

Assessing Excess Carbon Emissions and Soil
Toxicity as Unintended Consequences in
Applying Biochar as a Geoengineering
Scheme

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Executive Summary

In the years since the Industrial Revolution, atmospheric carbon dioxide levels have steadily risen, causing an associated increase in global warming. In an attempt to remedy some of the effects caused by global warming, various geoengineering schemes have been put forth as possible solutions in resolving the global warming problem. A large portion of these geoengineering solutions are categorized as carbon sequestration techniques, where the geoengineering schemes vary from injecting liquefied carbon dioxide into the deep ocean or fertilizing the oceans with iron to stimulate phytoplankton growth. The focus of this proposal is on carbon sequestration via biochar burial. Biochar is a form of carbon produced via pyrolysis, or combustion with no oxygen or very little oxygen. The pyrolysis process produces a high-density form of carbon, which can be used to sequester carbon through underground burial. A practical implementation of carbon sequestration via biochar would be to convert decaying plant matter into biochar, rather than to allow natural decay from occurring, which releases carbon contained in the biomass back into the atmosphere.

However, being an extremely new geoengineering method, biochar still needs to be tested for unintended consequences that may surface from its global application as a carbon sequestration technique. Therefore, this proposal identifies and tests for two important unintended consequences: unintentional carbon emissions from biochar production via the use of traditional kilns and soil toxicity affecting crop productivity due to residual hydrocarbon content contained in biochar.

In many parts around the world, farmers produce biochar as a supplemental fertilizer by utilizing traditional kilns often constructed of brick or clay. Although these kilns are inexpensive and easy to construct, there is no way of containing the gaseous pyrolysis byproduct (known as syngas). Syngas is rich in carbon emissions, which then

becomes released into the atmosphere and adds to the existing excess quantities of greenhouse gases already present in the atmosphere. A rigorous experiment needs to be conducted to assess the amount of carbon emissions emitted through biochar production via traditional kilns in order to establish a recommendation for the most eco-friendly method of producing biochar.

Additionally, hydrocarbons are produced naturally during the pyrolysis process, and are released during combustion in the form of liquid, which is often harvested in commercial pyrolysis machines as fuel. However, hydrocarbons may not be completely released from the solid char during pyrolysis, and residual hydrocarbon contained in biochar incorporated into the soil may be detrimental to crop productivity. This poses grave implications since a plot with buried biochar may be rendered unsuitable for cultivation. Globally, this may cause biochar burial to be an impractical method of carbon sequestration, because it is unrealistic to dedicate entire tracts of land around the world for biochar burial only.

At the conclusion of our experiments, we expect traditional kilns to be an impractical method of producing biochar due to the excess carbon emissions produced during combustion. Additionally, we would expect biochar containing low levels of residual hydrocarbon to have the least effect on soil toxicity, which can be measured through crop productivity. Based on these results, we recommend the use of commercial pyrolysis machines in the production of biochar to reduce pollution and optimize for the lowest level of residual hydrocarbon levels in the biochar. By testing for these two unintended consequences, we may then begin to explore the options of implementing biochar as a global carbon sequestration technique.

Introduction to Global Warming, Geoengineering, and the Use of Biochar Burial as a Carbon Sequestration Strategy

Global Warming

“Warming of the climate system is unequivocal, as it is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and increase in mean sea level.” The IPCC (Intergovernmental Panel on Climate Change) issued this dire warning in their 2007 Summary for Policymakers document (IPCC, 2007, p. 4). The interconnected link between these three factors is especially potent: for the last thirty years, the snow cover has been decreasing, while the global sea level increased for nearly 70 years, corresponding with a steady rise in global temperature since 1910 (Figure 1).

A correlation between reduction of glacial length and an increase in temperature is demonstrated in 169 glaciers around the world, regardless of elevation and continent (Oerlemans, 2005). Utilizing TOPEX-Poseidon satellite technology to monitor sea level increases from 1993 through 2003, scientists measured the sea-level increase at 3.1 mm per year, which increased 50% or more over measurements in the previous decades, which averaged around 1 to 2 mm per year (Cazenave and Nerem, 2004). Breaking down the temperature rise further, anthropogenic gases (greenhouse gases such as carbon dioxide) are shown to be the real long-term culprits of the rise in global temperature, over natural forces such as volcanic aerosols and solar radiation (Figure 2).

