mineralization and nitrification process (Lehmann Johannes, 2007a; Rogovska et al., 2011). Nevertheless, the addition of biochar in forest soil appears to increase nitrogen mineralization due to the inactivation of secondary plant compound normally decreasing microbial activity (Lehmann Johannes, 2007a).

3.6.2 Carbon sequestration via biochar amendment

Due to its stable conformation and its resilient nature, the production of biochar in combination with its storage in soil has been proposed has a potential method to reduce the atmospheric CO_2 concentration (Beverly D. McIntyre et al., 2009; Zheng et al., 2010; Weisberg et al., 2014; "Biochar: a new weapon in the war against greenhouse gases | Climate Solutions," 2013).

Other already existing carbon sequestration techniques such as no-tillage or afforestation will stop to capture carbon at some point. For instance, as the forest grows mature, it starts releasing as much carbon dioxide as it takes up and the carbon stored during no-tillage techniques is released when the land goes back to conventional tillage (Mekuria and Noble, 2013). Whereas when biochar is incorporated to soil, no incident or change in practice would cause the release of the stored carbon, indicating that biochar is a lower risk technique than other sequestering options (Lehmann Johannes, 2007b).

According to a study from Woolf et al. (2010), the global production of biochar from sustainably produced feedstock and its incorporation into soil for increased crops production could reduce the annual net emission of carbon dioxide, methane and nitrous oxide by a maximum of 1.8 Pg[2] of CO_2-C equivalent (CO_2-C_e) per year. This corresponds to 12% of the 15.4 Pg CO_2-C_e total anthropogenic emissions in 2010.

The study further shows that the mitigation impact of biochar is around one-fourth larger than the mitigation if the same biomass were combusted for energy. While the principal contribution of biomass combustion to avoid greenhouse gases emission is to substitute fossil fuel, the advantage of the use of charcoal as biochar over its use as bioenergy is the positive contribution to soil greenhouse gases fluxes and to raise crop yields, which in turn increases the CO_2 trapped by the plants.

However, if Woolf et al. (2010) take into account the biomass resource that is created without endangering food security, habitat or soil conservation, it does not consider the part of crop residue used for livestock consumption (chapter 2.3). The study also uses the yield of modern, low-emission pyrolysis method that most peasants in developing countries cannot afford. Indeed, biochar production systems such as traditional charcoal kiln may emit methane, nitrous oxide or volatile compound as a result of uncompleted combustion and mismanagement of pyrolysis parameter. Moreover, the traditional production systems result in lower biochar yield.

Furthermore, it does not take into account any economic, cultural or social difficulties that might limit the adoption of biochar technology. It also bases the available sustainably produced biomass on current data to predict the benefice of biochar sequestration for the future although the resource base will change depending on various factors including the potential effect of climate change, sea level, land use, technology, population, diet, agricultural practices and economic development. Certain factors might increase the biomass availability while others might decrease it.

Moreover, this study only considers the amount of sustainably produced biomass; it does not take into account the maximum amount of biochar that can be applied on a soil before seeing a reduction on the yield. Although most of the researched crop did not show any negative response at 140 Mg C ha-1, the beans (*Phaseolus vulgaris* .L) showed a reduction of yield when 60 Mg C/ha was applied (Lehmann et al., 2006) showing that one average could not be used and that further studies should be conducted to determine maximum quantities for different crops.

Although biochar has a great potential to mitigate climate change, determining its actual benefits requires much more research and different scenarios must be taken into account considering the advance in pyrolysis technology, the long-term effect of biochar on crop production, amount of sustainable biomass available and various consequences of climate change. Besides, considering the highly stable nature of biochar, the existence of a maximum amount might put a hold to the longevity of biochar sequestration if the beneficial effect on production is to be kept.

[2] 1 Pg (petagram) = 10^{15}g

3.6.3 Residence time of biochar in soil

The residence time of pyrogenic organic matter in the soil is difficult to determine. Some carbon-14 dating of charcoal from Terra pretas aged them around 7,000 years but this technique is not reliable since it only takes into account the remaining fraction thus does not give any degradation rate (Abiven Samuel, 2015).

A three-year incubation study suggests that the half-life of biochar under natural soil condition is about 1,400 years (Rogovska et al., 2011). The oldest (9 year old) laboratory incubation experiment estimates the residence time of pyrogenic organic matter to around 300 to 700 years depending on the biomass, pyrolysis temperature and incubation conditions. However, a field-test incubation shows a residence time of only 200 years (Abiven Samuel, 2015).

Moreover, according to different studies the residence time of biochar in soil is affected by:

- The production process or biochar's properties (chapter 3.3) (Lehmann et al., 2006).
- The soil components: Ions, organic matter and clays usually increase the residence time of biochar in the soil (Clay and Malo, 2012).
- The water regime: a biochar-amended soil alternating saturation and unsaturation condition shows higher C loss (Rogovska et al., 2011).
- The climate: a hot and humid climate increase the degradation rate of biochar (Abiven et al., 2014).

The estimate mean residence time of biochar in soil vary from centuries to millennia but, in general, scientists agree on a residence time of pyrogenic organic matter of around 2 to 20 times greater than soil organic matter (Abiven Samuel, 2015).

One source of such differences can be found in the methods used to quantify the amount of pyrogenic organic matter in soils. Each method reveals different results as shown in Figure 10 (Abiven Samuel, 2015). Research must be conducted to harmonize the techniques in order to have precise data on the actual amount of pyrogenic material in soils.

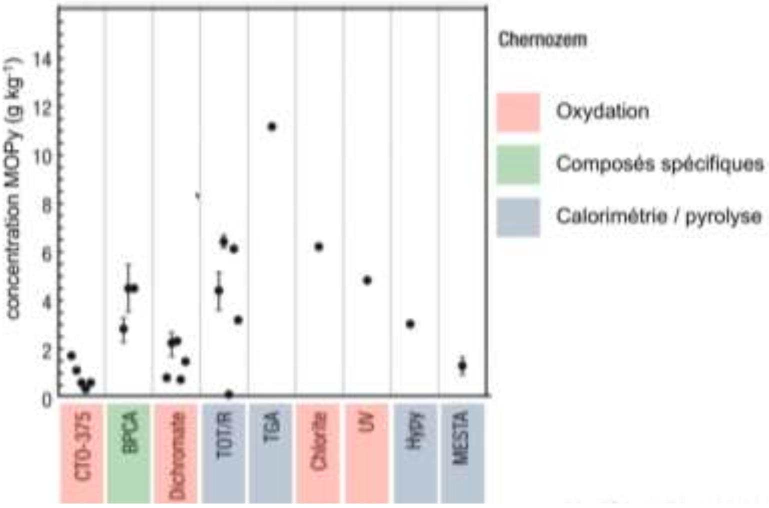


Figure 10: Different results of pyrogenic organic matter content (x-axis) from the same soil (chernozem) by different techniques (y-axis) (Abiven Samuel, 2015). The different color labels indicate the type of process used for the technique.

Another error factor is the unnatural conditions created in laboratories. Indeed, environmental conditions are kept constant and optimal for degradation while other factors, like the effect of local plant, may contribute to the degradation rate in field trials (Abiven et al., 2014).

3.6.4 Slash-and-Char compared to slash-and-burn

As presented in chapter 2.3, most small-scale farmer in tropical lowland rainforest relies on slash-and-burn techniques.

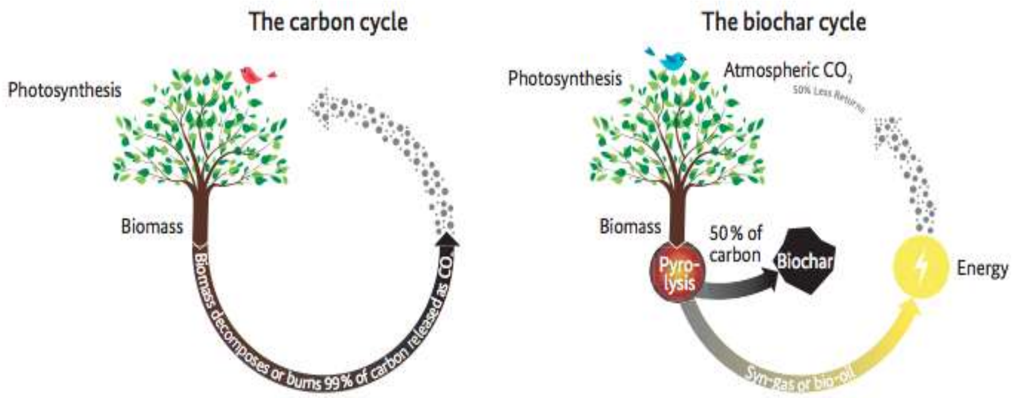


Figure 11: The carbon cycle versus the biochar cycle (Roth, 2014)

The main difference between slash-and-burn and slash-and-char relies on duration of the benefits of the application of carbon rich material. During the slash-and-burn process, the ashes produced increase the pH of the soil and supplies valuable nutrients to the crops. But those benefits do not last long and after a few cropping seasons the use of fertilizer is needed to maintain crop yields (Lehmann et al., 2002). Biochar, on the other hand, not only produces lasting benefits but it can also be easily produced locally, which can reduce transport costs (and environmental print) of intensive agriculture chemicals (“Biochar: a new weapon in the war against greenhouse gases | Climate Solutions,” 2013)

When the aboveground vegetation is burned during the slash-and-burn process, the amount of char created is less than 3% (Lehmann et al., 2006). The amount of biochar produced in simple kiln techniques is usually around 50% (Roth, 2014).

Moreover, during the slash-and-burn process, around 50% of the carbon present in the biomass is lost and released as CO_2 (Lehmann et al., 2002). Furthermore, the remaining fresh biomass that did not burn will also totally disappear within a few cropping seasons and release CO_2, especially in the tropics, where climatic conditions creates a fast turnover of organic matter (Mekuria and Noble, 2013).

More than sequestering carbon in the soil, biochar application can improve the soil properties (chapter 3.4.2) allowing a longer cultural time on each parcel and increase yield (chapter 3.4.3) thus income and food safety for small-scale farmers. Furthermore, the char produce can also be sold, generating a secondary source of income for the farmers.

Although the charring technique is affordable and accessible for rural areas the slash-and-char process will require more labor than slash-and-burn, with an estimate of 10.5 person-days to collect the woody material, 6.8 person-days to build the kiln and 2.8 person-days to integrate the pyrolytic material into the field. Unless the payback is sufficient, farmers, who already work hard, may not admit this increased labor (Scholz et al., 2014).

Moreover, to avoid any greenhouse gases emission during the pyrolysis process that could offset the carbon sequestration benefit, the kiln must be built according to a scheme that allows perfect combustion, requiring knowledge and formation.

3.6.5 Possible monetization of biochar

We have shown the agricultural and environmental benefits of biochar use. For tropical small-scale farming system relying on swidden agriculture, the switch to slash-and-char systems does not require important changes or adaptation in the farming practices, leading to easy adoption by farmers. Though, adding some financial benefits to biochar could facilitate the changes and speed up the adoption process.

