Biochar; methods for carbon sequestration and soil enhancement, past successes and future applications

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Abstract

Using biochar is a promising method for increasing soil fertility, sequestering carbon dioxide and providing renewable, carbon negative energy. Research was conducted to ascertain a

possible method for sequestering carbon from the atmosphere without creating more emissions. An emphasis was placed on ease of use, existing technologies, and low-infrastructure dependence.

This research was accomplished using relevant information from existing, public domain, scientific literature. The majority of the research was conducted online using Google Scholar and the HOLIS Library system at Harvard University. Supporting information was obtained utilizing the world wide web and other electronic resources.

The results of this research show that biochar can be effective in several applications and is not limited to sequestering carbon. Other uses for biochar include:

- Increasing crop yields
- Reducing the need for Nitrogen-Phosphorus-Potassium fertilizers
- Increasing soil moisture
- Reducing soil erosion
- Increasing the productivity of marginal soils
- Reclaiming 'infertile' soil
- Raising the pH of soils
- Creating renewable, carbon-negative energy

This research represents a brief sampling and discussion of the possibilities of using this technology. Other possible uses, and future avenues of research, are enumerated and discussed.

Acknowledgements

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Definition of Terms

bio-oil. Biomass derived base product for distillation into bio-diesel, bio-kerosene, and bio-gasoline. (Brown, R., 2009).

Cation Exchange Capacity. The principle of positively charged ions moving though water channels in soil. This driectly effects nutrient balances. (Cheng, C.H.; Lehmann, J.; Thies, J.E.; Burton, S.D.; Engelhard, M.H. 2006).

collier. A professional whose trade is to create charcoal from a lump of wood (GeoArch, 2011).

Columbian Exchange. The exchange of technology, cultures, foodstuffs, livestock and pathogens between the Americas and the Old World after Columbus made his first journey to the Americas in 1492. (Crosby, 1968).

lignin. A complex polymer occurring in certain plant cell walls making the plant rigid. (*Collins English Dictionary*, 2011)

lump. A collection of wood gathered and stacked for the purpose of making charcoal (GeoArch, 2011).

pH. The symbol for the logarithm of the reciprocal of hydrogen ion concentration in gram atoms per liter, used to express the acidity or alkalinity of a solution on a scale of 0 to 14, where less than 7 represents acidity, 7 neutrality, and more than 7 alkalinity. (*Collins English Dictionary*, 2011)

polyaromatic hydrocarbon (PAH). Rings of carbon with adjoined hydrogen atoms. These rings join into chains that can be quite long. PAH's contain reactive groups that are hazardous to human health and are often created in inccomplete combustion of carbon compounds. (Fetzer, J. C., 2000)

pyrolysis. The thermal decomposition of pulp-based feedstocks to biochar and syngas. Resulting products depend upon feedstock and tempratue of decomposition. (Glaser, B., Lehmann, J., Zech, W., 2002)

syngas. A combination of combustible hydrocarbon gasses that are a product of the thermal decomposition. (Levi, 1995)

tera perta do indio* and *tera mulatta do indio. Athropogenic dark soils located in Amazonian settlements. Created as a result of delberate charring of biomass. (Glaser, B. Haumaier, L., Guggenberger, G., Zech, W., 2000)

Acronyms

ADE	Amazonian Dark Earths
BNF	Biological Nitrogen Fixation
C	Elemental carbon
CDM	Clean Development Mechanism
CEC	Cation Exchange Capacity
CO_2	Carbon Dioxide
GHG	Green House Gases
N	Elemental nitrogen
NGO	Non-Governmental Originations
NPK	Nitrogen-Phosphorous-Potassium fertilizer
N_2O	Nitrogen dioxide
NOx	Various oxides of nitrogen
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SOx	Sulfur Dioxide
TP	*tera perta do indio.* The darker (black) form of ADE
TM	*tera mulatta do indio.* The lighter (brown) form of ADE

Introduction

"The power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race. The vices of mankind are active and able ministers of depopulation. They are the precursors in the great army of destruction, and often finish the dreadful work themselves. But should they fail in this war of extermination, sickly seasons, epidemics, pestilence, and plague advance in terrific array, and sweep off their thousands and tens of thousands. Should success be still incomplete, gigantic inevitable famine stalks in the rear, and with one mighty blow levels the population with the food of the world".

—Malthus T.R. 1798. *An essay on the principle of population*. Chapter VII, p61

In the 21st century it is obvious that there can be no one single solution to the problem of global climate change. The solutions needed to mitigate and even reverse this situation are as myriad as the causes for the problem. Global climate change did not begin overnight with some newly discovered technology that allowed a genie out of a bottle; it was the slow and inexorable progression of technology that led to the production of so many Green House Gasses (GHG) now prevalent in our atmosphere. All of these technologies have an ancient origin; the burning of carbon-based fuels for energy. From simple cooking and providing light, to multi-thousand mega-watt coal-fired power plants, the need for energy is on an ever-increasing trajectory. Oftentimes a solution to a problem lies in the problem itself, and the beginning of this dilemma holds the key to its end. The burning of biomass often leads behind a residue; we commonly call this residue charcoal, but it has another name indicating its origin - biochar. Biochar can be used to not only increase the yields from farmland, but also sequester carbon directly from the atmosphere. Biochar can be one of the many tools in the carbon reduction toolbox, if used appropriately.

Biochar is the scientific name for charcoal produced from biological feedstock. This feedstock can be vegetable or animal, but is generally vegetable, and typically from full standing trees, often hardwoods. Although biochar has a modern sounding name, the technology is quite old, and has been used in the Amazon basin for thousands of years (Woods and McCann, 1999).

Several cultures in Amazonia have practiced the use of biochar as a soil amendment to increase the fertility of marginal tropical soils. These cultures typically cleared a field by burning the standing biomass. But instead of allowing it to be burned to ash, as in slash and burn agriculture, the fires were doused and the standing timber buried whilst still smoldering (Glaser, B., Lehmann, J., Zech, W., 2002).

This anthropogenic soil containing biochar goes by two names in Portuguese; *tera perta do indio* and *tera mulatta do indio.* These two types name are abbreviated as TP and TM respectively, with TP soils being very dark, to almost black, and TM being a lighter brown color. They are collectively known as Amazonian Dark Earths (ADE). There is some debate as to whether the creation of ADE was a deliberate act, or simply the byproduct of native habitation. Arguments against being deliberate usually stem around the idea that these charcoal deposits were merely the trash heaps of the local populations. Overtime these garbage heaps, or middens, built up enough discarded charcoal that it began to directly affect the quality of the soil (Sombroek, W.M., De Lourdes Ruivo, M., Fearnside, P.M., Glaser, B.,Lehmann, J., 2003; Neves, E., Petersen, J., Bartone, R. Augusto Da Silva, C., 2004). However, some researchers feel that there is simply too much charcoal dispersed over such large locations that it could not possibility have been accidental or unintentional (Woods et al., 1999; Seiler and Crozen, 1980, Mann, 2005). This belief is further enhanced by the fact that broken clay pots found within layers of TP were fired, but never used for cooking or storage (Sombroek et al.). Implying that they were deliberately cast and fired, broken and buried. This casts further doubt on the claim that charcoal was just an outcast from middens. Further, these locations of broken pottery were not found in the middens actually used for the local populations, but sometimes kilometers from their respective sites of habitation.

The apparent increased fecundity of these soils has been the basis for very heated claims about the population of pre-Columbian America. Estimates of up to 100 million inhabitants throughout both continents as well as dense populations in Amazonia of up to a million in densely packed cities can only be supported by soils of this type and that densities at those levels cannot be maintained with shifting agriculture regimes (Mann, 2005; Heckenberger M.J., Kuikuro, A., Kuikuro. U.T., Russell, J.C., Schmidt, M., Fausto, C., Bruna Franchetto, B., 2003).

This technology may have been lost after the Columbian Exchange decimated populations throughout the Americas. The Columbian Exchange refers to the time period after Columbus' arrival in the New World in 1492. In this time period there was a great exchange of materials and cultural ideas between the New and Old world, usually to the detriment of the New (Crosby, 1968). After The Columbian Exchange, native populations were simply not large enough to necessitate the use of such technologies. However, this technology is still in use today at sites where it was previously utilized. Many Amazonian farmers speak of not having to ever fertilize their fields, and some reportedly never need to rotate their crops. (Woods et al., 1999). While some of this may be anecdotal, this has happened often enough to lend some credibility to these claims, and has prompted modern scientists to study this technology in-depth.

Biochar was not completely abandoned as a technology following the arrival of Europeans to the New World. In fact, it became one of the driving technologies in the First Industrial Revolution. Charcoal was needed to run blast furnaces and smelters for the production of iron and then steel tools. Charcoal had been used since the Bronze Age for this purpose, but hit its zenith before 1900 when the worldwide switched to anthracite grade coal as a fuel source. Many methods of producing charcoal had been perfected and put into use, with some of those methods more labor intensive than others. Further, those methods were very damaging to the environment, as the effects of Carbon (C) were not completely understood. Agriculture during this time began its long-term dependence on Nitrogen-Phosphorous-Potassium (NPK) fertilizers, and using C as an amendment fell to the wayside. Use of biochar as an amendment was almost cast aside to the midden of old human technologies.

In 1948 E.H. Tryon was intrigued by the notion of using biochar as an amendment, and then published a paper called "*Effect of charcoal on certain physical, chemical, and biological properties of forest soils."* In this seminal work, Tryon documented the properties of biochar and its effects on three types of soil. He found that biochar greatly improved the abilities of certain soils to retain moisture and nutrients, with sandy soils benefiting the most, and clay-like soils benefiting the least. Tryon was not interested in the C sequestration ability of biochar, since science had no yet come to understand its importance in climate at that time. However, this paper led the way to reigniting interest in this type of technology.

Studies have shown that biochar has increased the carbon, moisture, nitrogen and potassium content of the soils it has been incorporated too. Most importantly biochar has the ability to buffer acidic soils by raising the pH as much as 3 points (Tryon, 1948). This is the lynchpin in the argument for its use in Amazonian soils which, because of the leeching effects of tropical rain, are notoriously acidic.

Since its re-discovery, biochar has been shown to increase crop yields, retain moisture, reduce the outgassing of nitrogen dioxide (N_2O), stabilize erosion and lock away as much as 3.3 times the standing biomass of C in the soil for as much as, presumably, 1,000 years (Masiello and Druffel, 1998). However, the benefits from using biochar have been shown to only be the most effective in marginal soils (Tryon, 1948). Soils that are already productive show little improvement with the addition of biochar.

Since 70% of the world's agricultural soil has lost more than 50% of its Soil Organic Matter (SOM), there appears to be a large market for this resource. Additionally, the ability for biochar to lock in C for upwards of 1,000 years has potential to be used in the carbon trading market if that becomes a reality (Glaser et. al. 2002).

As seen in Figure 1 there us an outflow of energy that comes from the creation of biochar though the action of pyrolysis. Pyrolysis is the creation of charcoal and other hydrocarbon based forms of energy though the baking of organic materials in the absence of oxygen. Pyrolysis can provide a means of creating biochar which has a myriad of uses as a soil amendment, but can also provide a renewable energy source and sequester C from the atmosphere by physically storing it away in the charcoal of the pyrolysis feedstock. Carbon markets can then put a price on the biochar for sequestration incentives. This would translate into a farmer receiving money for half of his biomass that he cleared for agriculture instead of literally watching all of his trees go up in smoke.

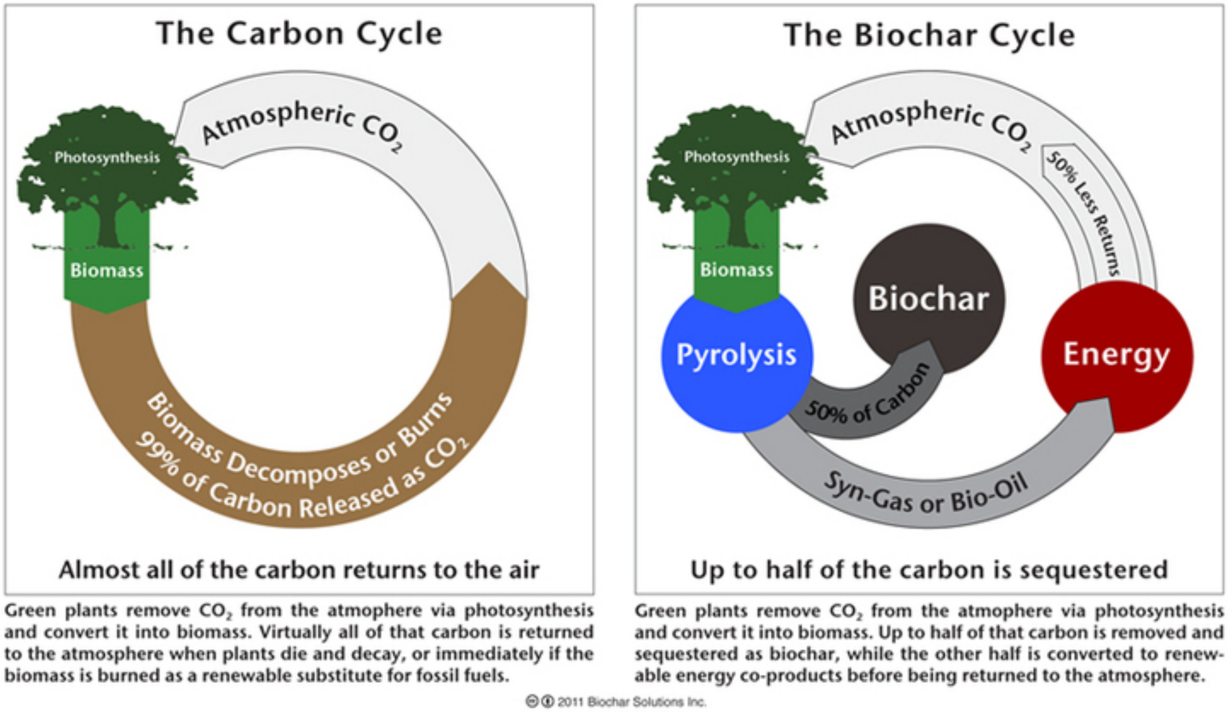


Figure 1: The Biochar Cycle. Illustration of how biochar interrupts the carbon cycle as created by human consumption (Biochar Solutions Inc., 2011)

However, biochar is not the panacea for all the worlds' problems. As noted, biochar only improves marginal soil. Biochar is also created at a 2 to 1 ratio to its feedstock, meaning that only 50% of the material utilized becomes biochar. However, when created in modern fast-pyrolysis kilns, biochar also yields 20% syngas, which is free hydrogen that can be bottled and transported and sold as a renewable energy source. Creating biochar in modern kilns also reduces the long-chain carbon pollution that is indicative of slow burring traditional methods (Pacific Pyrolysis, 2011).