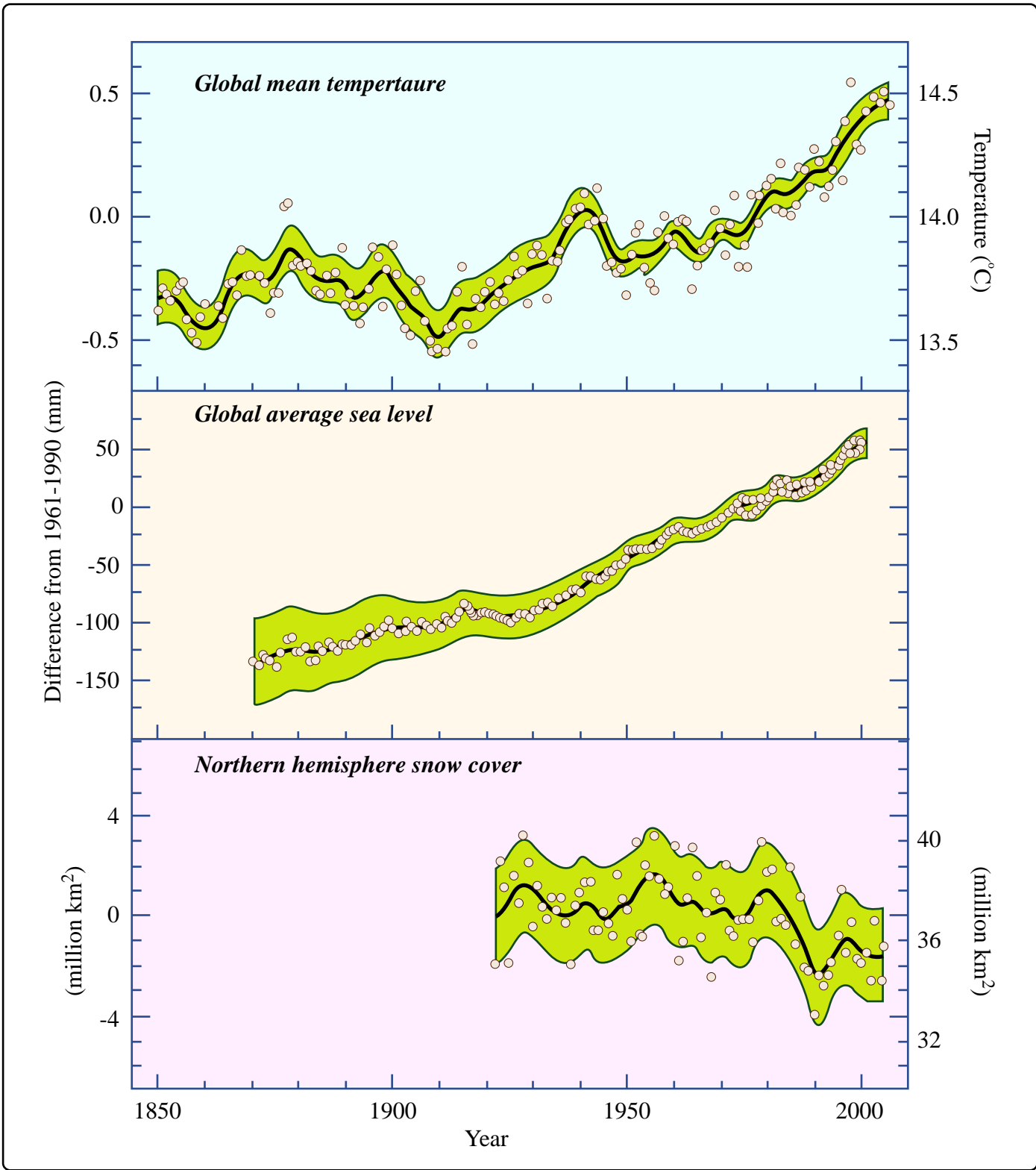


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Figure 1. Observed changes from 1961 to 1990 in (a) global mean temperature, (b) global average sea level, and (c) Northern Hemisphere snow cover. In (a) and (b), we see an increase in global mean temperature and global average sea level, with a corresponding decrease in (c) snow cover in the Northern Hemisphere (IPCC, 2007, p. 17).