For instance, the 1997 Kyoto protocol created a commitment for 38 industrialized countries to reduce their greenhouse gas emissions. This could be done either by reducing the emission or by sequestering carbon as a way to offset the emission. Purchasing "carbon credit" from countries not included in the Kyoto protocol could serve as carbon sequestration and is called the "Clean Development Mechanisms" (CDM) (Article 12 of the Kyoto protocol). CDM has as a purpose to assist non-included countries in achieving sustainable development, and contributing to the ultimate goal of the Convention while assisting Kyoto-included parties to achieve their emission limitation ("Kyoto Protocol to the United Nations Framework Convention on Climate Change," 1998).

To be considered as a CDM, a project must achieve, among other things, a *"real, measurable, and long-term benefits related to the mitigation of climate change"* ("Kyoto Protocol to the United Nations Framework Convention on Climate Change," 1998). So far, the only legal way to sequester carbon according to the CDM was to afforest land. The CDM did not take into account any agricultural practice that may sequester carbon.

As discussed above, the complete combustion of biomass lead to the release of CO2 through oxidation of more than 90% of the carbon present in an organic material, whereas biochar production under specific conditions lead to a conservation of approximately 50% of the carbon. The biochar, when amended in soil, has a proven long-term resilience and is distinguishable from other soil components; hence it allows verification of the sequestration if needed. Moreover, if the energy produced during the pyrolysis process is used to reduce fossil fuel consumption, this leads to a further reduction in greenhouse gas emissions. Theses avoided emissions are tradable entities under current CDM rules. Therefore, they could be monetized.

However, the pyrolytic organic matter appears to move much with time. According to Abiven Samuel (2015), particles are able to move up to kilometers horizontally due to water or wind displacement made easier by the change in particles size, result of degradation. This finding might create an issue for the verification entity in case of carbon sequestration monetization. Moreover, if the biochar is not integrated in the soil properly, the wind displacement of biochar grinded too finely can create air pollution and fire hazard (Weisberg et al., 2014) doing more harm than good concerning carbon sequestration.

In-depth research needs to be conducted concerning the soil injection's technology of biochar to avoid any non-desired effects. If too shallow, the biochar may be too exposed to erosion and wind displacement and if too deep, the expected effect of biochar might not be achieved (Lehmann Johannes, 2007a).

4 Problem statement

In the literature review above, we discussed the precarious situation of agriculture in the Amazon basin due to the lack of fertility of Amazonian soil and presented biochar as a technique to mitigate this poor fertility.

We mentioned that there is no such thing as one kind of biochar but that every biomass and pyrolysis temperature leads to biochars with different physical and chemical properties and emphasized the need for further research to understand these changes and their effect on soil properties.

We reported that most studies already available show beneficial effects of biochar amendment on soils' nutrient availability, water retention, CEC, and biota as well as an increase of crop yield. But we also stated that those effects vary significantly according to the type of soil, climate, and crop but also number of years of culture, type and quantity of biochar applied.

Finally, we discussed the capacity of biochar to contribute to climate change mitigation by sequestering carbon into the soil and the potential monetization of such technique.

These observations leave room for further in-depth study confirming or invalidating the current findings about the effects of biochar on soil fertility and crop yield.

However, the biochar response is depending on so many factors (e.g. soil, crops, and climate) that waiting for scientific reviews for each and every combination would postpone its adoption. The aim we pursue is to make this technology available for small-scale farms, even in the most remote location. Then, only after evaluating the biosafety of the biochar made from the specific biomass, populations could experiment its effects on their field, make their own experiments and assess its efficacy. To do so, we need to propose an affordable oven relying on local techniques and material.

In the following chapters, we firstly present the design of a small-scale biochar-making oven, affordable for rural population using locally produced material, aimed at family farms in the village of Pilcopata- Peru.

Secondly, we present the preliminary results of an experimental program aimed at measuring the effects of Paca-bamboo biochar on plantain and pineapple growth when mixed with lombricompost on a soil of Pilcopata-Peru to measure its potential benefit.

Experience and preliminary results

"Of the 200 light bulbs that didn't work, every failure told me something that I was able to incorporate into the next attempt"

Thomas Edison

5 Design and trial of an experimental biochar oven

As discussed in chapter 3.6.4 above, for the successful application of biochar in rural areas, the technology must be affordable and easy to build and use even in the most remote places.

In this chapter, we describe the design of an experimental biochar oven in Pilcopata, aimed at small-scale family farms, using locally available materials and tools.

5.1 Location

Pilcopata is a village situated in southeast part of Peru, in the Cusco region of Peru, at 500m above sea level. It is located where the Andes meets the Amazon rainforest.

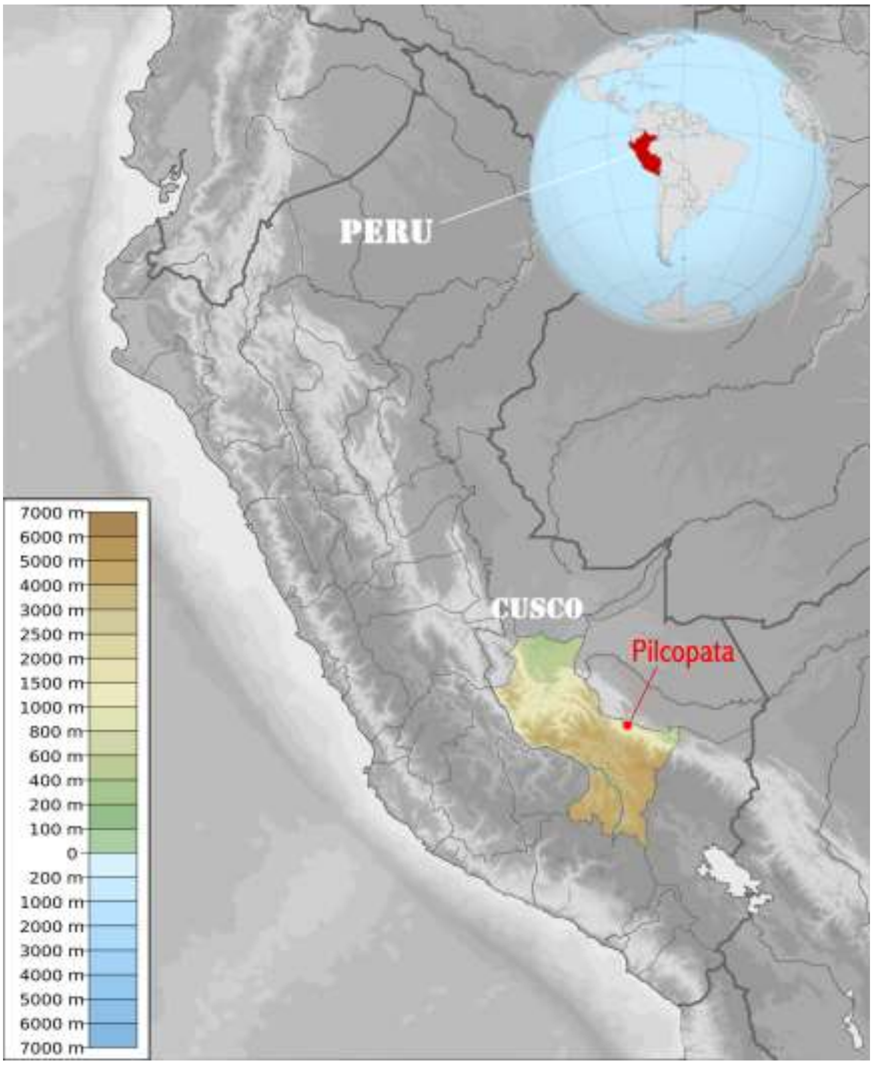


Figure 12: Map of Peru, the location of the Cusco region and the approximate place of Pilcopata (David Lefebvre; adapted from ("Peru physical map," n.d.) and ("Peru_Cuzco_Department," n.d.)).

5.2 Biomass used

The first step when trying to implement the biochar technique is to find a biomass available in sufficient quantity without creating any competition with other uses such as fodder or litter for livestock.

In our case, we used the Paca bamboo *(Guadua spp.)* see Figure 13. The Paca bamboo is a pioneer, fast growing plant of the Southwest Amazon (Carvalho et al., 2013). In Pilcopata, it grows rapidly in immense patches in recently cleared areas (e.g. roadsides or field edges); it prevents the growth of secondary forest and is considered a source of nuisance by the local population. Unlike other bamboo species, the one present in Pilcopata cannot be used for construction for it does not grow straight. Its value is therefore restrained to small furniture construction and cooking wood while the unused stock is piled or burned in the field.

Figure 13: (Left) Patch of Paca on the edge of a forest (Carvalho et al., 2013); (Right) Paca collected from surrounding population for biochar making process (David Lefebvre)

5.3 Material and tools

As said above, we only used locally available material.

- Two 208L (55 gallon) typical drums used to transport oil or gasoline: used as the main structure of the oven
- One electrical circular saw and its discs: to cut the drums
- One 1.5 cm diameter nail
- One metallic hammer: to use with the nail to punch holes in the drums
- One plier: used to cut the grid
- 1m^2 grid: to make the cooking grid and support the biomass inside the drum
- 2m^2 metallic plate: for the riser and the doors of the bottom part of the oven
- Chalk and ruler: to make marks on the drums
- Gloves and goggles: for protection when cutting metal

For increased accessibility, we did not use any soldering iron; all parts are cut and bended to fit in each other.

Figure 14: Material needed to build the oven (David Lefebvre)

**The surface of the grid and metallic plate in this picture are not sufficient, they are included for illustrative purposes.*

5.4 Principle and design

The goal behind the design is to be able to use the pyrolysis heat produced during the process to cook or boil water for everyday household use. The design is based on existing ovens reviewed in Roth (2014) but using local resources and tools.

It uses the “Top-Lit Up-Draft” (TLUD) principle as shown in Figure 15 below.

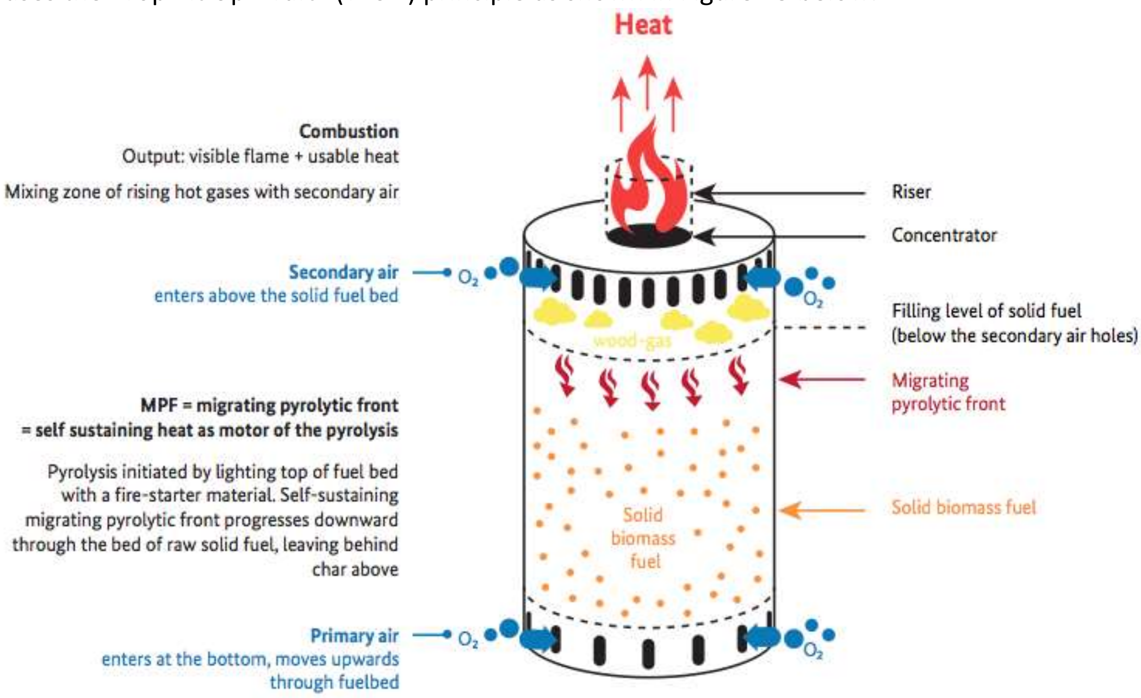


Figure 15: Scheme of a TLUD char-making device (Roth, 2014)