The use of ADE by native cultures is the first attempt in the New World to alter the physical environment to benefit mankind. These soils may have been directly responsible for Amazonian cultures to grow past their local carrying capacities and join in the long journey of mankind toward being master of its own destiny. The practice of creating these soils, and even knowledge of their existence, was almost wiped out during the Columbian Exchange. So stable and enduring, these soils are still in existence today, many of which are still used for their original purpose. Studying these ancient soil amendments, modern science has shown that not only does biochar increase crop yields, but also raises soil pH, increases soil moisture, reduces nitrogen oxides (NOx) outgassing, stabilize erosion, improve marginal soils and ultimately sequesters C locking it away and out of the C cycle; all the while creating a renewable energy source though the creation of syngas and bio-oils.

It is the assertion of this paper that creating biochar in fast-pyrolysis kilns, and applied where there is the most benefit, can both reduce global carbon dioxide (CO_2) to pre-industrial levels, as well as increase crop yields on marginal soils. This can help humanity combat both global hunger, remove excess C, and provide carbon-neutral energy, until our civilization has been weaned off the fossil fuels that we depend on.

Background

Charcoal has been both the by-product and the intended product of burning for centuries (Glaser, 2007, Tryon, 1948, Glaser et al., 2002). Originally the by-product of hearth fires, charcoal was later utilized as a fuel itself for smelting bronze. As a fuel it reached its height just before the industrial revolution and was responsible for a great deal of the deforestation of Europe (Mather, 2001). To fully understand how biochar is made and its properties, it is necessary to briefly review the steps needed to create charcoal. How do those steps compare to modern pyrolysis, which is the baking of organic materials at low temperatures without the presence of oxygen to produce charcoal.

Making Biochar

Since the making of charcoal and biochar are one and the same, we will now examine the various methods for producing charcoal/biochar. First direct burning, where biochar is created by lighting the feedstock on fire and then covering it, and its applications by pre-historic peoples. Second, indirect burning (or slow pyrolysis), where biochar is created by the burning of external fuel to bake or, thermally decompose, feedstock creating nothing but biochar. Lastly, gasification, or fast pyrolysis, which creates biochar with additional products such as bio-oil and syngas (Brown, 2009).

Making Biochar: Direct Burning

Direct burning is done as the name implies; wood is directly set alight to be converted into charcoal. This is done in a multi-step process called a burn. In a burn wood is collected and stacked into what is known as a 'lump'. The wood in a lump is stacked vertically, around a central void that acts as a chimney. The width of the circle varies with the amount of wood collected, but generally speaking the top of the lump is no taller than 2 meters. This height is necessary as the whole pile must be covered in turf or clay before it is burned and such a height would make the pile unstable under all the added weight. A lump is illustrated in Figure 2 (GeoArch, 2011).

Various sizes of wood were traditionally used in this process as the charcoal was often broken up to be utilized in various applications. However, a majority of the wood used for charcoal in Europe before 1900 came from coppices of various species, but predominately oak, which were trees cut at their base and harvested around a 7-10 year period. This allowed a continuous, predictable crop, which was also of a specific size and thus easy to bundle and transport (GeoArch, 2011).

Figure 2: Photo of a Lump. A German lump before being covered with soil. Circa 1890. (photo by Susan Fefferman, 2007)

At this point, the lump is covered with earth or clay; various methods alternate earth and straw, or thatch, etc. depending on the region and available resources. A space is left over the chimney top to allow air to escape, and several spaces are allowed in the bottoms of the lump to allow air to enter. A fire is then lit in the chimney and once established the chimney is covered with earth as well. This has the effect of having gasses enter and exit along the holes in the bottom of the structure. In effect re-burning the gasses on the way out in a double combustion chamber. Once the pile has burned for several days the wood is converted into charcoal. Tell-tale changes in the color and density of the escaping smoke tells the burners, or colliers, as they are professionally known, that the batch is ready. For example, white smoke indicates that the pile is in fact burning the feedstock and allowing hydrocarbon rich vapors to escape. To the collier this indicates that the fire is either not hot enough, or the batch is too wet. When the smoke changes to clear, the gasses given off in the burn are either being completely combusted or the batch has run out of burnable material. Noticing when this changeover occurs during the course of the burn and the typical length of the burn is the key to the colliers profession (GeoArch, 2011).

The lump was then unburied, allowed to cool, and the charcoal harvested, sorted and sent to its destination. This was a very efficient method of creating charcoal in large quantities, in slow burning (200°C), low temperature batches. However, this method of production does have several drawbacks (GeoArch, 2011):

- Its time consuming.
- Requires constant monitoring, hence the need for professionals
- Requires large amounts of resources
- Creates many of the more insidious types of carbon residue, such as Carbon Black, Soot, Polyaromatic Hydrocarbons, NOx and sulfur oxides (SOx) (Mohan, D.; Pittman, C.U., Jr.; Steele, P.H., 2006).

The implications of the last drawback were unknown to science when this method was popularly employed. This presents a limiting factor as far as carbon sequestration as this method introduces more atmospheric CO_2 than it removes. However, the principal of creating charcoal as a soil amendment is unchanged.

Making Biochar: tera preta and tera mulata

There is continuing debate as to whether the native production of biochar was a deliberate act, or simply the byproduct of native habitation. Several locations in Amazonia (and isolated sites around the world) have thick layers of charcoal buried from the surface up to a meter deep in their soils. These locations are often between 20ha to as much as 350ha in extent. The coverage of this soil is believed to be larger than possible from accidental burial of hearth fires or the residue of slash and burn agriculture. The exact method for creating this form of biochar is not known, but the processes listed above are likely candidates (Glaser, B. Haumaier, L., Guggenberger, G., Zech, W., 2000).

Figure 3: Profile of Amazonian soils. Tera Preta , left, and typical Amazonian Oxisoil right. (Glaser et al., 2000)

As illustrated in Figure 3, adding biochar can have a dramatic influence on the color of the soil. Notice that after the top 20cm the soil color gradually fades from the deep black to the color of the surrounding soil. Although not apparent in this photo plant yields are increased growing in soil with ADE versus soils that are not (Glaser et. al., 2000, 2002, Tryon 1948).

An interesting function of ADE is its ability to regenerate itself when removed from the soil. This has been explored by several researchers and, although some of the data is anecdotal, there is much promise for active management and even marketing of this soil (Somebroek, 1966, 2003; Woods et al., 1999).

Modern Biochar: Slow pyrolysis

Another method was eventually employed when airtight and fireproof containers were created. Essentially a double boiler for wood, this process is both shorter than the traditional direct method, and requires less supervision. However the process does produce less charcoal volume than the traditional method as it is limited by the amount of wood that can be contained in the double boiler.

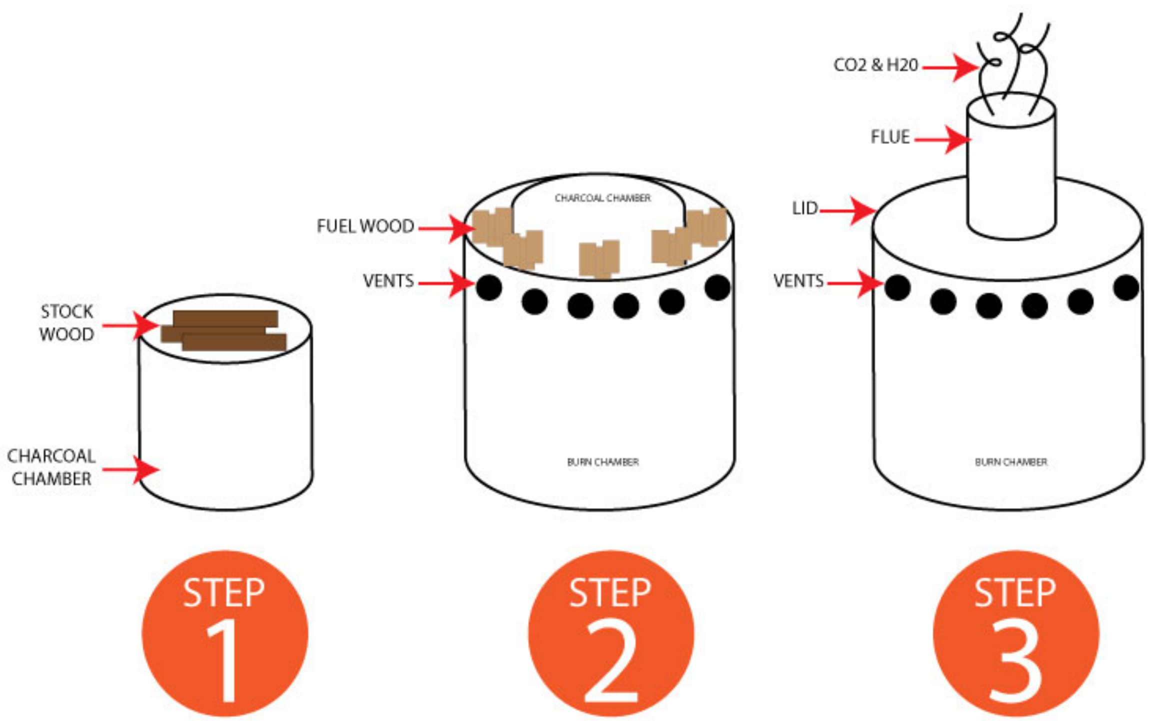


Figure 4: Slow pyrolysis kiln. Slow pyrolysis method for making biochar. Design by Peter Hirst, Illustration by Allie Shaw

The slow pyrolysis method is broken down into three steps as illustrated in Figure 4:

Step 1: Take one large container, steel or similar, and fill it with wood to be converted into charcoal. The top is left open so that gasses may escape without the fear of explosions.

Step 2: A second container is placed over the top of this container. This second container should be larger than the wood container, as this will be filled with stock wood to burn. This larger container, the burn chamber, should also have holes evenly spaced around the circumference of the top, several inches below the rim. These are the vents for the eventual burn process. The charcoal and burn chamber is then flipped over so that the top of the wood container now sits on the lid of the burn chamber. This seal should be tight enough that no oxygen can enter back into the charcoal chamber, but the combustible gasses can leak out of the bottom to be burned in the burning chamber. The space between the two chambers is now filled with fuel stock. An accelerant is sometimes used depending on the need to get the process started quickly. The fuel stock is lit evenly around the container to ensure a consistent burn.

Step 3: Once the burn has become 'fully involved', a lid and flue are added to the top of the container. This lid is needed to invoke the chimney effect, which will mix the gasses with oxygen from the top vents and thoroughly burn the escaping gasses. The gasses feed the burn from the burning chamber, thus allowing the burn to continue with little or no new fuel input, similar to a wick and candle (Hirst, 2009).

Like the direct method, the progress of the indirect burn can be deduced from the color of the escaping smoke. This is not as finely detailed a process as the direct method, and so a collier is not involved. Generally the process is complete after 4 hours and reaching a temperature of almost 1,000°C. The device is allowed to cool and is separated, the charcoal is extracted. Unlike the direct method, this method requires that the charcoal be inoculated before it can be used in soil based applications. The inoculation requires that the charcoal be mixed with equal parts wet soil and allowed to sit for one to two weeks. Since it was not covered in soil as in the direct method, raw charcoal would compete for moisture and nutrients normally in the soil and would represent a net loss for the soil. This is known as the Cation Exchange Capacity (CEC), which is how soils move negative (reactive) ions though water channels, which affects nutrient balance (Cheng, C.H., Lehmann, J., Thies, J.E., Burton, S.D., Engelhard, M.H. 2006, Cheng, C.H.; Lehmann, J., Engelhard, M.H., 2008).

There are many differences in the quality of the biochar produced which are directly based on the temperature of the burn. Structurally speaking, biochar is more stable when it is created at temperatures at around 700°C, as the carbon takes on a more crystalline structure. However, at lower temperatures, 250-400°C, biochar is less susceptible to oxidation. This may be due to a relation between pore size created in the char, as lower temperature pyrolysis creates a more chaotic structure in the carbon, and tighter aromatic chains, thus giving water and oxygen less bonding locations (Amonette and Joseph, 2009). This is a concept called "thermal decomposition" in that the organic matter is decomposed into char, whereas above 700°C the matter is forced into long-tightly packed carbon chains (Lehmann, 2007). Also since feedstocks can vary from site to site, other compounds and metals can be present in different quantities. Chief among these are sulfur, base cations, and heavy metals. All of these impurities can affect how biochar alters the CEC of the surrounding soil.

Modern Biochar: Fast pyrolysis

These methods of making charcoal are very effective in making the soil amendment in very low-tech efficient ways. However, there is obviously loss to the system. One of the common factors between the two processes mentioned above is smoke. While being the indicator for the process, it is also a hydrocarbon rich by-product that literally goes up in smoke. When incompletely burned, as in the direct method, the gas streams off with long-chain hydrocarbons and other carbon compounds. The indirect method burns these gasses to keep the process going, but still releases CO_2, water, and waste heat. In the defense of these two methods, neither has intended the product to be anything more than a soil amendment. (Glaser et al, 2002) What if it was possible to use these waste gases instead of burning them off. Can more than one useful product be made other than just biochar?