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Figure 2. This graph breaks down the contributions of (a) El Niño-Southern Oscillation (ENSO), (b) Volcanic Aerosols, (c) Solar Irradiance, and (d) Anthropogenic Forcing [including greenhouse gases (GHGs), tropospheric aerosols, and land surface and snow albedo components] to monthly mean global temperatures from 1900 to 2000. The right-hand vertical axis shows the actual measurements for each category, while the left-hand axis shows the fluctuations from expected standards (0.0). The gray lines indicate long-term trends from 1900 to 2000, which demonstrates that ENSO and Volcanic Aerosols do not contribute significantly to monthly mean global temperatures, while solar irradiance plays a minor role and anthropogenic forcing plays a major role (Lean and Rind, 2008).

This type of increase in atmospheric carbon dioxide is unprecedented, as demonstrated by ice core sampling from Lake Vostok in Antarctica (Figure 3). When the amplitude of carbon dioxide concentration change is plotted against the time period of

change, we see a sharp rise in carbon dioxide concentrations over the decade-century time range due to human perturbation, while carbon dioxide changes attributed to glacial-interglacial activities exhibit a change in amplitude distributed over a time scale of 10^5 years (Falkowski et al., 2000). Indeed, the global atmospheric carbon dioxide concentration has risen from 280 ppm before the start of the Industrial Revolution (~1750) to 381 ppm in 2006, showing a marked 36% increase (Canadell et al., 2007).

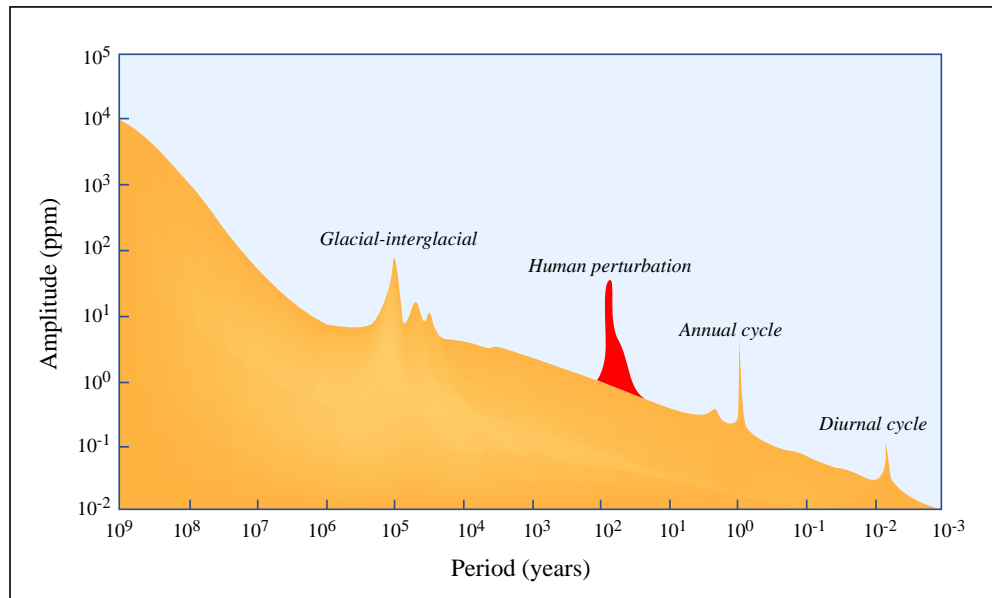


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Figure 3. Carbon dioxide concentration changes in the atmosphere plotted against the time period during which the change occurred, based on Lake Vostok ice core samples. Notice that the marked effects of human perturbation to carbon dioxide concentration occurred on a decade to century scale, while glacial-interglacial changes were distributed over a period of thousands of years (Falkowski et al., 2000).