The TLUD principle relies on a cylinder filled with biomass, lit at the top with a small fire ("Top-Lit") then covered by a concentrator ring and riser (see Figure 15). The primary air entrance at the bottom of the cylinder serves to "attract" the pyrolytic front but should be restricted as much as possible to increase pyrolysis instead of combustion (see Chapter 3.1). The pyrolytic front moves downward, while the primary air and wood gases move upward ("Up-Draft"). Wood gases (or syngas) are by-products of the pyrolysis process discussed in Chapter 3.1 above. As the pyrolytic front goes down, it leaves the pyrolysed material behind. The secondary air holes at the top of the cylinder increase the amount of oxygen in the wood gases. The riser and concentrator ring create turbulences that help mixing air and syngas together. If the amount of secondary air, the turbulences and the temperature inside the cylinder are optimal, this mix of air and syngas will burn completely, leaving nothing but the flame that can be used for cooking. If total combustion is achieved, this method is therefore safer to use inside households than traditional fire for it does not produce any smoke harmful for the health of nearby individuals.

The extinction of the flame above the riser announces the end of the batch. Indeed, since no more syngas is produced, the flame disappears and the pyrolysis process stops. To ensure the best yield of biochar, the oven should be cooled down with water to stop any combustion process that could take place due to the primary air entrance.

However, this basic design raises an issue regarding the time of cooking allowed. Indeed, the cooking time permitted is dictated by the quantity of biomass introduced in the cylinder. When the process starts it is impossible to refill the cylinder. The user needs to wait until the end of the batch and only then, start another one. This drawback could discourage the adoption of the technique by the population.

To address this problem, our design integrates two segments (C1 and C2, see Figure 16 and Figure 18 below) placed under the biomass reactor (B, see Figure 16 and Figure 17 below) allowing a further use of the oven if needed. When the batch ends, if more cooking time is needed, the user, using gloves, can lift the A part (see Figure 16 below), then lift the container situated in the B part of the oven (see Figure 17 below).

By doing so, the hot pyrolytic material will fall, break into small pieces, pass the metallic mesh and drop in the lower segment C1. Afterward, after lifting the B part, by opening the tertiary air entrances situated in the lower segment C2, the char will start to burn normally and can be refill for as long as the user needs. This process should be used as rarely as possible for it turns the whole pyrolysis process to simple combustion, burning the biochar produced and the biomass added to ashes and releasing smoke as harmful as any other traditional fire-pit. Nonetheless, the utilization plasticity achieved with this design may facilitate the adoption by the targeted population.

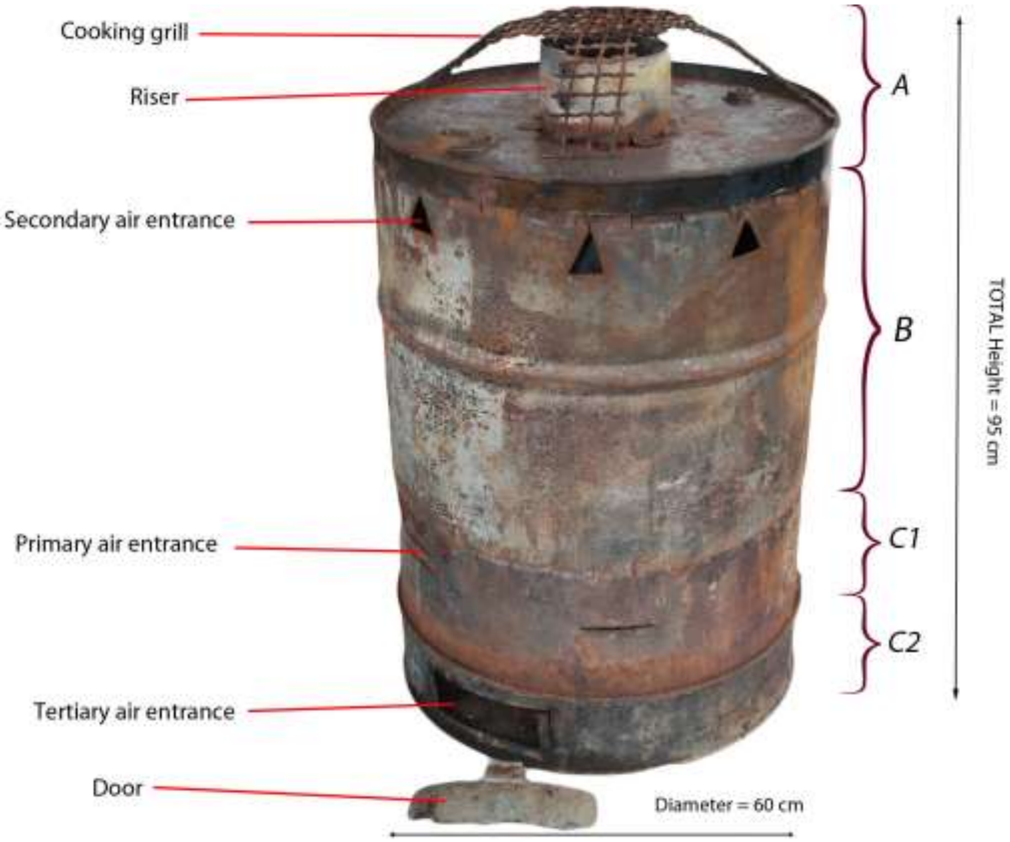


Figure 16: Complete view of our proposed design (David Lefebvre)

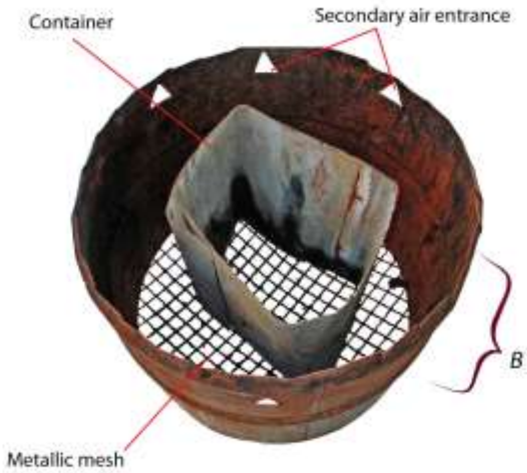


Figure 17: Inside view of the B segment of our design (David Lefebvre)

The B segment includes the secondary air entrance, a metallic mesh and a container. The metallic mesh permits the flow of primary air from segment C1 through the biomass and allows the hot char pieces to fall down into C1 when the container in the B segment is lift, in case of more cooking time needed.

The container was a final addition to the trial. Indeed, during our first tests, we filled the cylinder entirely with biomass but the heat created did not allow us to stay close enough to the oven to cook. Moreover, the amount of biomass burning was excessive and the air entrances and riser could not cope with it, resulting in a partial combustion of the syngas and thus smoke production.

The container allowed us to stand next to the cylinder during the entire process and the enhanced airflow inside the cylinder improved the combustion of the gases and no more smoke was produced.

Figure 18: Inside view of the "C1" segment over "C2" segment of our design (David Lefebvre)

The segments C1 and C2 were both produced using the bottom of the two drums. Segment C1 contains the primary air entrance holes and punched holes at the bottom to allow the air from the tertiary air entrance in C2 to create combustion of the char if needed. The doors (only one visible) are used to close the tertiary air entrance for the pyrolysis process to take place.

5.5 Results

Five batches were made. In each batch, we obtained a cooking time ranging from 75 to 90 minutes and a biochar yield of approximately 30% of the volume placed in the oven. Although we did not have any tools that allowed precise measurement of the temperature inside the oven, we succeeded to boil 15 liters of water in a closed cooking pot for 45 minutes, confirming its ability to cook.

Figure 19: Biochar making process using the created design (David Lefebvre)

5.6 Discussion

Considering an approximate plausible 3kg of biochar production per batch and one cook-use of the oven a day, by the end of the year, a household would produce about 1.000kg of biochar.

After a year, the farmer possessing a 1ha field could amend it with biochar at a rate of 1T/ha. According to Lehmann and Joseph, (2015) positive yield responses were measured after application of biochar at this rate. Meaning that after only one year, the farmer could witness an increase yield on its 1ha parcel. The successive years of biochar production can be used to increase the amount of biochar on its field or to sell the charcoal produced in the local market, ensuring a second source of revenue.

However, if we consider a 20% yield in mass with this biochar oven, the household would need roughly 5.400kg of paca bamboo per year. Although we do not possess data concerning the growing rate of paca bamboo in Pilcopata, we can assume that roadsides and fields edges production will not be sufficient to cope with a growing demand if the biochar proves itself useful.

Nevertheless, we need to bear in mind that this design is a prototype. More trials with precise biochar yield data should be made to improve the system and reach the average reported small-scale kiln yield of 50% in mass (Roth, 2014).

Moreover, the Paca bamboo is not the only biomass available. The cassava (*Manihot esculenta*) is a woody shrub commonly cultivated for its roots in Pilcopata, its residues could be used for biochar production after each harvest. Moreover, other biomass sources such as fallen trees or pruning could be pyrolysed as well.

Overall, this design is an affordable method to turn the biomass normally consumed for cooking into biochar while avoiding the release of toxic smokes. And even though it takes time to create the needed amount to amend the field, the stable nature of biochar allows slow soil integration without impairing its efficacy.

6 Biochar performance as an amendment: experimental design

As discussed in chapter 3.4.3, the use of biochar as an amendment usually leads to increased yields depending on various factors including the type of biomass used. The project was to test the effect of biochar made from Paca bamboo, a locally available biomass (see chapter 5.2) on pineapple and plantain fields.

Since biochar is not a fertilizer in itself (chapter 3.4.3 above) several treatments tested so far (Table 3 and Table 5) use a mix of biochar with lombricompost to sort of "fill" the biochar with nutrients before its application on the field.

Lombricompost (or vermicompost) is essentially the same product of normal compost: a nutrient-rich soil amendment created from solid organic waste through decomposition by microorganisms to which earthworms are added. Compared with regular composting, the vermicomposting process is a bit faster and require less work for the earthworms increase the aeration and help breaking down particles making the fresh organic matter more available to microorganisms for decomposition (Lazcano et al., 2008). Moreover, due to the transit of the organic matter by the digestive track of the earthworm, the lombricompost is said to contain more nutrients directly available to plants than regular compost (Punde and Ganorkar, 2012).