Enter the biochar plant. The point of using a pyrolysis plant is to assure that all products of the process are utilized in some form. When wood is heated, combustible gasses are given off. Wood is composed of many more compounds than just carbon. Lignin, hemicellulose, and cellulose make up the physical structure of the wood, and those in turn are made of many polyaromatic hydrocarbons. The chemical nature of these compounds are such that they are composed of many hydrogen-oxygen bonds which, when energized with heat, break, releasing large amounts of energy. When this occurs with low temperatures and without oxygen, these bonds break and form long hydrocarbon chains that are very reactive, and can contain large amounts of particulate carbon (Levi, 1995). When the wood is heated at higher temperatures, these polyaromatic compounds break down even further into molecular and atomic constituents.

The results of the pyrolysis process yields char and syngas. Syngas is combination of combustible hydrocarbon gasses that are a product of the thermal decomposition. As with structure mentioned above, different pyrolysis temperatures yield different amount of gasses. These gasses are listed in the Table 1 below:

	Temperature		
Gas composition (Volume %)	500°C	600°C	800°C
Carbon Dioxide	44.8	31.8	20.6
Carbon Monoxide	33.5	30.5	34.1
Methane	12.4	15.9	13.7
Hydrogen	5.56	16.6	28.6
Ethane	3.03	3.06	0.77
Ethylene	0.45	2.18	2.24

Table 1: Constituent gasses of Syngas based on temperature of pyrolysis method. (Levi, 1995, reprinted table)

Utilizing all of the materials provided during the biochar creation process is an avenue being pursued by several universities and private companies. One of those companies, Pacific Pyrolysis, has even gone so far as to trademark the biochar produced by their process, naming it 'Agrichar' emphasizing its use in the agricultural industry. Agrichar was previously trademarked by BEST Energies Australia, which is now owned by Pacific Pyrolysis. This product is the flagship of the process, but is also produced alongside heat, electricity and syngas, outlined in Figure 5.

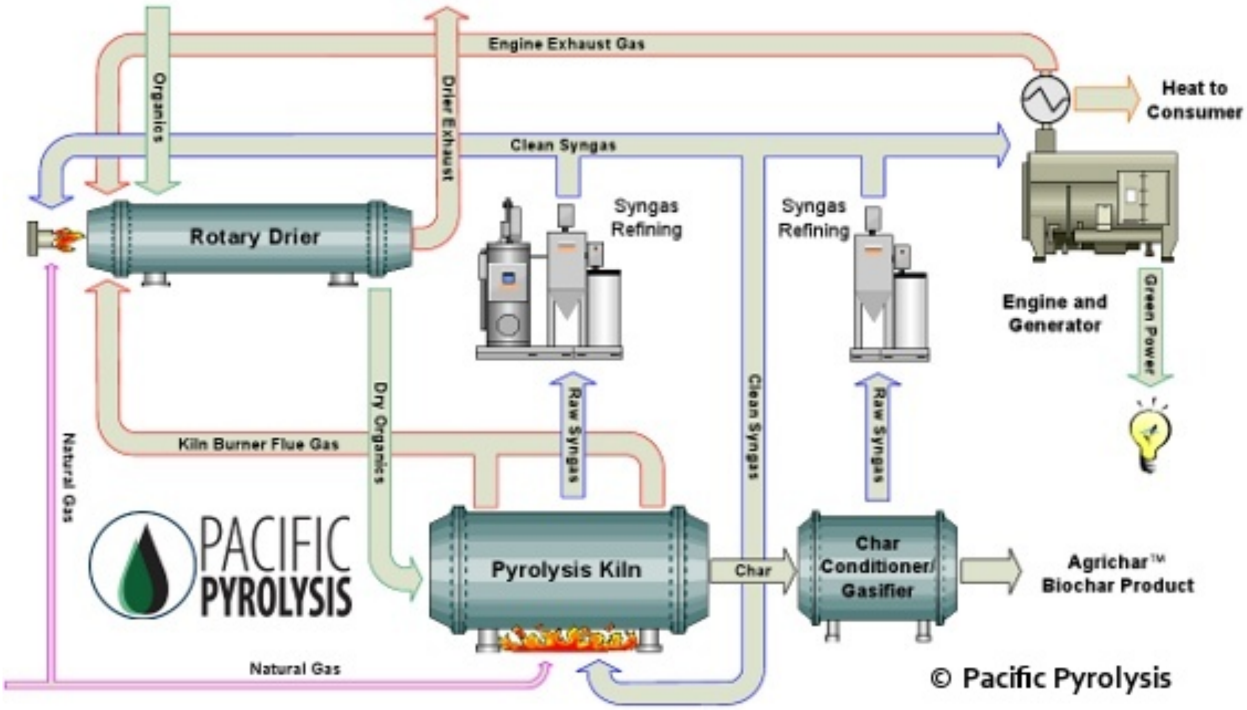


Figure 5: Pacific Pyrolysis setup. This is a simplified functional model of the process.

The process begins with the feedstock being introduced into rotary dryer the container with flames to the left in Figure 5. There the feedstock is dried to remove moisture to 10% by weight (Bridgewater, 2004). After this is accomplished, the material is then moved to the pyrolysis kiln where the action of pyrolysis is done. The gassifier/conditioner then cools the biochar and is a final opportunity to condense syngas (Glaser, 2007). At several stages in this process syngas is given off, some of which is added back into the system to keep if going.

Pacific Pyrolysis claims that their system is completely carbon neutral. This is not a peer-reviewed claim, nor is it used here to be illustrative of carbon neutrality, but rather to show how there are many products being produced than just biochar in this process. This is not a closed loop system as there is a continuous input of methane to keep the process going. This casts some doubt on the true carbon neutrality of this process as there is no data delineating the CO_2 accounting of the process (Pacific Pyrolysis, 2011).

Figure 6: BEST Energies Australia Slow pyrolysis plant. (Pacific Pyrolysis, 2011).

Modern Studies of Biochar

Scientific research into biochar, regardless of production method, began as early as 1948 with a seminal work called "*Effect of charcoal on certain physical, chemical, and biological properties of forest soils*" by E.H. Tryon. While not referencing biochar as a method of carbon sequestration, this was the first work in fairly recent times to mention the use of charcoal as a soil additive. The work intended to study the ability of charcoal to retain moisture in three types of soils: sand, loam, and clay (Tryon, 1948).

This study had interesting revelations on what biochar could accomplish as far as water retention was concerned. Of the three types of soil studied, water retention was increased in sandy and loamy clay, but water retention decreased in clay-like soils. Additionally, pH levels increased in all soil types, except clay, where it decreased (Tryon, 1948).

Biochar has also been shown to decrease the need for NPK fertilizers. This has a tremendous benefit as a majority of the worlds currently farmed soils are becoming increasingly over used and declining in fertility (Rondon, M.A.; Lehmann, J.; Ramirez, J.; Hurtado, M., 2007).

Lastly, biochar has been shown to sequester carbon from the atmosphere and locks it away in a stable form. Sequestration can occur simply as the final product of the last step of the pyrolysis process, where 50% of the standing biomass is converted to charcoal. This charred carbon, when added into the soil, locks that carbon in its physical state of charcoal. This would be analogous to cutting a tree in half and burying it into the ground. However this tree can take hundreds to thousands of years to decay (Masiello et al., 1998; Lehmann and Rondon 2006; Agee, 1996).

Methods

This research paper has been compiled from scientific literature regarding the subject. Whenever possible the latest peer reviewed literature was used as a primary source. No experiments were conducted by this researcher. No case studies or interviews, professional or personal, were used.

This paper utilized two focuses in its research methodology. Research was conducted to understand the historical uses of biochar and how it was created. Then current research in biochar was analyzed with several factors in mind; crop yield improvement, reduction of the use of fertilizer, increasing soil pH and moisture, and sequestering C from the atmosphere.

When needed, this research was guided by two excellent books on research; Kate Turabian's "*A Manual for Writers*" and "*The Craft of Research*" by Wayne C. Booth, et. al. Further guidance was given by the author's teaching staff.

Scientific Literature Review

This project is strictly a research paper. As such the data gathered for this project has been drawn from relevant sources in the available published literature. These sources were obtained using Google Scholar to search for primary sources, as well as the library system for Northern Virginia Community College, Annandale, VA, and the HOLIS online library system for

Harvard University. References gleaned from Google Scholar that contained the JSTOR system of sites were then searched for in the HOLIS system. This was performed to keep all references as free sources for academic scholars. No extra fees or monies were incurred to obtain research materials. Relevant supporting citations were then further explored as they were discovered using the same procedure as outlined above. Finally, the website, youtube.com, was utilized to provide visual confirmation of the process for making biochar on a small scale. This was necessary as finding a person or group that currently makes biochar for educational purposes would have been both cost and time prohibitive. These sources were backed up with relevant primary sources.

Because of the evolving nature of research into biochar, research papers more than twenty years old were avoided as viable sources. This is not because the data is irrelevant or worthless but the terms "global warming" and "carbon sequestration" had not yet made it into the scientific lexicon and a directed approach on the potential uses of biochar for sequestration were not explored. However, one paper in particular; "*Effect of charcoal on certain physical, chemical, and biological properties of forest soils."* by E.H. Tryon was included as this is a frequently cited work in a majority of the primary resources used in this project. Figure 7 below is a flow-chart illustrating the selection process that was used to determine fitness for sources to be used in this paper.

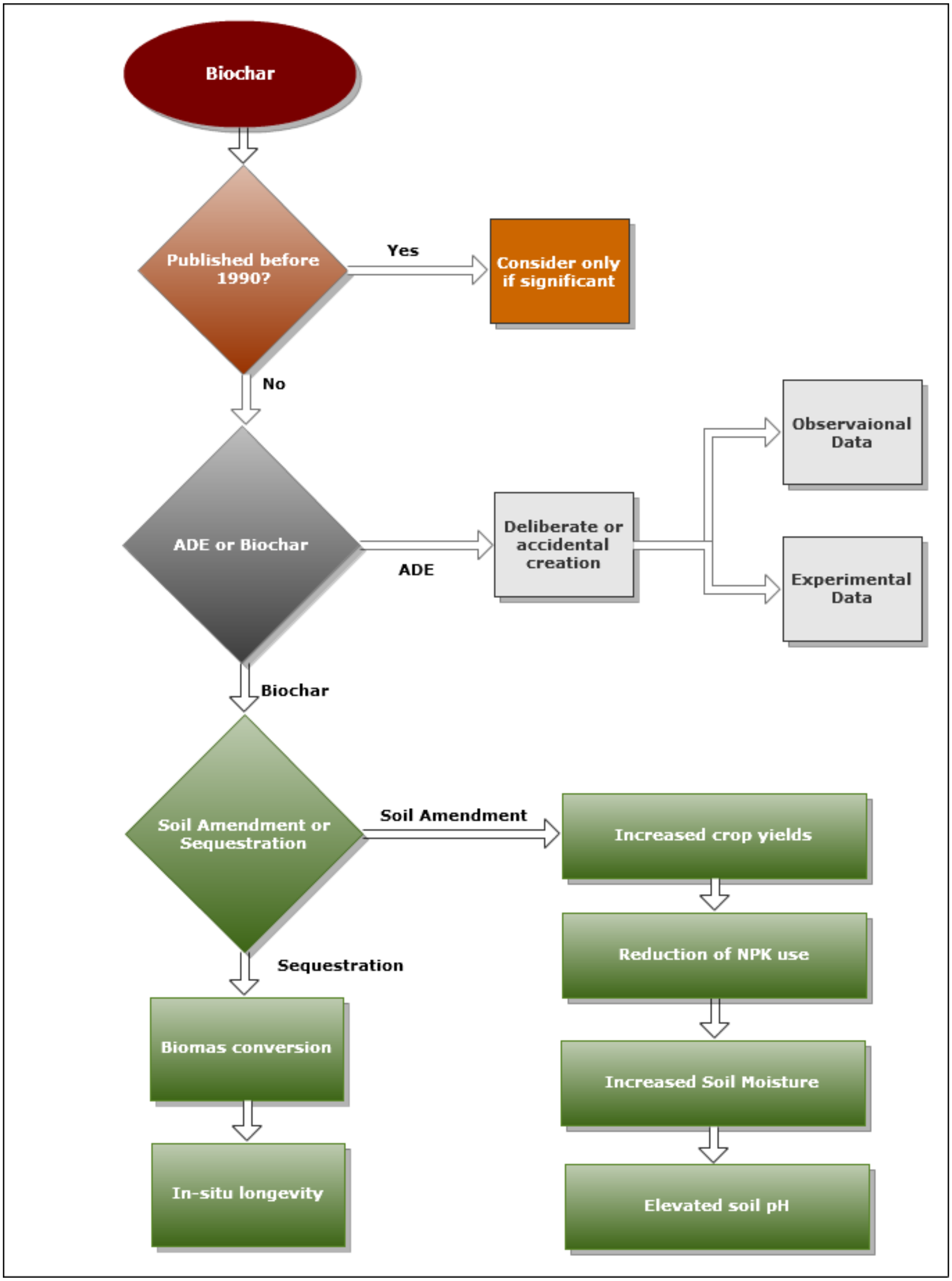


Figure 7: Reference selection flowchart. Flowchart outlining selection process for sources used in this paper.

There has been so much science directed towards global climate change in the past two decades, that there is a good deal of research on the subject pro and con. Whenever possible arguments for and against conclusions and data had been included. As in all good science, there is much debate over some aspects on the use of biochar, these arguments and limitations have been noted in the text. Reference materials came only from peer-reviewed literature or intergovernmental groups for primary sources. Secondary sources came from trade/industry publications such as Popular Science, published books on the subject, etc. Tertiary sources with no citations were avoided as this level of reporting introduces editorial bias on a much larger scale and contains less usable data.