One major societal implication due to global warming caused by rising carbon dioxide levels that is of significant concern in this century is the disappearance of low-lying island nations due to rising sea levels. Studies have indicated that the entire disappearance of island nations lying a few meters above the ocean surface is highly possible, given the rapid annual melting of polar ice. For example, the island nation of Maldives is extremely vulnerable to the rise in sea levels, with the entire nation lying less

than 5 meters above the sea level (Pelling and Ullito, 2001). With projected global sea-level increases of 3 to 5 meters due to possible future disintegration of Greenland and West Antarctic ice sheets (Dasgupta et al., 2009), the nation of Maldives may be permanently be erased from the face of the Earth should global warming contribute to the melting of these ice reserves.

The rise in global warming also contains ecological implications, such as the poleward migration of fauna and flora, changes in migration season of migratory species, and changes in breeding seasons of animals (Walther et al., 2002). A logical implication of this effect is species extinction, as exhibited by the example of species living on island ecosystems – if the species reach the northern or southern coastline due to a ecosystem shift caused by climate change and there is nowhere else to propagate, the species may simply become extinct.

Geoengineering

Keith (2000) defines the concept of geoengineering as the “intentional large-scale manipulation of the environment, particularly manipulation that is intended to reduce undesired anthropogenic climate change.” In order for schemes to qualify as geoengineering, however, Keith identifies three important elements – scale, intent, and manipulation. An observed result with intent but without scale (ornamental gardening) and scale without intent (carbon dioxide increase in the atmosphere due to industry) cannot qualify as geoengineering schemes. Finally, geoengineering must go further than mitigation. Mitigation techniques, which are not a subset of geoengineering (Wigley, 2006), adjust current practices (lowering carbon dioxide emissions of industrial plants), but do not directly manipulate through introducing new environmental measures. For example, carbon sequestration techniques (adding iron into oceans to stimulate plankton

growth, injection of carbon dioxide into saline aquifers) qualify as geoengineering, while the global reduction of emission levels by power plants can only be categorized as mitigation.

In the 1992 report on greenhouse warming published by the National Academy of Science, reforestation, “sunlight screening” (albedo modification techniques), “ocean biomass stimulation” (ocean fertilization), and removal of atmospheric chlorofluorocarbons are identified as the four subfields under geoengineering. Albedo techniques aim at raising the Earth’s albedo, so sunlight is reflected back into space. The other three techniques aim at reducing the amount of greenhouse gases trapped in the atmosphere, either through sequestration via trees in the forest, photosynthetic plankton, or laser destruction of atmospheric chlorofluorocarbon particles (Committee on Science, Engineering, and Public Policy (U.S.), 1992).

Lal’s (2008) study on sequestration techniques for atmospheric carbon dioxide provides a review of current practices, broadly categorizing methods into three categories: sequestration via aquatic ecosystems, sequestration via terrestrial ecosystems, and geoengineering techniques. Lal adopts a restrictive definition on geoengineering technology, constraining geoengineering to carbon-capture techniques resulting in the injection of the liquefied captured carbon dioxide into geological formations (saline aquifers or basalt) or under the ocean surface. Terrestrial methods discussed include reforestation, ocean fertilization, and sequestration in soil (through conservation cropping or biochar application). Finally, aquatic techniques focus on the improvement of carbon containment in aquatic ecosystems such as wetlands and mangroves (Figure 4).

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Figure 4. The figure graphically presents current methods used in carbon sequestration, broken down into geoengineering schemes and sequestration through aquatic and terrestrial ecosystems. Although Lal does not list biochar burial under a geoengineering scheme, biochar is categorized in this figure to fall under “below ground biomass” under “biota” and “terrestrial ecosystem” (Lal, 2008).

Major challenges underlying geoengineering technologies include cost, feasibility, and unintended consequences. The installation of a space mirror has been suggested as a way to counter global warming by reflecting incoming sunlight back into space, countering global warming. However, current technology does not yet permit this advance and costs are certain to be astronomical. A study indicated that painting every rooftop of the 100 largest metropolitan cities in the world white will trigger an atmospheric effect equivalent to the removal of 40 gigatons of carbon dioxide per year, due the increase in global albedo (Akbari and Menon, 2008). Nonetheless, the feasibility

of this proposal depends on widespread international cooperation, dialogue between national governments, and citizen activism. Finally, although the feasibility of ocean fertilization has been extensively studied, the technology was never implemented on a large scale, due to fear of unintended irreversible damages to the environment (Chisholm et al., 2001; Cullen and Boyd, 2008).