6.1 Soil, materials and method

6.1.1 Site and soil

The study was conducted at the biological research station Villa Carmen run by ACCA (Asociación para la Conservación de la Cuenca Amazónica) situated near the town of Pilcopata, Peru.

This experiment started almost one year ago and is run by the Wake Forest University of North Carolina (USA) and led by Dr. Silman. Upon our arrival in May 2015, the treatments were decided, the amendment done, the fields planted and some measures were already taken. We took on an ongoing research project and thus had no influence on the experiment design. The data before May 2015 were available in paper format on site and were used to complete the measures taken afterward. The research is still in progress and data are sent to us for further analysis by trained volunteers on site.

The soil of the experimental site is gray loamy sand with a pH between 6.0 and 6.5. This soil is considered to have a relatively high overall fertility (Trejedor, 2012) probably due to its location (i.e. at the foot of the Andes) allowing sedimentation of all the alluvium coming from higher up in the mountains. The site was previously used as pasture land.

The biochar used was made from Paca bamboo at a pyrolysis temperature of about 800°C in an industrial oven available on site.

The data presented were collected between February and July 2015.

6.1.2 Experimental design

We planted parcels of 3,000m^2 of plantain (*Musa ssp*) and 4,000m^2 of pineapple (*Ananas comosus*). The parcels were planted at a density of 1,200 plantain/ha and 24,000 pineapple/ha.

The pineapples and plantains were implanted on September 29th 2014 and October 11th 2014 respectively.

Each parcel was divided in sub-plots of 10x10m. Each sub-plot contains a different quantity of biochar and lombricompost, referred to as treatment Tx in Table 3 for pineapple and Table 5 for plantain below.

All the different treatments where incorporated before transplanting in the topsoil for the pineapple and inside the planting hole for the plantain.

Table 3: Amount of biochar (BC) and lombricompost (LC) applied in the different treatments of the pineapple

Pineapple				
Treatment	BC (kg)	LC (kg)	BC (t/ha)	LC (t/ha)
T1	150	150	15	15
T2	150	100	15	10
T3	150	50	15	5
T4	150	25	15	2,25
T5	150	0	15	0
T6	0	0	0	0
T7	100	0	10	0
T8	0	100	0	10
T9	50	0	5	0
T10	0	50	0	5

The pineapple parcel has four repetitions of the ten treatments, randomly placed. In every sub-plot, 15 plants randomly chosen were measured. The measures taken were: height, number of leaves (referred to in graphs and tables below as # Leaves) and the length of the longest leaf (referred to in graphs and table below as D-Leaf).

Table 4: Disposition of the different pineapple sub-plots on the parcel. Each sub-plot is 10x10m.

	1	2	3	6	5	7	10	8	9
	4	1	3	5	4	8	9	7	
ROAD	2	6	4	2	6	10	8	9	
	3	5	1	3	2	9	7	10	
	4	6	5	1	6	7	10	8	

Table 5: Amount of biochar (BC) and lombricompost (LC) applied in the different sub-plots of the plantain parcel

Plantain				
Sub-plot ID	BC (kg)	LC (kg)	BC (t/ha)	LC (t/ha)
T1	150	150	15	15
T2	150	100	15	10
T3	150	50	15	5
T4	150	25	15	2,5
T5	150	0	15	0
T6	0	0	0	0
T7	100	0	10	0
T8	0	100	0	10
T9	50	0	5	0
T10	0	50	0	5

The plantain parcel has three repetitions of each treatment, randomly placed. In every sub-plot, the total 12 plants were measured. The measures taken were: height, number of leaves (referred to in graphs and tables below as # Leaves), the circumference at breast height and the cumulative appearance of flower or fruits.

Table 6: Disposition of the different plantain sub-plots on the parcel. Each sub-plot is 10x10m.

ROAD	1	2	3	4	5	6	7	8	9	10
	8	2	3	4	6	9	10	1	7	5
	5	7	1	2	6	10	9	4	8	3

6.1.3 Crop management

In the plantain parcel, pruning was realized at different occasions and the leaves were applied as mulch between the plants.

In the pineapple parcel, weeding was done.

6.2 Results

Using pivot tables, we were able to calculate the mean for every characteristic (i.e.: height, # Leaves, circumference, D-leaves and number of fruits or flowers) for each treatment and for the 360 plantains and 600 pineapples measured in every sampling date.

Table 7 shows an example of a pivot table produced with data for the 21st of July and regarding the plantain plots. The “Average Height (m)” line shows the average height of all plants for each treatment. The “Maximum height (m)” shows the highest measurement for each treatment. The “% difference height compared to control (T6)” indicates how tall the plants from each treatment are as compared to treatment 6, which has no biochar and no lombricompost (see Table 5). For instance, according to Table 7, the plantains in treatment 3 are, in July 21st, on average, 3.14% taller than in treatment 6. The “Total Mean” column on the right represents the mean all treatments included.

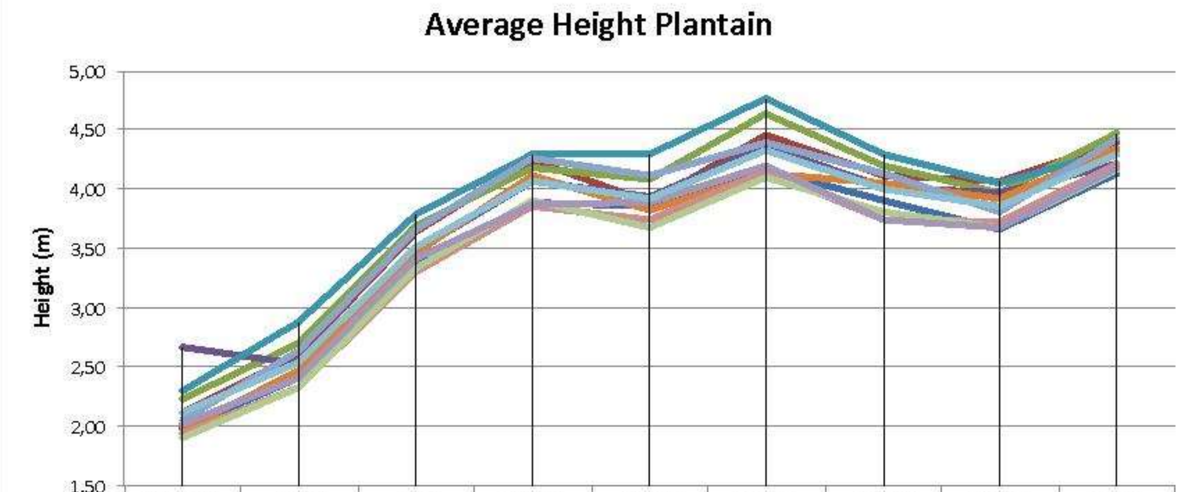
Table 7: Example of a pivot table using the plantain - 21st of July's data

Each column represents a treatment. The last column shows the average for all treatments.

Pivot Table: Plantain 21 July 2015											
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Total Mean
Average Height (m)	4,14	4,40	4,47	4,22	4,33	4,34	4,42	4,22	4,17	4,18	4,29
Standard deviation Height (m)	0,92	0,68	0,40	0,64	0,68	0,30	0,29	0,65	0,73	0,93	0,66
Maximum Height (m)	4,82	5	4,85	5,2	5,06	4,83	4,81	4,85	4,84	4,85	5,2
% difference Height compared to Control (T6)	-4,48%	1,39%	3,14%	-2,74%	-0,24%		1,79%	-2,81%	-3,91%	-3,71%	
Average # Leaves	7,25	7,31	7,64	7,36	7,58	7,53	7,69	7,47	7,39	7,42	7,46
Standard deviation # Leaves	1,84	0,98	1,02	1,38	0,87	0,94	0,75	1,06	0,69	1,63	1,17
Maximum # Leaves	11	9	9	10	9	10	9	10	9	10	11
% difference # Leaves compared to Control (T6)	-3,69%	-2,95%	1,48%	-2,21%	0,74%		2,21%	-0,74%	-1,85%	-1,48%	
Average Circumference (cm)	42,97	46,11	46,75	45,08	46,78	44,53	46,33	44,19	44,19	44,69	45,16
Standard deviation Circumference (Cm)	10,38	6,68	4,63	6,16	4,54	6,22	4,01	6,54	7,38	9,88	6,96
Maximum Circumference (cm)	53	57	54	51	53	52	52	55	53	56	57
% difference Circumference compared to Control (T6)	-3,49%	3,56%	4,99%	1,25%	5,05%		4,05%	-0,75%	-0,75%	0,37%	
Amount Flower or Fruit	15	17	21	14	15	18	17	12	10	19	158

6.2.1 Results for plantain

We isolated every characteristic from the pivot tables and created a table with all the means according to the treatments for every sampling date. From the tables created, we generated graphs showing visually the evolution of each characteristic according to the different treatments.