ADE is similar both structurally and physically to biochar which is made in the lab though the process of pyrolysis. However, there are differences when biochar is produced in a "fast pyrolysis" process as it uses a much higher temperature than "slow pyrolysis" which is the production terminology of native methods (Downie, A., Crosky, A, and Munroe, P. , 2009). Relevant literature was analyzed to examine any differences and qualitatively discern if one method of production was more efficient than the other. Analysis was conducted to separate the effectiveness of ADE, from other aspects of fertilization not yet realized or studied. Sequestration and fertilization rates for field tested, industrially produced biochar, was analyzed versus control fields and yields.

Limiting Factors

In a research paper such as this aspects of numerous disciplines come into play. This multidisciplinary approach leads to significant amounts of data and analysis that is just not possible to explore in a paper of this relatively small scope. Sections of data and complete avenues of research would have to be abandoned or truncated in the interest of time. These limitations are enumerated here.

Testing methods were not consistent across all possible testing sites. ADE was studied more from an observational standpoint rather than a reproducible experiment. However, modern biochar was mostly tested in temperate environments with reproducible methodologies. One to one parity of analysis was therefore not conducted. This leads to some of the conclusions drawn, for utilizing biochar in temperate as well as tropical environments, as logical extrapolations instead of concrete comparisons.

Where biochar was tested in the field, there was an observed tendency to test it in tropical environment. This appears to occur because of the need to be close to native reserves as a control. As such there is limited data on biochar being utilized similarly to ADE in non-tropical environments. Some other limiting factors were that studies rarely attempted to ascertain all aspects of the use of biochar at the same time. For example, in only one study (Glaser et al., 2002) was the study of biochar as a soil amendment and crop enhancer coupled with its effectiveness as a carbon sequestration tool. Although this is no fault of the researchers as the two approaches physically are means to different ends.

Many of the sources on the creation of small scale and 'traditional' biochar are not scientifically reviewed literature. Although the process has been well documented and illustrated many times and with varying methods readily available on the internet, no scientific literature on the exact method for producing this form of biochar has been found by this researcher. This interjects a large amount of variability into the data that would support the ease and return on investment of small-scale, in-situ forms of biochar production such as 'slash and char'. Larger scale "mobile" forms of biochar have been studied and observed. However those forms are several orders of magnitude larger than the simple "steel can with a chimney" configuration employed in truly small-scale methods.

Economic incentives for utilizing biochar vis a vie a-forestation could not be determined as there is no existing carbon market to evaluate performance by. Programs like UNREDD and the Clean Development Mechanism (CDM), created in the Kyoto Protocol, are not ready to analyze the differences as they are concerned more with establishing 'shovel ready' plans, instead of major geo-engineering like biochar would espouse (UNEP, 2009).

Results

Historical usage of biochar: Amazonian Dark Earths

Biochar has been be used by indigenous Amazonian cultures for thousands of years (Sombroek et al., 2003, Woods et al., 1999). This has resulted in many sites scattered about the Amazon Basin containing high concentrations of what is called Anthrosoil, or anthropogenic soil. These locations are shown in Figure 8.

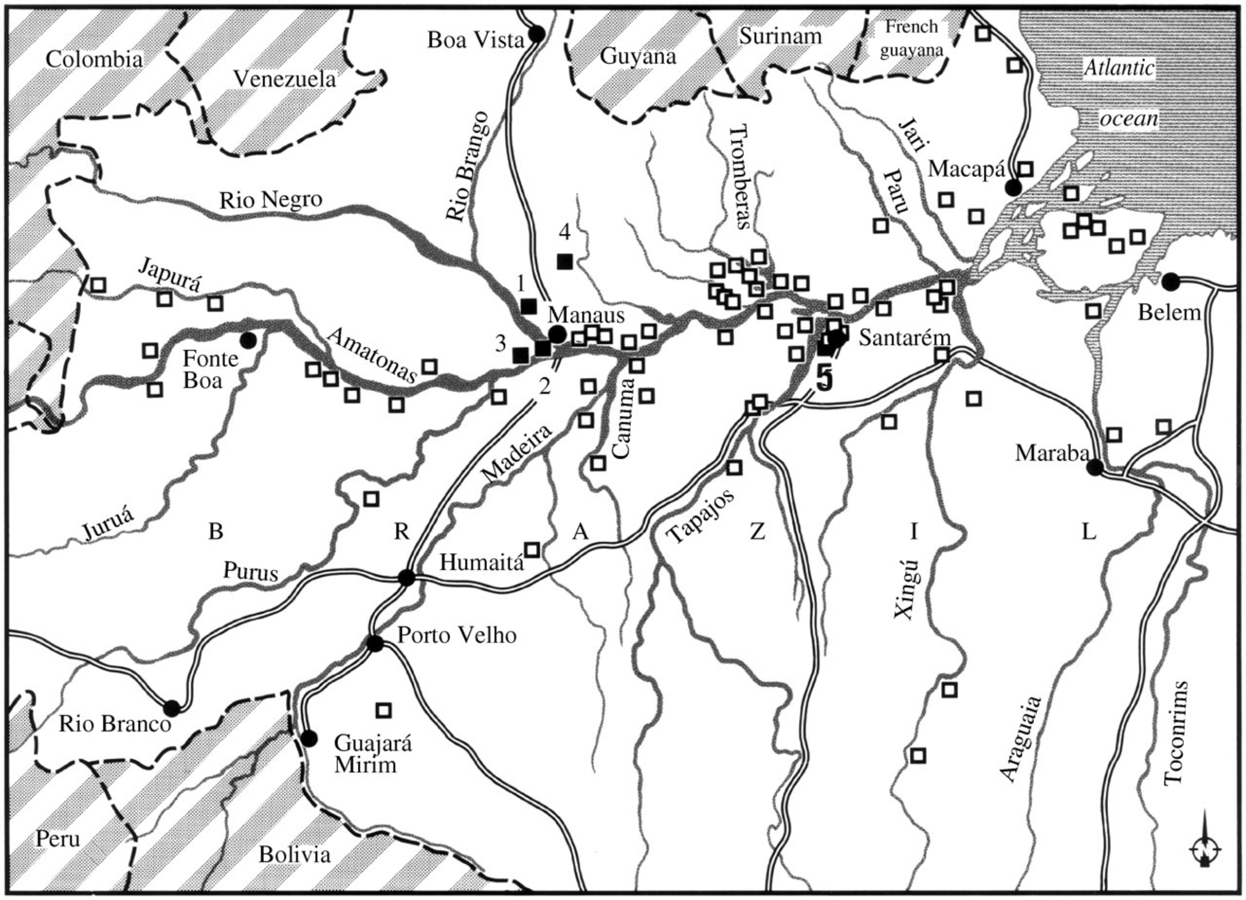
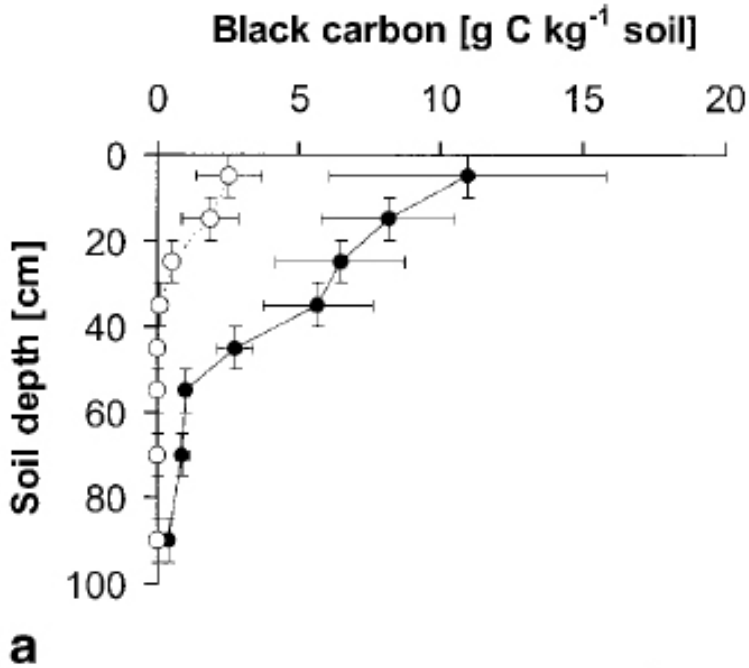


Figure 8: Amazonian Dark Earths and their locations in the Amazon Basin. Black dots represent settlements, hollow squares represent ADE sites, numbered solid squares are settlements that contain ADE. (Glaser, 2007)

All anthropogenic soils are not created equally however, and variations on the nomenclature of the soils are directly related to the amount of C they contain. These soils are named in the colonial Portuguese and are contrasted to naturally made soils. Natural soil, *terra firme,* contains from 80 to 130 Mg C ha^{-1} stored as Soil Organic Carbon (SOC). *Terra firme* SOC concentrations vary with soil types, with sandy soils containing less C and clay-like soils containing more. Generally these upland, non-flooded soils, have little to no evidence of human manipulation. (Sombroek, 1966; Sombroek et al., 2003). ADE contains as much as 250 Mg C

ha^{-1} in layers almost 100cm deep, although the highest density occurs at 40cm (Glaser, 2000).

ADE soil densities are indicated in Figure 9 below.



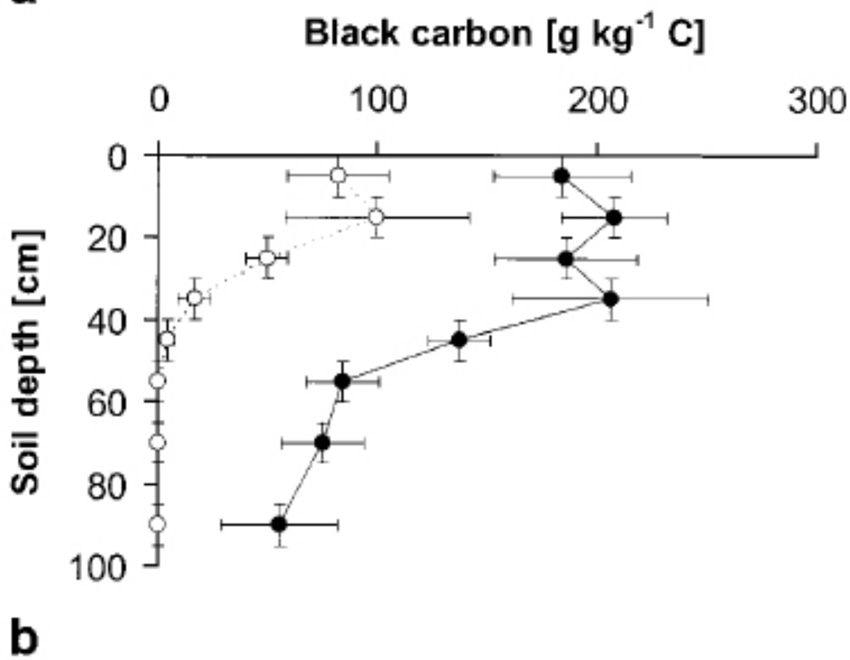


Figure 9: Amount of C stored in ADE soils of Manaus, and Santarém, Brazil. C is denoted by a black dot and the control is a white dot. a is sandy soil and b clay soil. (Glaser, 2000)

In keeping with Sombroek's definition (Sombroek 1966, Woods et al.,1999) TM is brown to black soil that has no indication of human artifacts included in it. TP is black soil that has evidence of human manipulation, including broken pottery, bones, tools, and other human artifacts. Studies by Woods et al, Sombroek, and Neves, et. al. (2004) suggest that the creation of these soils were both deliberate and accidental.

TM, appears to have been created by the buildup of charcoals in the soils around settlements. This buildup has been attributed to brief fallowing, slash and burn, kitchen gardens and possibly runoff and accumulation from larger deposits of anthrisoil (Woods et al., 1999; Seiler and Crotzen, 1980). TP, by contrast appears to be the deliberate buildup of the soil though some form of management. This is accomplished by including refuse from settlements such as household garbage, deliberate burning and burying of waste, even the cremation of the dead (Sombroek 2003). Figure 10 illustrates the basic layout of an Amazonian village, with locations of TP and TM noted.