Carbon Sequestration Strategy via Biochar Burial

The introduction of biochar (charcoal or carbon derived from biomass via pyrolysis) to the soil produces a long-term carbon sink in terrestrial ecosystems (Lehmann et al., 2006). Biochar is produced by heating of biomass by pyrolysis, a heating process in the absence of oxygen (or partial combustion in the presence of a small quantity of oxygen) (Bridgwater, 2003).

The discovery of biochar as a possible application to carbon sequestration originated from the dark “terra preta” soils of the Amazonian forest. Researchers discovered that terra preta soils contained up to 2.7 times amount of organic carbon as regular soil, which is attributed to the high black-carbon content (Glaser et al., 2001). Black carbon is generated from the charred residues of biomass after a forest fire and has been speculated as a sink for atmospheric carbon dioxide since 1996 (Kuhlbusch et al. 1996).

In normal photosynthesis, plants remove carbon dioxide from the atmosphere and incorporate the carbon into biomass through photosynthesis. Once the plant degenerates or is burned, however, the carbon is returned to the atmosphere. The premise of using biochar as a sequestration technique rest on the idea that a portion of the carbon from the plant matter is transformed into high-yield carbon matter (biochar) via the pyrolysis process, which can be stored underground and does not contain the

risk of re-release of carbon into the atmosphere. In addition, the energy produced during pyrolysis can be harnessed and recycled as a carbon-neutral form of bioenergy (compare to the burning of fossil fuel, which releases additional carbon into the atmosphere during energy release) (Figure 5).

In general, scientists do not advocate converting existing forests into biochar for the purpose of carbon sequestration. Instead, scientists advocate these three avenues for biochar application: the adoption of “slash-and-char” farming methods, using charcoal waste as biochar, and turning plant refuse into biochar (Lehmann et al., 2006). When clearing fields, traditional farmers often clear the land by removing plant growth and burning it (“slash-and-burn”), allowing unchecked release of carbon dioxide into the air. Through plant material pyrolysis in a standard kiln after removal from the field (“slash-and-char”), 50% of the carbon can be sequestered in biochar, preventing re-release of carbon into the atmosphere (Lehmann et al., 2002). In addition, charcoal waste from cooking and industrial plant waste (from the logging industry or paper mills) can also be transformed into biochar through kilns or pyrolysis processors (Lehmann et al., 2006).

According to the International Biochar Initiative’s estimates, biochar technology can successfully offset a quarter of a gigaton of carbon by the year 2030. Adopting more optimistic estimates through more aggressive methods, human beings may even be able to bring that figure up to one gigaton by 2050 (International Biochar Initiative, 2009).

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Figure 5. The schematic shows the comparison between the standard carbon cycle (0% net carbon withdrawal from the atmosphere) compared with the introduction of biochar for carbon sequestration (20% net carbon withdrawal from the atmosphere). This difference in net carbon withdrawal from the atmosphere demonstrates that biochar may potentially be used as a method to sequester atmospheric carbon (International Biochar Initiative, 2009).

Although Lal (2008) does not categorize biochar as a geoengineering technique in his assessment of carbon sequestration methods, biochar application may still be considered as a geoengineering technique if the three criteria provided by Keith (2000) are applied. Utilizing biochar for carbon sequestration introduces a dynamic approach aimed at reducing the level of atmospheric carbon, fulfilling the criterion of manipulation.

The two other key points are scale and intent, which is demonstrated by a long-term, multi-national, global application of biochar for the purposes of carbon sequestration. For the purposes of the following discussion, these premises will be assumed.