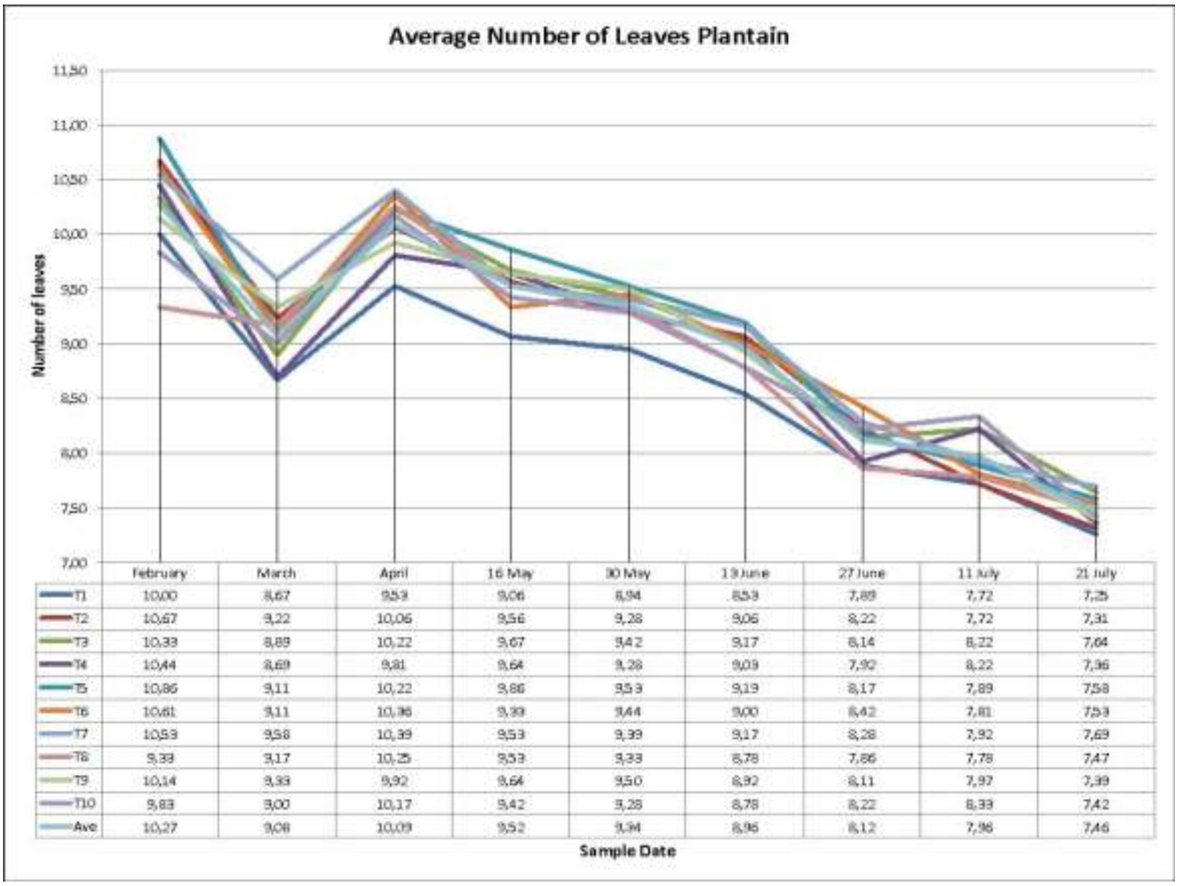


	February	March	April	16 May	30 May	13 June	27 June	11 July	21 July
T1	1,98	2,41	3,39	3,89	3,85	4,17	3,91	3,66	4,14
T2	2,12	2,61	3,64	4,25	3,89	4,45	4,11	4,07	4,40
T3	2,23	2,70	3,70	4,18	4,09	4,63	4,20	3,98	4,47
T4	2,66	2,53	3,47	4,07	3,94	4,36	4,02	3,97	4,22
T5	2,30	2,88	3,79	4,29	4,29	4,77	4,29	4,06	4,33
T6	1,96	2,48	3,47	4,11	3,82	4,14	4,05	3,92	4,34
T7	2,05	2,63	3,67	4,26	4,12	4,39	4,13	3,80	4,42
T8	1,94	2,33	3,31	3,86	3,75	4,15	3,75	3,73	4,22
T9	1,90	2,33	3,33	3,90	3,67	4,10	3,81	3,68	4,17
T10	2,02	2,41	3,42	3,87	3,89	4,20	3,74	3,67	4,18
Ave	2,11	2,53	3,52	4,07	3,93	4,33	4,00	3,85	4,29

Sample Date

Figure 20: Average height evolution of plantains between February and July 21st 2015 according to each treatment.

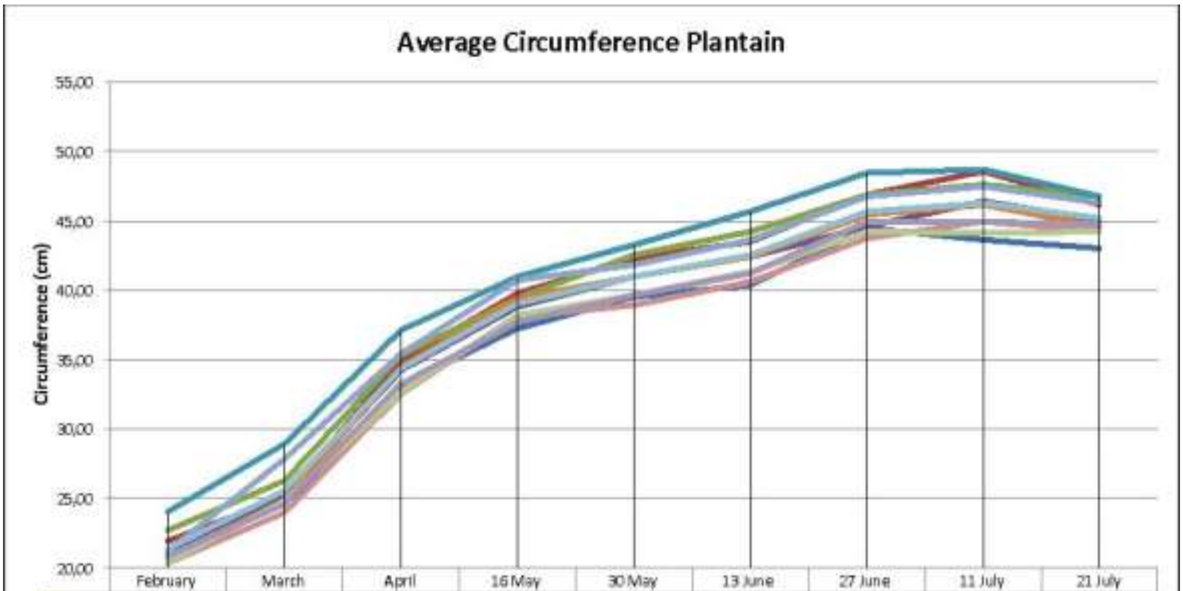
In Figure 20 we can observe a steady increase of all plantains from February to May 16th. We then notice a small decline of the average from May 16th until May 30th, followed by a small increase on June 13th. From June 13th until the last sample date, we witness a stabilization of the height. On July 21st, we observe that all treatments results are grouped.



	February	March	April	16 May	30 May	13 June	27 June	11 July	21 July
T1	10,00	8,67	9,53	9,06	8,94	8,53	7,89	7,72	7,25
T2	10,67	9,22	10,06	9,56	9,28	9,06	8,22	7,72	7,31
T3	10,33	8,89	10,22	9,67	9,42	9,17	8,14	8,22	7,64
T4	10,44	8,69	9,81	9,64	9,28	9,03	7,92	8,22	7,36
T5	10,86	9,11	10,22	9,86	9,53	9,19	8,17	7,89	7,58
T6	10,61	9,11	10,36	9,39	9,44	9,00	8,42	7,81	7,53
T7	10,53	9,58	10,39	9,53	9,39	9,17	8,28	7,92	7,69
T8	9,33	9,17	10,25	9,53	9,33	8,78	7,86	7,78	7,47
T9	10,14	9,33	9,92	9,64	9,50	8,92	8,11	7,97	7,39
T10	9,83	9,00	10,17	9,42	9,28	8,78	8,22	8,33	7,42
Ave	10,27	9,08	10,09	9,52	9,34	8,96	8,12	7,96	7,46

Figure 21: Average number of leaves evolution of plantains between February and July 21st 2015 according to each treatment.

In Figure 21 we see an overall decline of number of leaves. The decrease accelerates after June 13th until the last sample date. On July 21st, we witness a regrouping of the results.

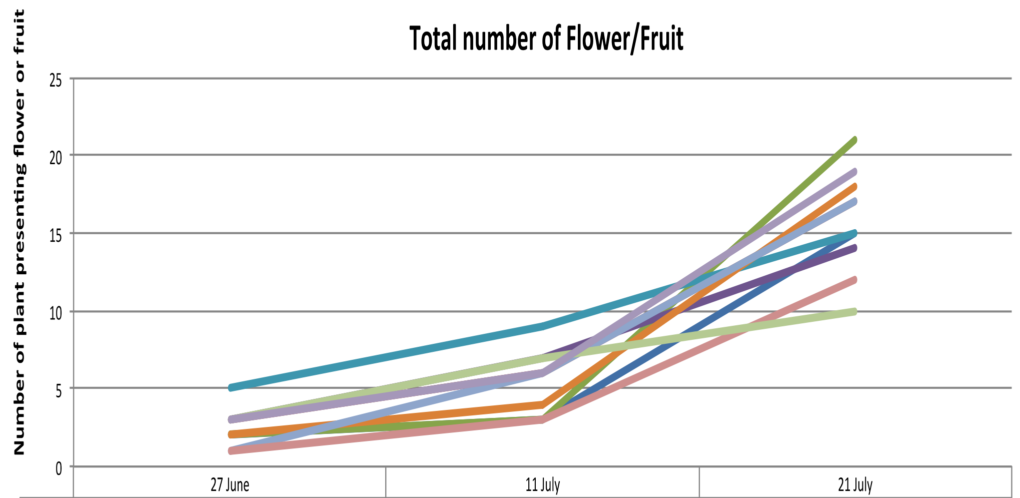


	February	March	April	16 May	30 May	13 June	27 June	11 July	21 July
T1	20,86	24,58	33,17	37,25	39,53	40,33	44,47	43,64	42,97
T2	21,86	25,10	34,92	39,75	42,25	43,47	46,92	48,53	46,11
T3	22,69	26,22	35,31	39,39	42,58	44,19	46,83	47,64	46,75
T4	20,92	25,14	34,17	38,78	40,92	42,42	44,56	46,42	45,08
T5	24,03	28,92	37,17	40,92	43,22	45,69	48,39	48,72	46,78
T6	20,75	24,78	34,42	39,36	41,00	42,42	45,42	46,17	44,53
T7	21,20	27,81	35,39	40,67	41,86	43,67	46,72	47,50	46,33
T8	20,31	23,92	32,56	38,03	38,86	40,56	43,78	44,92	44,19
T9	20,39	24,81	32,69	38,14	39,61	41,36	44,17	44,06	44,19
T10	20,81	24,56	33,28	37,67	39,69	41,19	45,00	44,94	44,69
Ave	21,36	25,58	34,31	38,99	40,95	42,53	45,63	46,25	45,16

Sample Date

Figure 22: Average circumference evolution of plantains between February and July 21st 2015 according to each treatment.

Figure 22 shows a steady increase of plant circumference from February to June 27th followed by stabilization and a small average decrease from July 11th until July 21st. On the last sample date, the data are grouped.



	27 June	11 July	21 July
T1	2	3	15
T2	3	6	17
T3	2	3	21
T4	3	7	14
T5	5	9	15
T6	2	4	18
T7	1	6	17
T8	1	3	12
T9	3	7	10
T10	3	6	19

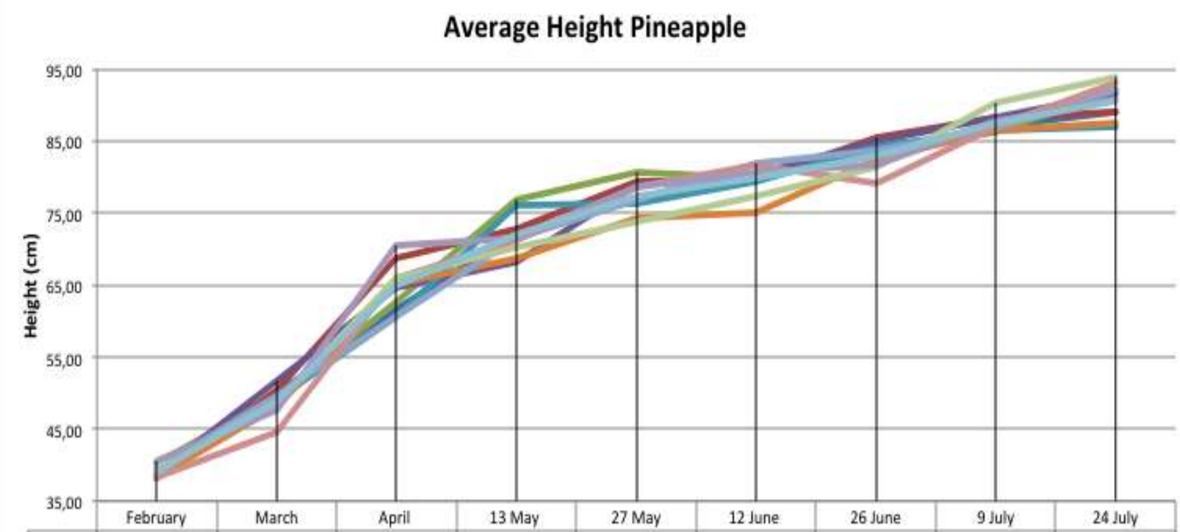
Sample Date

Figure 23: Evolution of the number of flowers or fruits on plantains between the June 27th and July 21st 2015 according to each treatment

The Figure 23 shows the first flower/fruit apparition on June 27th.