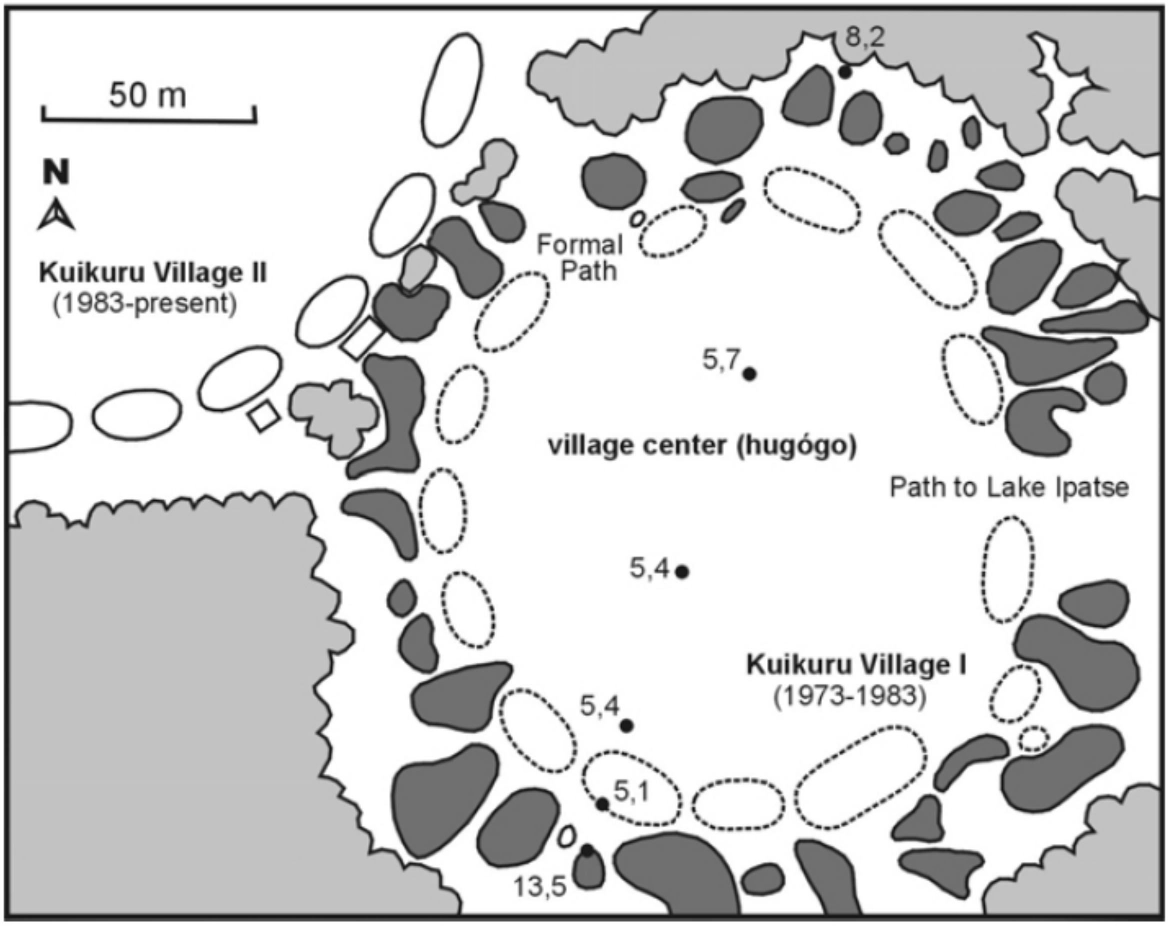


Figure 10: Indigenous village layout in Xingú, Brazil. The dark gray circles indicate areas of high ADE concentrations. Note, no concentrations in the center of the village, where agriculture was not practiced. (Sombroek 2003).

There is great debate whether this was intentional or not, and this debate is called the "midden model" where ADE was unintentionally created by the accumulation of charred remains from households garbage pits, or middens; or was it actively and intentionally managed. There is serious debate over this issue, and that is beyond the scope of this paper. Whatever the origin ADE has had a direct effect on the soils of Amazonia. It should be noted that the addition of biochar alone is not solely responsible for altering the soils fertility (Woods et al., 1999). As noted in Tryon 1948, adding C helps the most in marginal to poor soils that are nutrient deficient. The needed Calcium (Ca), Magnesium (Mg), and NPK had been added by adding the refuse of the village; including bones, human and animal excrement, green manure, and mulch (Glaser, 2007). With these additions, fecundity of ADE areas had improved yields of 0.5–3.8 Mg C ha^{-1}. Sites where ADE was not present yield varied from .3–1.8 Mg C ha^{-1} (Lehmann, J., Gaunt, J. , Rondon, M., 2006). This is almost double the yield of non ADE sites. This variation on yields depends on which crop has been sown, with beans increasing least, and rice increasing most (Lehmann et al. 2006).

Amazonian Dark Earth regeneration

Regardless of the intention of its creation, the most significant aspect of biochar may not be what it was originally created to do, but rather what it does as a secondary process. Biochar "grows"; increasing its ability to sequester C from the atmosphere. This occurs by the process of the charcoal increasing the SOC wherever it is placed with a certain thickness in the soil. This process is outlined in Figure 11 (Sombroek et al., 2003) (Woods et al., 1999).

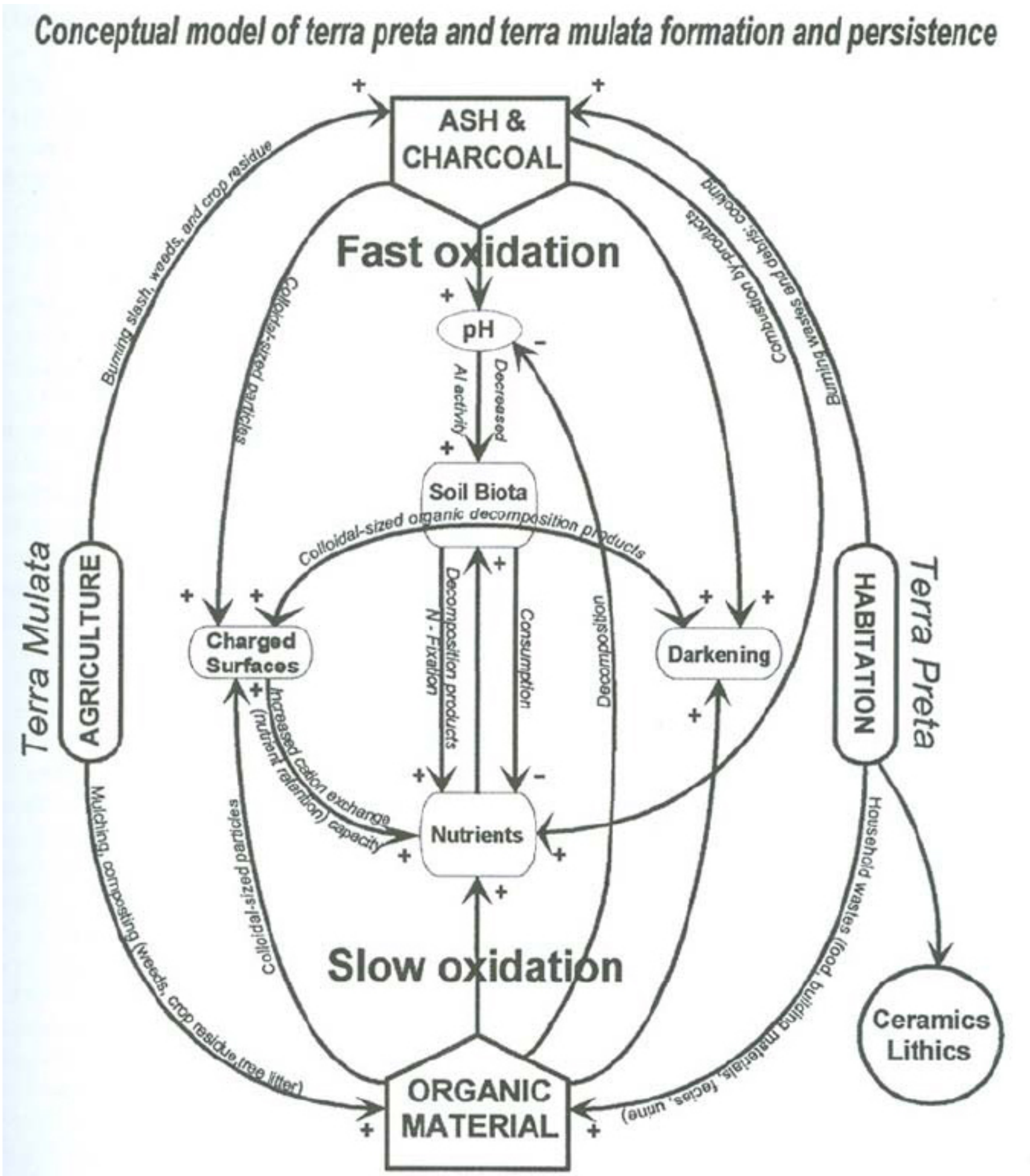


Figure 11: Conceptual model of how ADE regenerates itself. The looping structure of this diagram suggests that ADE need only have a small amount of organic material to perpetuate and grow once a critical mass has been achieved. (Woods et al., 1999)

Because of this relationship crop yields have expanded, have had shorter fallow periods, or have been in continuous cultivation. Woods et al. (1999) have reported of fields near the Arapiuns River of Brazil that have been in continuous cultivation for almost 50 years. The local population also knows when it is time to eventually allow a field to fallow to reclaim all of its lost productivity. There is further, although anecdotal, evidence that suggests that ADE can regenerate itself with as little as a 20cm layer in the ground. Woods et al. speak of ADE being 'mined' for potting soil, and as long as there is a 20cm layer left, given time, what was removed will 'grow back'. This has led to the idea that ADE in many ways beings to act as a sort of skeletal structure for microbes (soil biota in the framework above) with a critical thickness of 20cm. This is an indirect method of carbon sequestration by increasing SOC. This, in turn, may lead to better crop yields.

Biochar increases crop yields

Simply adding any type of charcoal to marginal soil will improve yields, up to 324% for certain crops (Glaser et al., 2002). However, Tryon notes that this is not always the case. His research indicates that adding coniferous based biochar can limit the amount of yield given, and in some ways reduce yields (Tryon, 1948; Glaser et al.). Tryon's data suggests that adding coniferous biochar lowers instead of raising soil pH thus lowering yields. Further, he contends that coniferous biochar can lead to the accumulation of salts in the soil thus further lowering their productivity. Tryon was possibly looking at biochar to increase yields after post-war shortages. In his paper, the sequestering power of carbon was not considered, almost as if it was an inert component.

Indeed, Tryon's data would contradict the notion held by several researchers, Glaser et al. (2002), Warnock, Lehmann, Kuyper, Thomas, and Rillig, (2007) in particular, that biochar can be effective when made from any type of biomass. In fact Glaser et al. compiles a list of various charcoal types and their effect on crop yields, reproduced as Table 2 below. Part of this might simply be that they are not studying the same aspect of using biochar.

Glaser et al. (2002) illustrates in Table 2, adding any type of charcoal will increase yields in almost every soil condition. The largest variables appear to be in soil that is already considered healthy; volcanic ash soil with loam. Soybeans planed in that soil with .5Mg/ha responded well with an 151% increase in biomass. However, increasing the volume of charcoal past that point actually decreased yields. Glaser et al. (2002) attributes this to micro-changes in the overall pH of the soil that affects nutrient transfer in the plants, Kishimoto and Sugiura, (as cited in Glaser et al. 2002) suggests that the use of pine hardwood for feedstock may have been the culprit. This supports Tryon's (1948) data that suggests pine hardwood lowers pH and increases soil salt content.

Treatment	Amendment (Mg ha^{-1})	Biomass production (%)	Plant height (%)	Root biomass (%)	Shoot biomass (%)	Plant type	Soil type	Reference
Control	–	100	100	–	–	Bauhinia wood	Alfisol/Ultisol	Chidumayo (1994)
Charcoal	Unknown	113	124	–	–	Bauhinia wood	Alfisol/Ultisol	
Control	–	100	–	–	–	Soybean	Volcanic ash soil, loam	Kishimoto and Sugiura (1985)
Charcoal	0.5	151	–	–	–	Soybean	Volcanic ash soil, loam	Iswaran et al. (1980)
Charcoal	5.0	63	–	–	–	Soybean	Volcanic ash soil, loam	Kishimoto and Sugiura (1985)
Charcoal	15.0	29	–	–	–	Soybean	Volcanic ash soil, loam	
Control	–	100	–	–	–	Pea	Dehli soil	Iswaran et al. (1980)
Charcoal	0.5	160	–	–	–	Pea	Dehli soil	
Control	–	100	–	–	–	Moong	Dehli soil	
Charcoal	0.5	122	–	–	–	Moong	Dehli soil	
Control	–	100	–	100	–	Cowpea	Xanthic Ferralsol	Glaser et al. (2002a, 2002b)
Charcoal	33.6	127	–	–	–	Oats	Sand	
Charcoal	67.2	120	–	–	–	Rice	Xanthic Ferralsol	
Charcoal	67.2	150	–	140	–	Cowpea	Xanthic Ferralsol	
Charcoal	135.2	200	–	190	–	Cowpea	Xanthic Ferralsol	
Control	–	100	100	100	100	Maize	Alfisol	Mbagwu and Piccolo (1997)
Coal humic acid	0.2	118	114	122	114	Maize	Alfisol	
Coal humic acid	2.0	176	145	186	166	Maize	Alfisol	
Coal humic acid	20.0	132	125	144	120	Maize	Alfisol	
Control	–	100	100	100	100	Maize	Inceptisol	
Coal humic acid	0.2	125	119	122	127	Maize	Inceptisol	
Coal humic acid	2.0	186	148	198	173	Maize	Inceptisol	
Coal humic acid	20.0	139	131	147	130	Maize	Inceptisol	
Control	–	100	100	100	–	Sugi trees	Clay loam	Kishimoto and Sugiura (1985)
Wood charcoal	0.5	249	126	130	–	Sugi trees	Clay loam	
Bark charcoal	0.5	324	132	115	–	Sugi trees	Clay loam	
Activated charcoal	0.5	244	135	136	–	Sugi trees	Clay loam	

Table 2: Crop yields from various inputs of charcoal types. (From Glaser et. al. 2002).

One limiting factor of the crop yields conducted by all the researchers in this series is that these studies were conducted in the humid tropics. An area with poor soils to be sure, but also with very complex nutrient cycling. Similar results in temperate poor soils with temperate species may not produce the same results. Although not stated, there may also be an advantage to using biochar in areas where ADE is currently cultivated. There is a fair amount of local knowledge that researchers can derive, which would either be lacking or completely absent in temperate locations. There are a few studies of biochar and crop yields in temperate areas, but all of these include the use of NPK fertilizers.

Biochar reduces the need for Nitrogen-Phosphorous-Potassium fertilizers

When applied to the soil, biochar radically changes the nutrient uptake by plants from the soil. Three factors may play a role in this ability:

- N immobilization is higher thus retaining it longer fro plants to effectively utilize. This is evidenced in ADE locations (Glaser et. al. 2002).
- Higher pH allowing cation exchange to happen more readily (Tryon, 1948).
- Biochar's distinctive structure allowing mycorrhizal fungi to infect plant roots more effectively (Saito M. and Marumoto T., 2002).