6.2.2 Results for pineapple

Based on the same approach as for the plantains (Chapter 6.2.1 above) we generated the graphs below for the pineapples.

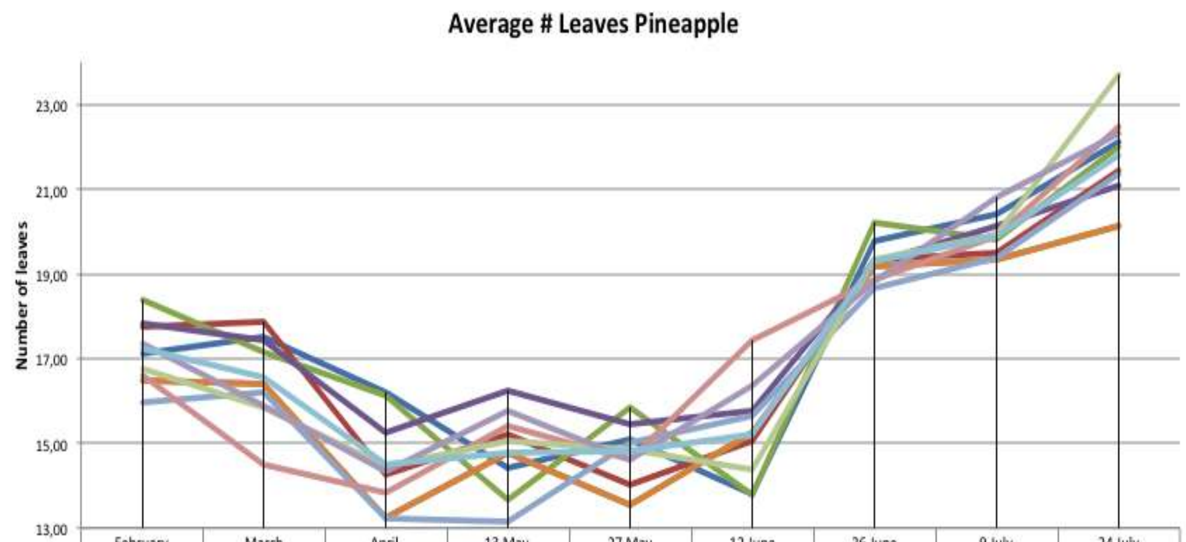


	February	March	April	13 May	27 May	12 June	26 June	9 July	24 July
T1	38,45	49,92	61,67	72,25	76,77	80,47	83,68	87,08	89,08
T2	38,20	50,53	68,82	72,90	79,32	79,63	85,58	88,17	89,08
T3	40,15	49,49	62,67	76,90	80,68	79,93	83,71	86,28	92,03
T4	38,75	51,70	64,72	68,30	78,96	80,52	84,88	88,27	91,50
T5	38,15	49,27	60,67	76,03	76,37	79,43	84,30	86,62	87,12
T6	38,24	48,24	65,20	68,84	74,28	75,18	82,47	86,40	87,51
T7	39,48	49,58	60,72	71,62	76,92	81,93	83,62	86,65	92,04
T8	38,28	44,58	65,92	71,35	78,60	81,76	79,13	87,07	93,12
T9	39,40	48,62	65,82	70,22	73,92	77,40	81,45	90,23	93,88
T10	40,43	47,67	70,52	71,53	78,65	80,73	81,62	87,85	90,93
Ave	39,00	48,95	64,81	71,97	77,33	79,80	82,96	87,44	90,50

Sample Date

Figure 24: Growth of pineapples between February and the 24th of July 2015 according to each treatment.

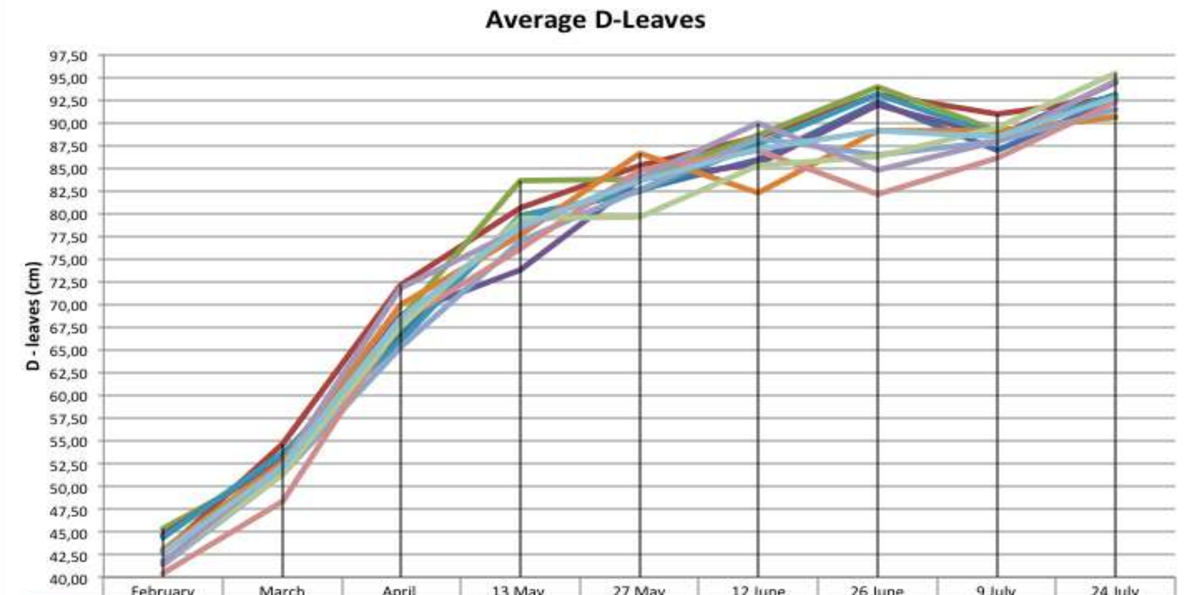
The Figure 24 shows an overall and constant increase of height from February to July 21st. On the last sample date, the treatments results are grouped.



	February	March	April	13 May	27 May	12 June	26 June	9 July	24 July
T1	17,13	17,50	16,20	14,40	15,08	13,80	19,77	20,43	22,10
T2	17,73	17,87	14,25	15,22	14,02	15,05	19,33	19,48	21,45
T3	18,40	17,17	16,11	13,65	15,83	13,77	20,22	19,83	22,00
T4	17,82	17,43	15,23	16,23	15,44	15,77	19,28	20,15	21,08
T5	16,47	16,40	13,24	14,77	13,56	15,24	19,17	19,33	20,12
T6	16,47	16,40	13,24	14,77	13,56	15,24	19,17	19,33	20,12
T7	15,97	16,20	13,23	13,15	15,00	15,65	18,68	19,38	21,38
T8	16,60	14,50	13,83	15,42	14,63	17,44	18,88	19,90	22,46
T9	16,76	15,87	14,47	15,07	14,87	14,36	19,35	19,95	23,72
T10	17,37	15,88	14,33	15,77	14,62	16,35	18,82	20,80	22,30
Ave	17,23	16,55	14,50	14,77	14,80	15,22	19,32	19,88	21,82

Figure 25: Evolution of the number of leaves of pineapple between February and the 24th of July 2015 according to each treatment.

In Figure 25 we witness larges difference within treatments between each sample date. We observe an important increase from June 12th until June 26th followed by a smaller, but still overall, increase. On the last sample date, most of the treatments results are grouped except for treatment 9, which shows a greater increase than the average and the control (treatment 6), which shows more of a stabilization.



	February	March	April	13 May	27 May	12 June	26 June	9 July	24 July
T1	42,80	52,00	66,71	79,30	82,70	85,91	92,33	86,95	92,65
T2	42,65	54,58	72,08	80,68	85,33	88,43	93,07	90,88	92,80
T3	45,27	52,45	68,42	83,62	83,72	88,63	94,02	89,10	90,60
T4	44,65	53,22	68,73	73,88	83,80	85,40	91,90	88,52	94,50
T5	44,34	53,60	65,92	79,80	82,38	87,63	93,13	88,58	93,12
T6	42,97	52,61	69,96	77,63	86,57	82,33	89,08	89,16	90,67
T7	41,32	51,30	65,30	76,95	82,58	88,32	86,37	87,92	91,38
T8	40,43	48,33	68,20	76,08	84,83	86,93	82,10	86,15	92,32
T9	41,76	51,38	67,62	79,53	79,70	85,31	86,27	89,43	95,38
T10	41,61	52,35	71,75	78,27	83,92	89,97	84,78	87,97	94,60
Ave	42,71	52,17	68,55	78,56	83,62	87,12	89,08	88,48	92,79

Figure 26: Data and graph representing the evolution of the length of the longest leaf of pineapple between February and the 24th of July 2015 according to each treatment.

The Figure 26 shows an important increase of the length of the longest leaf from February until May 27th followed by a stabilization until July 24th where all the treatments results are group.

6.3 Statistical analysis

As stated above, the data are still being collected; the plants are still growing thus the study is not finished yet. Moreover, the only data presented so far concern the biomass evolution whereas, when doing agricultural research, only final yield matters. There is, therefore, no reason to make any statistical analyses at this point.

However, in this chapter we will show the procedure and tests to use for further yield analyses. The following analyses have been done using the height data of plantains on June 13th and the SPSS IBM© program.

The main goal of these analyses is to show whether or not there are statistical differences between the treatments according to the height of plantains on June 13th.

To do so, we used the analysis of variance (ANOVA) to show first if there is a significant difference between all the treatments followed by a post-hoc Bonferoni test to determine which treatments induce the differences.

In order to do an ANOVA, we first need to fulfil three assumptions:

- Independence of the observation

- Normal distribution of our data
- Homogeneity of variances

6.3.1 Independence of the observation

Our data being measured on different plots, on different plants, we can assume the independence of our data since each measure does not influence in any way the others.

6.3.2 Normal distribution

To test the normality of our data set, we used the Shapiro-Wilk test commonly used as a goodness of fit test.

Our two hypotheses are:

- H_0: The sampled height is normally distributed within the treatments
- H_1: The sampled height is not normally distributed within the treatments

With a significance level = 5% and number of observation for each treatment =36

When the *p*-value is equal or smaller than the significance level it indicates that the data observed are inconsistent with the assumption that H_0 is true. And hence, H_0 must be rejected.

For the totality of our dataset, the Shapiro-Wilk test shows a p=0.000<0.05. The null hypothesis must therefore be rejected. We can conclude that the data are not normally distributed.

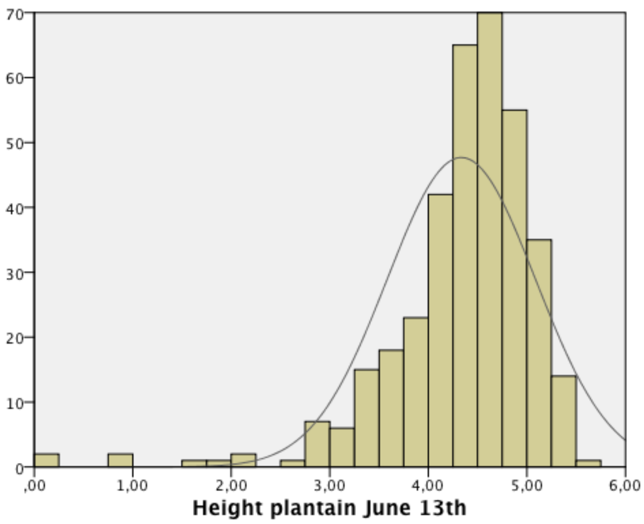


Figure 27: Histogram of plantains' data on June 13th and normality curve from SPSS IBM ©. The y-axis represents the number of occurrence

In case of a non-normally distributed dataset, we must change our parametric ANOVA to a Kruskal-Wallis test, considered the equivalent nonparametric to an ANOVA.

The homogeneity of variances assumption still needs to be accepted for the Kruskal-Wallis test.

6.3.3 Homogeneity of variance

Since our dataset is not normally distributed we will use the nonparametric Levene's test to assess the homogeneity of variances.

Null hypothesis H_0: the variances are equal

The nonparametric Levene's test shows a *p*= 0.154>0.05. The null hypothesis can therefore be accepted. We can assume the homogeneity of the variances.

6.3.4 Kruskal-Wallis

As said above, this test is the nonparametric equivalent of the ANOVA. It looks into all the treatments and sees if there is at least one treatment that differs from the others.

Null hypothesis H_0: all the treatments are equal.

The result of the Kruskal-Wallis test gives us $p=0.000<p=0.05$. H_0 must therefore be rejected. We can assume that there is at least one difference between the treatments.

Unfortunately, SPSS IBM © does not offer post-hoc tests for Kruskal-Wallis that could directly show us which treatments are statistically different. We therefore needed to compare them one by one.
To avoid excessive comparisons we looked at the mean rank of each treatment given by the first analysis and listed in Table 8 below.

Table 8: Mean rank of each treatment for plantain's data on June 13th. N represents the number of plant measured (SPSS IBM ©).

Ranks

	Treatment	N	Mean Rank
@13JuneHeightm	1,0	36	167,40
	2,0	36	202,67
	3,0	36	226,83
	4,0	36	188,51
	5,0	36	248,31
	6,0	36	137,18
	7,0	36	175,42
	8,0	36	142,71
	9,0	36	147,21
	10,0	36	168,76
	Total	360	

Indeed, the higher the difference between two treatments' means rank, the more likely they are to be significantly different.

By doing so, we found that T5 is significantly different from T6 ($p=0.014<0.05$), T8 ($p=0.017<0.05$), T9 ($p=0.005<0.05$) and T10 ($p=0.047<0.05$).

Using the Figure 20 in chapter 6.2.1 above and the Table 5 in chapter 6.1.2 above we can state that on June 13th, the parcels amended with 15T/ha of biochar and no lombricompost (T5) have a significantly higher plantain biomass than the parcels amended with:

- no biochar and no lombricompost (T6);
- no biochar and 10T/ha of lombricompost (T8);
- 5T/ha of biochar and no lombricompost (T9);

- no biochar and 5T/ha of lombricompost (T10).

However, the non-normal distribution of the dataset was not expected. One plausible reason for this non-normality is called “parcel effect”. To verify it, we should test the different sub-plots of each treatment. Unfortunately, in our case, the three parcels for each treatment were not separated during the data collection resulting in 36 measures for each treatment and not the 3x12 needed to test the parcel effect.

Eventually, when the yield data will be available, statistical analyses using the parametric test ANOVA if the data are normally distributed or the nonparametric test Kruskal-Wallis if the data are not normally distributed could allow us to find significant differences between treatments and assess which treatment is associated with the best yield

6.4 Discussion

6.4.1 Plantain

The decrease in number of leaves (Figure 21) and the stabilization of circumference (Figure 22) witnessed on June 13th and June 27th respectively are correlated with the apparition of flowers/fruits on June 27th (Figure 23). Indeed, according to Chaves et al. (2009), the beginning of the fructification phase generates a reduction of leaf dry biomass and a stabilization of stem biomass. The average small reduction of plantains’ height after June 13th can only be explained by the cessation of growth generated by the stabilization of stem biomass prior to fructification accompanied with inaccuracies during the measurement.

According to Banful et al. (2000), soil moisture has a significant positive effect on yield. The same study shows a positive and significant correlation between the yield and the number of leaves at fructification time. Therefore, we can assume that the soil moisture has an effect on the number of leaves. Knowing the water retention ability of biochar (see chapter 3.4.2 above) we should witness a higher number of leaves in treatments that include biochar. However, data in Figure 21 show no differences. This can be explained by the pruning left as mulch between the plants (chapter6.1.3 above). Indeed, pruning enhances soil moisture by reducing soil evaporation (Banful et al., 2000) thus, hiding the potential relative beneficial effect of biochar.

Although we expected overall improvement in biomass production from biochar-amended soils the results are unclear and no treatment stands out from the others so far.

6.4.2 Pineapple

D-Leaves represents the length of the longest leaf present in each plant and is considered a reliable indication of the plant nutritional status that has a direct, positive influence on the size of the fruit produced thus on the yield (Arshad and Armanto, 2012).

Moreover, another study shows that, in general, the dry matter weight at harvest is positively correlated with the yield of a pineapple plant (Hanafi and Halimah, 2004). Therefore, comparing the biomass production between treatments during the vegetative phase can give an indication of the yield that will be produced.

Although we expected to observe an overall difference in biomass production between biochar-amended soils and the control plots, the results are unclear so far, since no treatment stands out from the others.

The only difference between treatments observed on the last sample date concerns the number of leaves (Figure 25). However, this is not a reliable observation for the differences between each sample date are so important that one cannot know if the slight difference observed on one date is not going to reverse on the next sampling date.

6.4.3 Reasons for unconvincing results

There are several reasons that can explain our inability to identify any favorable effect of biochar on the tested plots so far.

First of all, the biochar used as amendment was made at a pyrolysis temperature of 800°C. However, we discussed in chapter 3.3 above, the effect of pyrolysis temperature on biochar properties and stated that a higher temperature increases the specific surface area and pH of biochar while decreases the CEC. The decreased CEC and application of high pH biochar on a soil that presents already a pH of 6-6.5 (chapter 6.1.1) could reduce the benefits usually associates with biochar amendment. Using other types of biochar in further studies could confirm or invalidate this hypothesis.

Second, as discussed in chapter 3.4.3 above, the positive effect of biochar is usually observed on poor and acidic soil. However, the soil of the experimental site is classified as having a “relatively high fertility”, thus reducing the potential favorable effect of biochar application. Translocate the experimental site on a less fertile soil could allow for more convincing results.

Third, in chapter 3.4.2 above, we discussed the time effect of biochar in the soil and the fact that some studies show that biochar’s beneficial effect generally gets stronger as the years of culture pass. In our case, the soil was amended by the treatments right before the transplant. A potentially stronger effect should take place in the years to come, which would allow us to observe greater differences between the treatments.

Moreover, as far as we know, at least 8 people were involved in collecting measures of the plants according to their availability. Although they have all been briefed and trained on how to collect the different measurements, the human factor can always be a source of imprecision leading to non-reliable data.

Overall, even if the above-mentioned indicators of biomass production have not shown any evidence of the efficacy of biochar so far, only the final fruit yield matters to compare the economic benefits of the different treatments. Even though correlations are made by some studies between the number of leaves and the fruit yield for plantain and the overall biomass and the final fruit yield for pineapple, only further statistical analyses of fruit production data can establish trustworthy conclusions.

6.4.4 Further Analysis

First of all, statistical analyses using the parametric ANOVA and Bonferroni post hoc if the data are normally distributed or the nonparametric test Kruskal-Wallis if the data are not normally distributed should be use on precise yield data to statistically compare the efficacy of each treatment.

Secondly, in order to fully understand the potential effect of biochar and lombricompost on yield, we need to better observe the effects of different biochar treatments on the soil of the different plots. Further soil analysis should therefore be made such as pH, CEC, nutrient content, bulk density, water retention, and soil biota.

Finally, in-depth analysis should be made on the paca biochar itself to determine its biosafety before further applications.

7 Conclusion and prospects

Based on the review of literature, the biochar technique appears to be an appropriate response to the constraints of agriculture in the Amazon rainforest. Results from papers are convincing, especially when applied on weathered, poor and acidic types of soil typical of the ones found in the Amazon.

The increased soil fertility could allow farmers to cultivate longer in each parcel, if not indefinitely, and be less subject to delocalization in search of new areas of forest to slash, which is increasingly limited by new environmental regulations. Moreover, this fertility gain could allow smallholders to grow crops otherwise too demanding in nutrients, which would allow a diversification of production amongst villages thus less competition and more stable prices. Crop diversification and higher yields could contribute to higher and more stable rural incomes.

Biochar production technologies are simple and affordable. And with little training (especially to ensure total combustion thus avoid the release of harmful greenhouse gas) most households could possess a biochar oven. The change from pit-fire to biochar-making device for everyday use could reduce respiratory and eye problems due to harmful smoke emission and produce charcoal at the same time. The charcoal produced could then be used in the field or sold as a secondary source of income.

Another positive aspect of biochar is its ability to sequester carbon. Due to its persistent nature, its ability to contribute to climate change mitigation is plausible, which opens opportunities for international monetization and, therefore, broaden the scope for utilization. However, the lack of precise data concerning its residence time in the soil puts a hold that first needs to be addressed if any monetization ever has to take place.

Despite the impressive prospects of biochar, it must be noted that the subject is in its early stage of exploration and, although most research shows attractive results, biochar is not universally beneficial. Its effects are diverse and depend widely on numerous factors (e.g. biochar’s properties, type of soil, climate). Biochar could even do more harm than good if not thoroughly thought about. Instead of viewing biochar as a whole, further research should focus on custom made biochar systems for specific objectives such as a biochar mainly designed to prevent chemical leaching, another to increase water retention, to sequester carbon, to enhance CEC, to elevate soil pH and so forth.

Moreover, one must be aware of the potential danger of biochar, not only regarding the PAHs and heavy metal concentration, but also its potential consequences on food security or environment that could lead to terrible consequences if not supervised properly.

The results of our experiments, although unconvincing for our oven or incomplete for our yield experimentation, plant good bases for further studies and emphasize the need to consider biochar making and use not as one solution but as multi-purpose technology needing a case by case application.

Overall, the future of biochar relies on its integration inside pre-existing systems and its ability to counter precise difficulties linked to specific situations.

Bibliography

Abiven Samuel, 2015. Que faut-il penser des biochars ? Webinaire de l'Association Française pour l'Etude des Sols.

Abiven, S., Schmidt, M.W.I., Lehmann, J., 2014. Biochar by design. Nat. Geosci. 7, 326–327.

Agronomic Principles | Soil & Water Requirements | Orchard Systems | Tree Manipulation | Yara [WWW Document], n.d. URL http://www.yara.us (accessed 8.2.15).

Arshad, A.M., Armanto, M.E., 2012. Effect of Nitrogen on Growth and Yield of Pineapple Grown on BRIS Soil. J. Environ. Sci. Eng. B 1 1285 1289.

Banful, B., Dzietror, A., Ofori, I., Hemeng, O.B., 2000. Yield of plantain alley cropped with Leucaena leucocephala and Flemingia macrophylla in Kumasi, Ghana. Agrofor. Syst. 49, 189–199.