As noted in the previous section concerning crop yields, adding too much biochar to a particular test plot has been shown to reduce the amount of nutrient uptake. As the data in Figure 13 indicates, at concentrations of more than 60 g/kg of biochar to soil *Phaseolus vulgaris* L. begins to decline in its ability to fix nutrients. Possibly the leaf area and shoot to root ratio of the test species cannot continue increasing exponentially, thus interrupting the Biological Nitrogen Fixation (BNF) cycle (Figure 13). Mycorrhizal fungi however, continued to infect the root systems of the test plants. This lends credence to the idea that the limitation of the plants itself led to the decline in nutrient uptake and not external elements. (Rondon et. al. 2007).

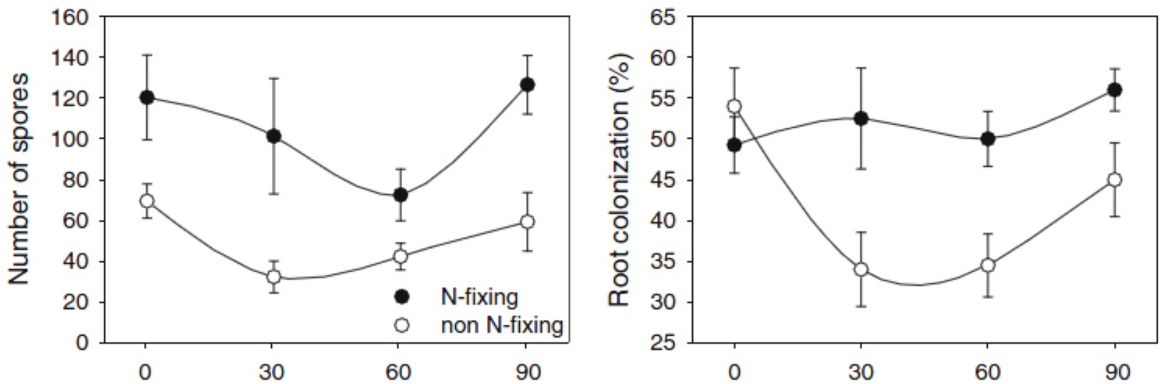


Figure 12: Mycorrhizal fungi responds to biochar. Number of spores and percentage of root infection of two types of *Phaseolus vulgaris* L. Two varieties of the species, N fixing and not, were tested. (from Rondon et. al. 2007)

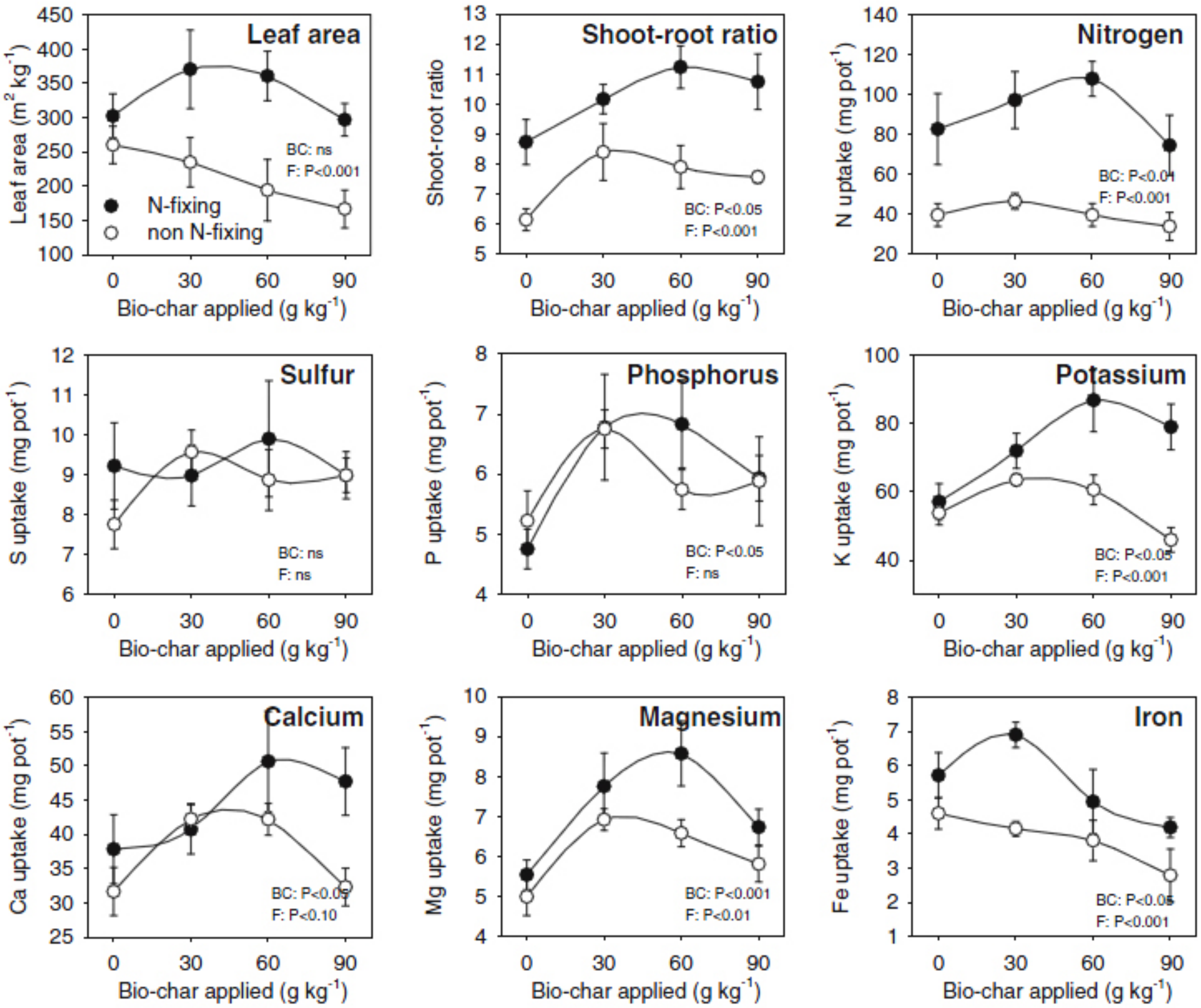


Figure 13: Biological Nitrogen Fixation (BNF) cycle illustrated. Increases in plant size ratios and nutrient uptake by *Phaseolus vulgaris* L when biochar is added to the soil. Units are grams of biochar per kilograms of soil. Two varieties of the species, N fixing and not, were tested. (from Rondon et. al. 2007, datasets removed not illustrating NPK yields.)

Biochar increases moisture levels in soil

It would seem obvious that the addition of so much biochar would affect the physical composition of soil, since charred material in soils rarely happens unless under conditions of forest fires, volcanoes, etc. The addition of non-naturally occurring SOM can have dramatic consequences for basic soil structure as well as moisture retention.

Tryon (1948) notes that different sized particles of charcoal were responsible for nutrient availability, but interestingly the moisture retention depended on both the size of the particles as well as the feedstock material. Further, Tryon was surprised that conifer particles retained more moisture at larger sizes than hardwood particles. This was almost contradictory to his earlier results that stated conifer feedstock was useless as a soil amendment.

	Size of Charcoal	
Type of Charcoal	<1mm	2-5mm
Hardwood	12.88	10.67
Conifer	11.64	12.12

Table 3: Sizes of biochar vs. feedstock. Sizes of both types of charcoal and the moisture retention capability measured in a linear relationship. (Reproduced from Tryon, 1948)

Moisture retention was also based as a function of the percentage of charcoal mixed with the soil. Tryon (1948) found, and was later confirmed by Glaser et al. (2002), that the larger the percentage of charcoal to soil, the higher the water retention. Except in clay soils, where there was a significant reduction in moisture retention. Tryon suggests that the charcoal has the ability to impede the moisture retention ability of clay by altering its hygroscopic coefficient, which is the amount of water left in soils after capillary action is eliminated. Glaser et al. does not observe the same results and states that the addition of charcoal did not significantly alter the moisture of loamy soil. The breaking up of finely grained soil by charcoal apparently allows water to flow more readily out of the soil, reducing its moisture content.

Size of Charcoal	% Charcoal (sand)			% Charcoal (loam)			% Charcoal (clay)		
	10	30	45	10	30	45	10	30	45
<1mm	10.94	12.14	13.7	2.54	2.61	2.97	29.78	28.05	27.83
2-5mm	10.71	11.4	12.08	2.3	2.35	2.44	29.66	27.35	25.22

Table 4: Compilation of moisture data for Tryon's observations. Note the decrease in clay moisture independent of the charcoal size. (Reproduced from Tryon, 1948)

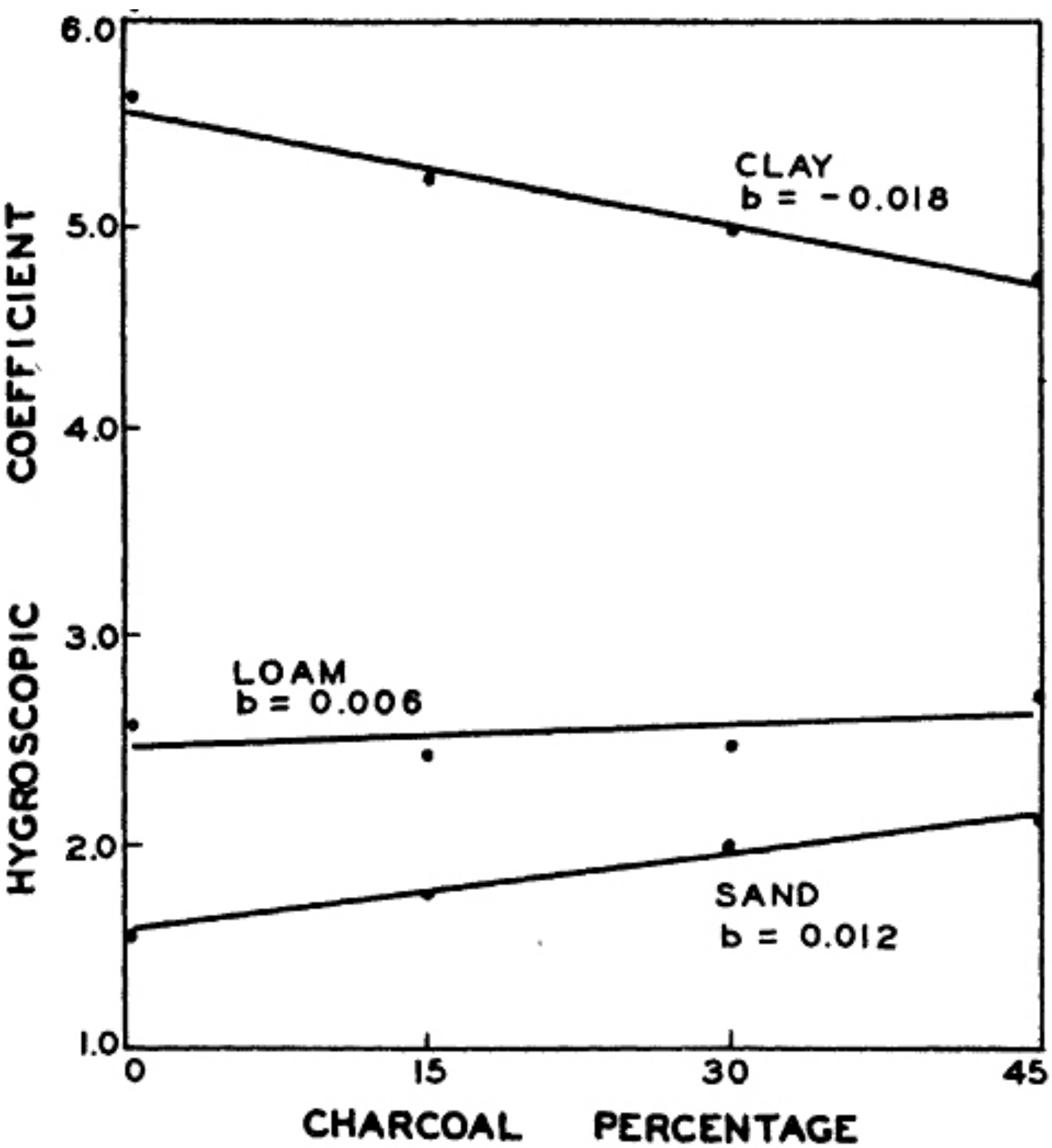


Figure 14: Hygroscopic coefficient of biochar in soils. Linear regressions of the hygroscopic coefficient for the 3 soil types and their charcoal percentages. Note these lines include controls groups not represented in the data table. (From Tryon, 1948.)

Biochar raises the pH of the soil

Several studies have noted the ability of charcoal to raise the pH of soils. Tryon, again, goes into great length describing its effects, and in-turn, he references other works going as far back as 1914 (Tryon, 1948). Those articles have not been included here per the decision outlined in the methods section to set Tryon as the earliest work cited. Tryon's work is distinguished for being the basis of so many other pieces of work detailing pH and nutrient levels from biochar. Glaser et al. (2002) reinforces Tryon's assertion that not all feedstock is created equally. Specifically Tryon states that conifer biomass tends to not raise pH as high as hardwood feedstock, as illustrated in Table 5.

	Type of Charcoal	
Soil	Hardwood	Conifer
loam and clay	6.14	5.42
sand	6.17	5.83

Table 5: Average of type of soil vs. pH values separated by biochar feedstock. Not noted in this table is he control value of 5.15. (Reproduced from Tryon, 1948)

Tryon (1948) states that the pH change in a soil is directly related to the size of particles of charcoal used, and there relative abundances in the sample. Charcoal sizes below 1mm raise the pH of surrounding soils more than larger particles.

	Size of Charcoal	
Soil	< 1mm	2-5 mm
loam and clay	6.2	5.36
sand	6.23	5.76

Table 6: Average of type of soil vs. pH values separated by biochar particle size. Not noted in this table is he control value of 5.15. (Reproduced from Tryon, 1948)

It would then stand to reason that there is a relationship between both the size of the particles as well as their constituent feedstock. This draws several conclusions; adding biochar to loam and sand has a greater effect than to clay, hardwood charcoal is more effective than conifer charcoal, and fine charcoal is more effective than coarse charcoal. (Tryon, 1948)

	Size of Charcoal	
Type of Charcoal	< 1mm	2-5 mm
Hardwood	6.63	5.76
Conifer	5.79	5.32

Table 7: pH levels with type of charcoal vs. size. (Reproduced from Tryon, 1948)

Finally, percentage of charcoal mixed into test soils has a linear relationship to the amount that acids are buffered. The higher the percentage, the higher pH is raised. This data is illustrated clearly in Tryon's (1948) graph on the relationship, Figure 15.

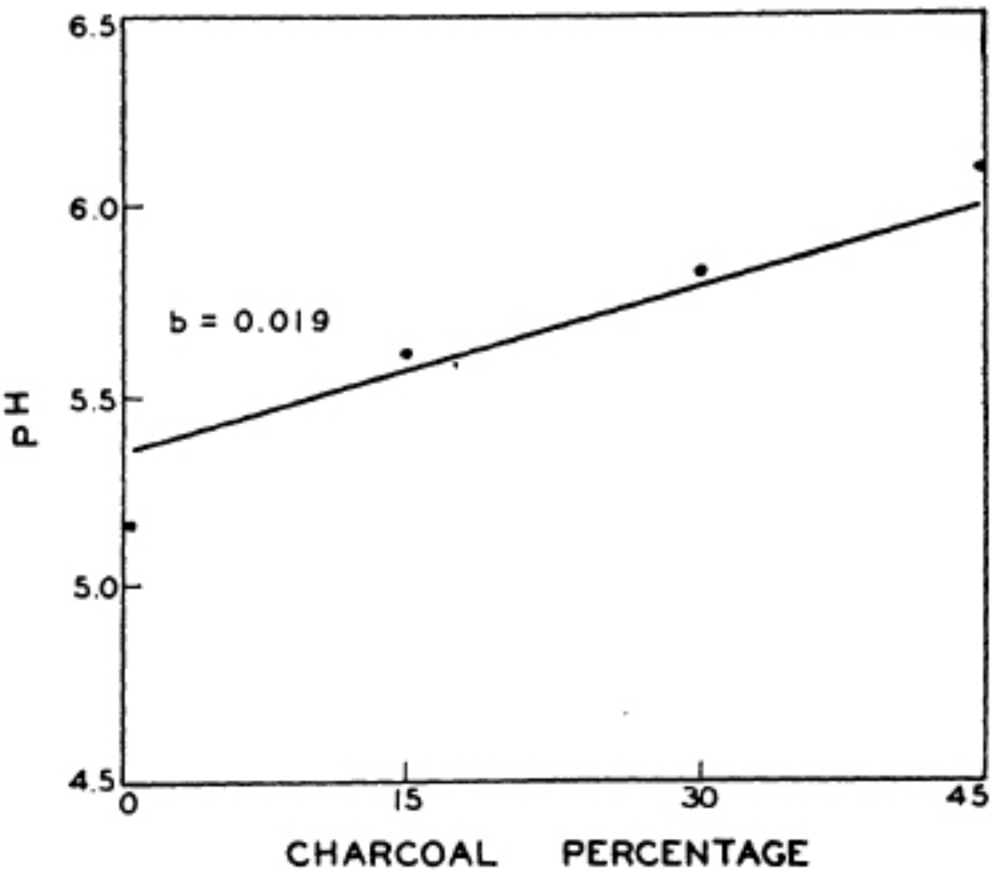


Figure 15: pH levels as a function of percentage of charcoal. A statistically significant linear relationship exists. Note this line includes a control group not represented in the data table. (From Tryon, 1948)

One noted limitation of the Tryon data is that sand and loam were mixed together to get the results noted for pH. However, in his work for soil moisture, the three types of soil are studied independently (Tryon, 1948). This leads to ambiguity as to the true pH when biochar is applied to simply sandy soil. Several of Tryon's adherents Glaser et al. (2002) and Lehmann et al. (2006) mention that biochar works better with the addition of fertilizer, and this might be having a halo effect on pH levels.

Conversion of biomass to biochar

Growing forests has been considered a viable avenue for long term C sequestration (IPCC, 2007). However, this is unstable since a forest can burn down, or for whatever reason stakeholders decide not to use it for sequestration after a period of time (Woods et al., 1999). This would therefore negate all the benefits of such aforestation, or the regrowth of a forest, in opposition of de-forestation. Biochar maybe a stable method for locking away C for great lengths of time (IPCC, 2007).

Biomass to biochar conversion generates about 50% biochar as opposed to simply slash and burn agriculture which converts only 3% biomass to C. Further, simply protecting a forest and allowing natural sequestration to take place only sequesters less than 20% of the standing biomass after 10 years (Lehmann, et. al. 2006).

Conversion of standing biomass does allow for the other 50% of the remaining biomass to be released as CO_2 and other gasses into the atmosphere. Although this seems like a great deal of CO_2 traditional slash and burn converts and releases between 38-84% of its biomass as CO_2 (Hughes, et. al. 2000).

In their 2006 paper Lehmann, et. al. were generally concerned with 'in-situ' biochar; ie portable kilns brought onsite to slash and burn operations in the tropics. Lehmann et. al. (2002) earlier coined the term slash-and-char for this type of operation. Referencing fairly complicated calculations provided by Lehmann et al. (2006) have surmised that as much as 12% of human land-use emissions would be recovered from slash-and-char procedures on a 5-25 year fallow rotation.

A great deal of the stability of biochar as a C sink comes from the temperature at which the conversion takes place (Lehmann et al., 2006). The critical temperature appears to be at 400°C, this can be regarded as a fairly low temperature comparable to low temperature pyrolysis described in the Background section of this paper. (Hirsh, 2009) Oxidation was observed to be slower for biochars produced between 250-400°C, even though charcoal is more structurally stable when produced above 700°C (Nishimiya, K., Hata, T., Imamura, Y., Ishihara, S., 1998).

Although no long-term studies have been conducted on the permanence of biochar C, studies of C buried in deep sea sediments have dates going back further than 13,900 years (Masiello et al., 1998). One caveat is that deep-sea sediments are relatively stable compared to terrestrial environments, and more data would be needed to ascertain comparable time scales.

Byproducts of pyrolysis; syngas and bio-oil

Apart from the many aspects of biochar such as soil augmentation and carbon sequestration, biochar also can create a renewable energy resource that is carbon negative (Lehmann, 2007). Syngas and bio-oil can be created from the biochar feedstock as well as the solid form of biochar. These useful products are created when time and temperature in the pyrolysis plant has been changed (Sohi, S., Lopez-Capel, E., Krull, E., Bol R., 2009). These co-products are outlined in Table 8.

Process	Liquid (bio-oil)	Solid (biochar)	Gas (syngas)
FAST PYROLYSIS Moderate temperature (~500 °C) Short hot vapour residence time (<2s)	75% (25% water)	12%	13%
INTERMEDIATE PYROLYSIS Low-moderate temperature, Moderate hot vapour residence time	50% (50% water)	25%	25%
SLOW PYROLYSIS Low-moderate temperature, Long residence time	30% (70% water)	35%	35%
GASIFICATION high temperature (>800 °C) Long vapour residence time	5% tar 5% water	10%	85%

Table 8: Various byproducts of pyrolysis. Outcomes are a function of temperature and time allowed for vapor to remain in pyrolysis chamber. These are generalized values for average available feedstock (from Demirbas, 2006).

Further, products of these processes vary dependent on the feedstock that they use. Generally speaking, the higher the lignin content of the plant stock, the more syngas and biochar is created. Conversely, the more non-plant based material, the more bio-oil is produced. Under the slow pyrolysis regime outlined above, the maximal biochar to bio-oil ratio is about 37% lignin content by volume as illustrated in Figure 16 (Demirbas, 2001). With time, temperature, and feedstock as variables, almost any percentage of useable products can be created given the resources to manufacture the products. However, there is no maximal point for all three products created in this regime.

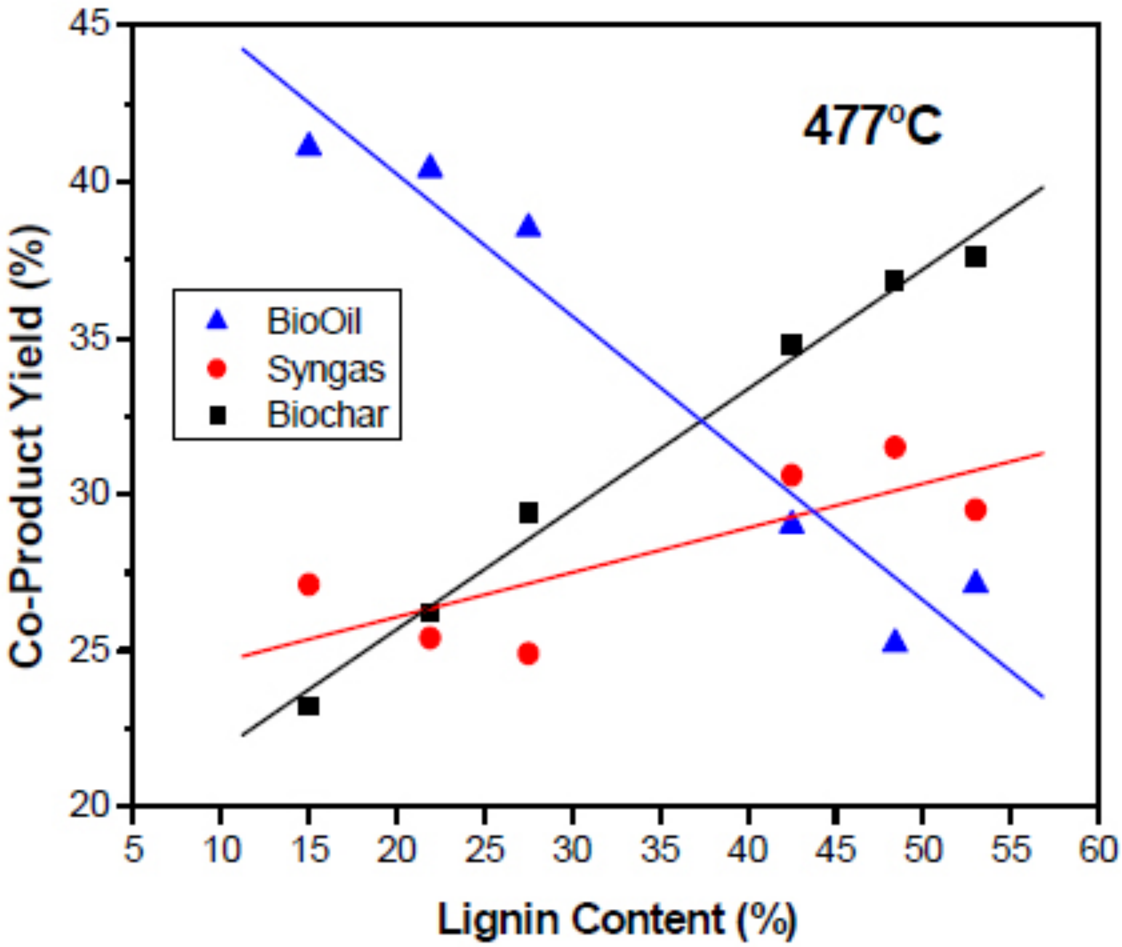


Figure 16: biochar and bio-oil quantities produced in slow pyrolysis trials. (from Demirbas, 2001).

Graber and Hadas (2009) have taken the idea that anything organic can be converted into a useable bio product a step further. Using data from Demirbas (2001, 2006) they have concluded the co-products of slow pyrolysis of various feedstocks. However, the comparison is somewhat out of context as Demirbras' research deals mostly with agricultural feedstocks. These outcomes are enumerated in Table 9.

Waste	Lignin Content (%)	Biochar (%)	Bio-oil (%)	Syngas (%)
Orchard wastes	19	25	41	26
Greenhouse wastes	14	23	43	25
Open pasture wastes	14	23	43	25
Animal wastes	…	60	35	7
Sewage sludge	…	60	35	7
Municipal wastes	…	60	35	7
Forestry wastes	30	30	36	27
Roadside wastes	28	29	37	27
Yard waste	15	24	43	25
Greenhouse plastic wastes	0	0	65	32

Ash makes up the remainder to 100%.

Table 9: Constituent co-products from slow pyrolysis on various organic materials. (from Graber et al., 2009)

It should be noted that these percentages vary based on feedstock and process, and that similar results are not possible at all locations and under all regimes. Localized experiments and co-products were not included as that would be out of the scope of this paper. Much more research would need to be conducted in various locations to give a specific outcomes of various processes. These myriad products are enumerated in Figure 17 and represent a small amount of possible co-products. This diagram is not considered exhaustive.