Beverly D. McIntyre, Hans R. Herren, Judi Wakhungu, Robert T. Watson (Eds.), 2009. Agriculture at a crossroads Global report, International Assessment of Agricultural Knowledge, Science, and Technology for Development. ed. Island Press, Washington, DC.

Biochar: a new weapon in the war against greenhouse gases | Climate Solutions [WWW Document], 2013. URL http://climatesolutions.org (accessed 5.21.15).

Butler, R., 2012. Sustainable Agriculture in Rainforests [WWW Document]. URL http://rainforests.mongabay.com (accessed 12.7.14).

Butler, R., n.d. Rainforests: facts, figures, news, and pictures [WWW Document]. URL http://rainforests.mongabay.com/ (accessed 12.7.14).

Carvalho, A.L. de, Nelson, B.W., Bianchini, M.C., Plagnol, D., Kuplich, T.M., Daly, D.C., 2013. Bamboo-Dominated Forests of the Southwest Amazon: Detection, Spatial Extent, Life Cycle Length and Flowering Waves. PLoS ONE 8, e54852. doi:10.1371/journal.pone.0054852

Chaves, C., Cayón, S., Jones, J.W., others, 2009. Modeling plantain (Musa AAB Simmonds) potential yield. Agron. Colomb. 27, 359–366.

Clay, S.A., Malo, D.D., 2012. The influence of biochar production on herbicide sorption characteristics. INTECH Open Access Publisher.

Climate of the Amazon Rainforest [WWW Document], n.d. . Adithyarainforest -. URL http://adithyarainforest.wikispaces.com (accessed 8.3.15).

Crane-Droesch, A., Abiven, S., Jeffery, S., Torn, M.S., 2013. Heterogeneous global crop yield response to biochar: a meta-regression analysis. Environ. Res. Lett. 8, 044049. doi:10.1088/1748-9326/8/4/044049

Demirbas, A., 2004. Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. J. Anal. Appl. Pyrolysis 72, 243–248. doi:10.1016/j.jaap.2004.07.003

Driessen, P., Deckers, J. (Eds.), 2001. Lecture notes on the major soils of the world, World soil resources reports. Food and Agriculture Organization of the United Nations, Rome.

Edmunds, C.W., 2012. The effects of biochar amendment to soil on bioenergy crop yield and biomass composition.

Fabbri, D., Rombolà, A.G., Torri, C., Spokas, K.A., 2013. Determination of polycyclic aromatic hydrocarbons in biochar and biochar amended soil. J. Anal. Appl. Pyrolysis 103, 60–67. doi:10.1016/j.jaap.2012.10.003

Fuchs, M., Garcia-Perez, M., Small, P., Flora, G., 2014. The Biochar Journal:Campfire Lessons - breaking down the combustion process to understand biochar production [WWW Document]. URL http://www.biochar-journal.org/en/ct/47 (accessed 5.22.15).

Gaskin, J.W., Steiner, C., Harris, K., Das, K.C., Bibens, B., others, 2008. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. Trans Asabe 51, 2061–2069.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. Biol. Fertil. Soils 35, 219–230. doi:10.1007/s00374-002-0466-4

Global Ecosystem Monitoring network [WWW Document], 2015. URL http://gem.tropicalforests.ox.ac.uk (accessed 8.3.15).

Hale, S.E., Lehmann, J., Rutherford, D., Zimmerman, A.R., Bachmann, R.T., Shitumbanuma, V., O'Toole, A., Sundqvist, K.L., Arp, H.P.H., Cornelissen, G., 2012. Quantifying the Total and Bioavailable Polycyclic Aromatic Hydrocarbons and Dioxins in Biochars. Environ. Sci. Technol. 46, 2830–2838. doi:10.1021/es203984k

Hanafi, M.M., Halimah, A., 2004. Nutrient supply and dry-matter partitioning of pineapple cv. Josapine on sandy tin tailings. Fruits 59, 359–366. doi:10.1051/fruits:2004034

Herbert, L., Hosek, I., Kripalani, R., 2012. The characterization and comparison of biochar produced from a decentralized reactor using forced air and natural draft pyrolysis.

Kenneth L. Dickson, John P. Giesy, Rodney Parrish, Lee Wolfe, 1994. BIOAVAILABILITY Physical, Chemical, and Biological Interactions, Lewis Publishers. ed, Society of Environmental Toxicology and Chemistry Special Publications Series.

Kumar, B.M., Nair, P.K.R. (Eds.), 2006. Tropical homegardens: a time-tested example of sustainable agroforestry, Advances in agroforestry. Springer, Dordrecht.

Kyoto Protocol to the United Nations Framework Convention on Climate Change, 1998.

Lazcano, C., Gómez-Brandón, M., Domínguez, J., 2008. Comparison of the effectiveness of composting and vermicomposting for the biological stabilization of cattle manure. Chemosphere 72, 1013–1019. doi:10.1016/j.chemosphere.2008.04.016

Lehmann, J., Da Silva, J.P.J., Rondon, M., Da Silva, C.M., Greenwood, J., Nehls, T., Steiner, C., Glaser, B., 2002. Slash-and-char: a feasible alternative for soil fertility management in the Central Amazon?

Lehmann, J., da Silva Jr, J.P., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249, 343–357.

Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char Sequestration in Terrestrial Ecosystems – A Review. Mitig. Adapt. Strateg. Glob. Change 11, 395–419. doi:10.1007/s11027-005-9006-5

Lehmann, J., Joseph, S. (Eds.), 2015. Biochar for environmental management: science, technology and implementation, Second edition. ed. Routledge, Taylor & Francis Group, London ; New York.

Lehmann Johannes, 2007a. Bio-energy in the black. FrontiersEcolEnv, The Ecological Society of America 5, 381–387.

Lehmann Johannes, 2007b. A handful of Carbon. Nature 447, 143–144.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – A review. Soil Biol. Biochem. 43, 1812–1836. doi:10.1016/j.soilbio.2011.04.022

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizão, F.J., Petersen, J., Neves, E.G., 2006. Black Carbon Increases Cation Exchange Capacity in Soils. Soil Sci. Soc. Am. J. 70, 1719. doi:10.2136/sssaj2005.0383

Li, J., Li, Y., Wu, M., Zhang, Z., Lü, J., 2013. Effectiveness of low-temperature biochar in controlling the release and leaching of herbicides in soil. Plant Soil 370, 333–344. doi:10.1007/s11104-013-1639-7

Mekuria, W., Noble, A., 2013. The Role of Biochar in Ameliorating Disturbed Soils and Sequestering Soil Carbon in Tropical Agricultural Production Systems. Appl. Environ. Soil Sci. 2013, 1–10. doi:10.1155/2013/354965

Nguyen, B.T., Lehmann, J., 2009. Black carbon decomposition under varying water regimes. Org. Geochem. 40, 846–853. doi:10.1016/j.orggeochem.2009.05.004

Nguyen, D.H., Biala, J., Grace, P.R., Scheer, C., Rowlings, D.W., 2014. Greenhouse gas emissions from sub-tropical agricultural soils after addition of organic by-products. SpringerPlus 3, 491.

Piu, H.C., Menton, M., 2014. The context of REDD+ in Peru: Drivers, agents and institutions. CIFOR.

Prommer, J., Wanek, W., Hofhansl, F., Trojan, D., Offre, P., Urich, T., Schleper, C., Sassmann, S., Kitzler, B., Soja, G., Hood-Nowotny, R.C., 2014. Biochar Decelerates Soil Organic Nitrogen Cycling but Stimulates Soil Nitrification in a Temperate Arable Field Trial. PLoS ONE 9, e86388. doi:10.1371/journal.pone.0086388

Punde, B.D., Ganorkar, R.A., 2012. Vermicomposting-Recycling Waste Into Valuable Organic Fertilizer. Int. J. Eng. Res. Appl. IJERA Vol 2, 2342–2347.

Quesada, C.A., Lloyd, J., Anderson, L.O., Fyllas, N.M., Schwarz, M., Czimczik, C.I., 2011. Soils of Amazonia with particular reference to the RAINFOR sites. Biogeosciences 8, 1415–1440. doi:10.5194/bg-8-1415-2011

Ricigliano, K., 2011. Terra Pretas: Charcoal Amendments Influence on Relict Soils and Modern Agriculture. J. Nat. Resour. Life Sci. Educ. 40, 69–72.

Rogovska, N., Laird, D., Cruse, R., Fleming, P., Parkin, T., Meek, D., 2011. Impact of Biochar on Manure Carbon Stabilization and Greenhouse Gas Emissions. Soil Sci. Soc. Am. J. 75, 871. doi:10.2136/sssaj2010.0270

Roth, C., 2014. Micro-gasification: Cooking with gas from dry biomass.

Scholz, S.B., Sembres, T., Roberts, K., Whitman, T., Wilson, K., Lehmann, J., 2014. Biochar Systems for Smallholders in Developing Countries: Leveraging Current Knowledge and Exploring Future Potential for Climate-Smart

Agriculture. The World Bank.

Seguy, L., Husson, O., Charpentier, H., Bouzinac, S., Michellon, R., Chabanne, A., Boulakia, S., Tivet, F., Naudin, K., Enjalric, F., Ramaroson, I., Rakotondramanana, 2009. Manuel pratique du semis direct à Madacascar.

Takasaki, Y., 2013. Deforestation, Forest Fallowing, and Soil Conservation in Shifting Cultivation. Theor. Econ. Lett. 03, 30–38. doi:10.4236/tel.2013.35A1005

Trejedor, A., 2012. Villa Carmen : Agricultural Soils and Geology.

van Wambeke, A., 1974. Management Properties of Ferralsols [WWW Document]. URL http://www.fao.org (accessed 5.28.15).

Van Zwieten, L., Kimber, S., Morris, S., Chan, K.Y., Downie, A., Rust, J., Joseph, S., Cowie, A., 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. Plant Soil 327, 235–246. doi:10.1007/s11104-009-0050-x

Vera, R.R., 2006. Country Pasture/Forage Resource Profiles - Peru [WWW Document]. URL http://www.fao.org (accessed 12.7.14).

Verheijen, F., Jeffery, S., Bastos, A.., European Commission, Joint Research Centre, Institute for Environment and Sustainability, 2010. Biochar application to soils a critical scientific review of effects on soil properties, processes and functions. Publications Office, Luxembourg.

Vickery, J., Vickery, D., 1982. Intensive Vegetable Gardening for Profit and Self-sufficiency, Peace Corps. ed, Appropriate technologies for development. Merlyn Kettering.

Weisberg, P., Delaney, M., Hawkes, J., 2014. Carbon Market Investment Criteria for Biochar Projects (Final Project Report No. CEC-500-2014-048), Public Interest Energy Research (PIER) Program. The Climate Trust.

Wick, B., n.d. Mineral Soils conditined by a wet (sub) Tropical Climate - Humboldt University Berlin [WWW Document]. URL http://www.bodenkunde-projekte.hu-berlin.de (accessed 5.28.15).

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., Joseph, S., 2010. Sustainable biochar to mitigate global climate change. Nat. Commun. 1, 1–9. doi:10.1038/ncomms1053

Zheng, W., Sharma, B.K., Rajagopalan, N., 2010. Using biochar as a soil amendment for sustainable agriculture.

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