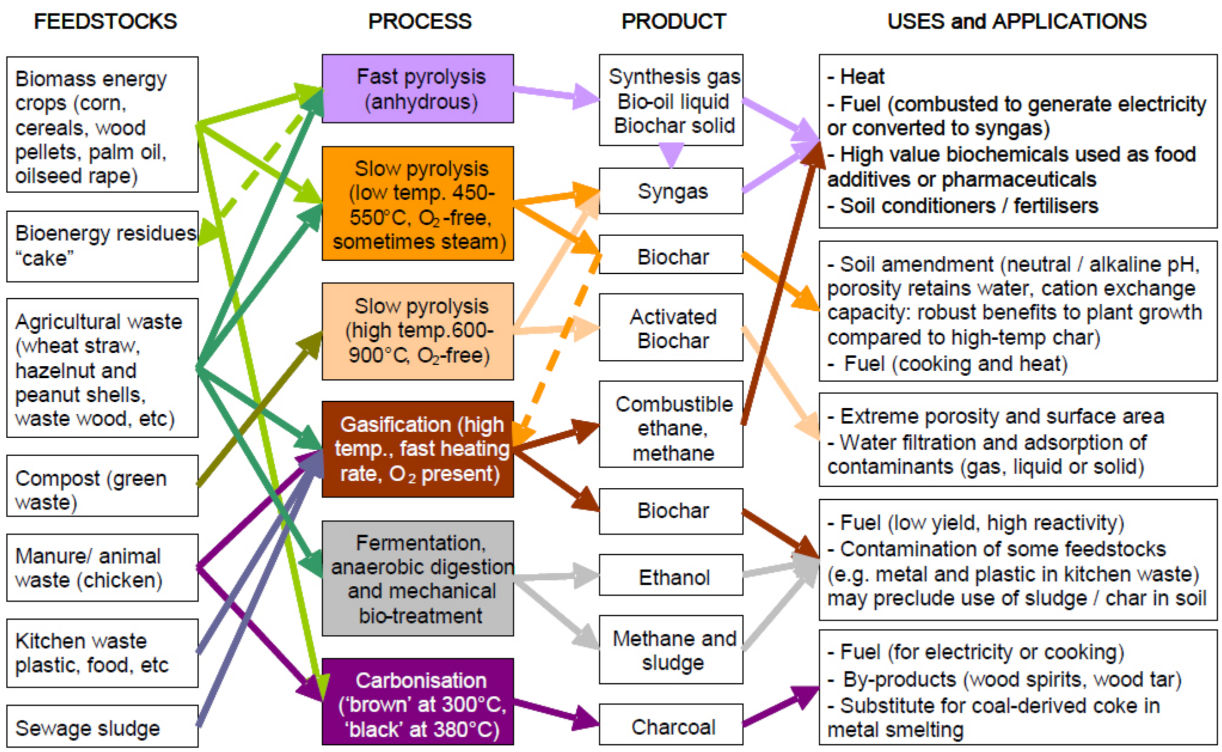


Figure 17: Pyrolysis regimes, their feedstock, and co-products. (from Sohi et. al. 2009)

Discussion

The 21st century will be one of radical change from the centuries that have come before. Never in the history of mankind have we been able to totally alter our environment. Through our ignorance and mismanagement, we have put our planet in danger. Global climate change is not simply another flag to be waved by eager environmentalists. This is not a cause of the same magnitude as "save the whales" or the plight of the spotted owl. This particular dilemma can potentially alter the climate of this planet so that our survival as a civilized species will be threatened. In many ways this threat is more dangerous than nuclear war was perceived to be at the height of the cold war. In that sense it was quite easy to ascertain the threats to our existence; nuclear weapons possessed by both sides of the conflict. These threats were external to our survival; weapons don't make food, house the homeless or provide energy. Global climate change is directly related to how our species conducts its daily business. Industrialization has allowed out species to conquer every corner of the globe. Private corporations are now reaching out toward other planets in the solar system. Our population has just reached 7 billion. All of this has been made possible by one thing: fossil fuels. These fuels emit greenhouse gases when utilized, and those are direct contributors to global climate change.

There are many aspects of taming the beast that is global climate change. One of the simplest ways of dealing with the problem is to stop emitting carbon dioxide altogether. While simple in concept, in practice this will prove exceptionally difficult. Regardless of the difficulties inherent in this process, there still lies a problem in reducing the carbon dioxide already present in the atmosphere. Doing so is not possible with public awareness and a catchy slogan like "reduce, reuse and recycle". A very volatile gas must be removed from the atmosphere, and in large amounts.

Removing excess carbon from the atmosphere is a process called "geo-engineering" or the deliberate act of modifying some aspect of the planet to achieve some aim. In a way we have been practicing geo-engineering since the beginning of the industrial revolution, only it was unintentional and not as apparent as soot or blackened skies. Now that we are aware of it, it seems fitting that we can reverse the process to begin cleaning up the mess. This can be accomplished with biochar.

It has been speculated (Mann, 2005; Glaser 2007; Heckenberger et. al. 2007) that Amazonian cultures were much larger before The Conquest, and that these cultures collapsed because of the upheaval of their civilizations. Further, these cultures supported extremely large and dense population centers despite their very marginal soils. All of is was achieved by the creation of Amazonian Dark Earths (ADE).

ADE in its two forms, *tera perta do indio* and *tera mulatta do indio* (TM and TP respectively) is still in use in some sections of the Amazon basin. These ancient fields have been either in continuous cultivation, or in short fallow rotations for hundreds if not thousands of years. There is debate as to the exact nature of the creation of these soils, but whatever their origin, Glaser (2007) and Lehmann et al. (2006) have shown that crop yields increase in these types of soils. Almost to the point of being double the yields of regular, non-ADE soils. This ability to increase the fecundity of marginal soils is coupled with ADE to actually regenerate itself after removal, given enough of the material is left as a substrate (Glaser et al., 2002). This is achieved by a complex interaction between biochar in the soil and the soil biota that naturally exists in the area. These areas should be protected and utilized only for agriculture and the possible sale of ADE, and then its subsequent regeneration. Once ADE is removed, or of the soil surface is cut off from the environment, the soil eventually reverts back to the local Oxisoils. These soils are the same fragile, nutrient lacking soils that are common throughout the Amazon and the rest of the tropics. Covering or removing the soil destroys hundreds of years of work by indigenous tribes, some completely lost to history, and destroys some of our rich heritage as a species.

Although any type of charcoal can be beneficial to marginal soils, it is important to realize that biochar cannot improve soils that are already fertile. Nor does biochar appear to have much improvement in clay-based soils except to lower its moisture content. Feedstock for biochar is also important as it has effects on the soils, with conifer biochar appearing to reduce fecundity (Tryon, 1948). Thus making biochar from standing biomass in the Taiga regions of the world may actually reduce the fecundity of those soils and lower carbon (C) sequestration by limiting the soil organic matter (SOM) stored therein.

Since the majority of in-field biochar experiments have taken place in the tropics and have shown positive results, it would stand to reason that conversion of standing biomass to biochar would be most productive in the tropical regions of the world. Of course no one would suggest that topical forests be converted en masse to sequester carbon. So much biodiversity would be lost that the cure may end up being worse than the disease. Although a current global level carbon price is not set, and carbon sequestration is currently only considered achievable by leaving standing biomass, a future market may exist here. Companies, governments and Non-

Governmental Originations (NGOs) can offer land owners monies equal to 50% of there biomass as incentives to store carbon. This would allow interested parties to receive carbon credits, and landowners can still convert and use their land for agriculture or grazing. Even better, landowners can allow for their site to be utilized for both C sequestration as biochar, and as standing biomass. This would 'double count' the land set aside for sequestration, and landowners have can receive twice the incentive. Further, this counts as two strategies for Climate Stabilization Wedges, proposed by Princeton University in their Climate Mitigation Initiative (CMI). (CMI, 2011)

When these lands are allowed to revert back to forest or if they are continued to be grazed, at least half of the original biomass would still be locked away instead of 85% or more being instantly converted to carbon dioxide (CO_2) (Warnock et al., 2007). The largest hurdle here would be to find a way to create incentives for the landowner not to sell this plot for building development. This action can include the removal of biochar from the soil during excavation thus removing all the gains created. Some form of in perpetuity agreement must be reached, possibly though the CMI or under the auspices of the Kyoto Protocol. This is an avenue of further research that will no doubt be hotly debated.

Large-scale conversion of forested landscapes (as in converting virgin forest for other uses) to biochar for C sequestration should only be done under controlled situations. When landscapes are converted, only 50% of the stored biomass is converted to char, the other 50% is given off as greenhouse gases. This should not be accomplished simply with portable kilns as would be used in charring refuse. Greenhouse gasses would escape into the atmosphere and, temporarily at least, increase the amount of greenhouse gasses. Biochar for sequestration should be carried out in bioconversion plants that have the capacity to capture the flammable gasses as syngas. This would require fairly large biochar plants to be erected onsite and may not be financially feasible for small operations such as subsistence farming. However, since sequestration efforts are usually carried out on very large scales, there may be enough syngas produced to offset the cost of the transporting the plant onsite. There is not a global market for syngas either at the moment, however in a world looking for renewable energy, a market will not be far off.

The ability of biochar to raise pH should be no surprise. For years activated charcoal has been used to buffer strong acids, purify gases and liquids, and as a buffer in garden soils. Wood ash, by extension, has also been extensively used in agriculture to buffer acidic soils (Bááth and Arnebrant, 1994). Unlike wood ash, biochar can take up to 20 years before it starts degrading and washing out of the soil, wood ash begins to wash out as early as the same season (Nishimiya et al. 1998). As Tryon (1948) points out, pH can be raised by as much as a full point depending on three factors: type of feedstock used, size of feedstock particles, and volume of biochar added to soil. This is a further incentive for farmers to practice slash and char as mentioned above as this will buffer the usually acidic tropical soils. This will have the effect of increasing the potential of the soils to support other forms of agriculture.

World population has just reached 7 billion people, with a majority of those people coming from the developing world (US Census Bureau, 2011). Because the developing world also happens to be the part of the world that has been settled the longest, essentially all of the arable land has long been put to use, and some of that land is heavily degraded. With the advent of the "green revolution" of the 1960's and 70's these lands have been pushed to their limits with the use of artificial Nitrogen-Phosphorus-Potassium (NPK) fertilizers. Over time these lands have been experiencing degradation in productivity due to the constant application of hydrocarbon based fertilizers and pesticides (FAO, 1998). The population had ballooned since that time, and has only recently began to slow down. Coupled with declining birth rates in the developed world, this boils of population will begin to decline by 2050 after possibly hitting a high of 10 billion (US Census Bureau, 2011). In the interim, these people must be fed from soils that are already in decline.

Biochar has been shown to increase the amount of NPK taken up by plants. For certain species of common beans (*Phaseolus vulgaris* L.) this increased fixation can be up to 78% more than in untreated soil. This represents a very cost-effective way for subsistence and even large-scale farmers to increase their yields. Simply adding a 'fallow' season that utilizes a leguminous or nitrogen fixing cover crop, nitrogen (N) and other nutrients can be substantially increased. This reduces the need to utilize external, and sometimes synthetic, NPK based fertilizers (Rondon et. al, 2007).

The solutions discussed here are part of the toolbox of possible solutions to the twin problems of global climate change and declining crop yields. These are not a complete panacea for all of the ills created by global climate change, nor will they work at all times and at all locations. Biochar must be used where it is most effective, and if only for certain aspects if need be. Other greenhouse gas solutions must be utilized in concert with biochar. Only a blended solution will work. When we look at the problems facing the world today, the choice to explore this new technology becomes obvious.

Recommendations

The use of biochar can have multiple affects ranging from sequestering C, to increasing the amount of C stored away in soil organic matter, to increasing crop yields and improving marginal soil. This offers tremendous potential to begin the reversal of global climate change. In light of these assertions, there are several aspects of using this technology that must still be studied further, these are:

1) Further testing of biochar in marginal soils of the temperate sections of the planet.
2) Analyzing the stability of biochar in the terrestrial soils of the world.
3) Determining which feedstock species are appropriate for soils in various locations planet wide.
4) Understanding the interplay between the use of NPK fertilizers and biochar cation exchange. Specifically, what is its about biochar that facilitates cation exchange and how does that reduce the need for fertilizer.
5) More compete understanding the interplay between biochar particles and mycorrhizal fungi.

6) In-depth analysis of possible carbon prices to determine the feasibility of using biochar for carbon credits instead of standing biomass.
7) A complement economic model to convince small/subsistence farmers in the tropics to employ slash and char methods instead of current slash and burn.

The world of the 21st century is one that presents challenges never before faced by mankind. For the first time ever, the global health of the planet has become a very real and impending issue that our very survival as a species hinges upon. Though the use of biochar, mankind can reverse the buildup of anthropogenic CO_2 in our atmosphere and improve marginal soils and crop yields simultaneously. This technology has existed for thousands of years and created extremely large populations from very meager soil. Modern science has shown that the potential exists to produce the same results on a global scale. All that remains is the political will and the foresight to look back into the past to save the future.

Conclusions

Despite the debate in the popular press and around office water coolers, global climate change is a real issue that faces all of humanity. There is as much serious debate as to the best approach to switch to less greenhouse gas producing forms of energy. However there is not much discussion of actually removing excess carbon from the atmosphere. These concepts of geo-engineering should be approached with caution as the ramifications of deliberately changing the atmosphere with new, untested, technologies is fraught with problems.

Biochar exists as an ancient form of geo-engineering that has been in practice, in one form or another, for thousands of years. Its humble beginnings have brought it from a simple soil amendment and kitchen waste disposal, to complex pyrolysis plants creating biochar from agricultural refuse and providing syngas as a "carbon neutral" form of energy.

Biochar is not merely a form of carbon sequestration. It can, in some instances and locations do many more things; dramatically increase crop yields, help fortify marginal soils, increase moisture content, and reduce the need for NPK fertilizers.

The modern use of biochar as carbon sequester and soil enhancer is still in its infancy. Much research still needs to be done in order to completely understand the costs and benefits of using this ancient technology in a modern application. This research may not be done in the short term as governments are currently more occupied with faltering economies than crop yields. However, this technology will eventually need to be employed as part of the multifaceted battle against global climate change.

"When you think you've tried / Every road, every avenue / Take one more look at what you found old / And in it you'll find something new."

—Gore, Martin. One Caress. *Songs of Faith and Devotion*, 1993

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