Assessing Biochar Burial as a Carbon Sequestration

Strategy Through Experimentation

Potential Negative Effects of Biochar

Many scientists view biochar as the end-all solution to carbon dioxide emissions. One of the strongest proponents of biochar research, Johannes Lehmann, pointed out optimistically, “If biochar could be massively applied around the globe, we could end the emissions problem in one to two years.” (Abend, 2008) Tim Flannery, the chair of the Copenhagen Climate Council, noted, “Slow pyrolysis biochar is a superior solution of [drawing down the carbon stock in the atmosphere] to anything else that’s been proposed.” (Abend, 2008)

The optimism stemming from biochar technology comes from its capacity of containing 25 kg of stable carbon for every 100 kg of biomass produced. This represents 91.5 kg of carbon dioxide, of which 88% are stored as stable carbon (Day et al., 2005). Steinbass et al. (2009) calculated carbon residence times in biochar to be from 4 to 29 years, demonstrating the effectiveness of biochar as a carbon sink. In regards to greenhouse gas containment, Rondon and Lehmann (2005) showed that the addition of charcoal to pots containing soybean eliminated nearly all methane fluxes and 50 to 80% of nitrous oxide fluxes. Additionally, biochar can also improve agricultural productivity. When applied in conjunction with nitrogen fertilizer, biochar is capable of significantly

improving plant crop yields by maximizing the efficiency of nitrogen assimilation (Chan et al., 2007).

However, current gaps in ongoing research may still be identified. In order for biochar application to be considered as a geoengineering scheme, there must be an element of scale. Currently, biochar derived from pyrolysis is produced in commercial pyrolysis machines, which are expensive (e.g. \$100,000) and must be engineered by companies who specialize in the production of these machines (Austin, 2009). Consequently, a large-scale dissemination of these machines around the world is highly impractical. Biochar can also be produced through traditional pyrolysis machinery, such as the pit kiln, the mound kiln, the brick kiln, and the transportable metal kiln, all of which causes additional carbon emission problems during biochar production (Lehmann and Joseph, 2009). Commercial pyrolysis machines harvest the gases produced during the pyrolysis process (syngas) into energy sources, but traditional kilns do not recover the syngas. The sheer amount of carbon gases emitted from the biochar manufacturing process in these traditional methods may be enough to counteract any positive benefits of carbon sequestration stemming from biochar application. Therefore, a careful analysis of traditional methods of producing biochar must be conducted to examine the adverse effects from released emissions.

In addition to the syngas byproduct, bio-oil is also another byproduct of pyrolysis. During the heating of biomass, the amount of solid char decreases, as carbon contained in the biomass is released steadily through chemical reactions (Emmons and Atreya, 1982). William and Besler (1996) observed that, as the temperature is increased in the biomass heating system, the liquid yield shows a corresponding increase. Therefore, they hypothesized that the liquid, now known commonly as bio-oil, must be the result of volatilization of hydrocarbon molecules originally contained in the biomass. The bio-oils can be harnessed as an energy source due to their rich carbon content (Mohan et al.

2006). Chemically, bio-oil is produced by the devolatilization of cellulose and hemicellulose, which happens during the transformation of the biomass into charcoal (Piskorz et al., 1986). As such, the hydrocarbon content contained in biochar after pyrolysis is highly variable, depending on how much of the carbon has been transformed into bio-oil. Because excess hydrocarbon present in the soil is toxic (Alexander, 1995), any large-scale application of biochar warrants further experimentation on its influence on soil toxicity. This may be measured through the application of biochar to a tract of soil and subsequently determining the crop productivity of the plot.

From this discussion, we have identified two unintended consequences of applying biochar on a large-scale basis – excess carbon dioxide emissions from the biochar production process through traditional kilns and potential effects on soil toxicity due to residual hydrocarbon content contained in biochar generated. These effects are important factors to determine because excess carbon dioxide emissions from the production of biochar process may be enough to counteract any potential carbon sequestration benefits from the biochar generated and soil toxicity from residual hydrocarbon in biochar may render a plot of land with buried biochar unsuitable for cultivation. This latter implication is especially important, as with the current strains in food production to ensure adequate food supplies (von Braun, 2007), we cannot afford to turn arable land simply into biochar burial plantations.

In addition, the differences between commercial (modern) pyrolysis machines and traditional kilns are summarized in Table 1. Currently, traditional kilns are much more prevalent and accessible than commercial pyrolysis machines. However, there exist many concerns regarding the syngas, bio-oil, and residual hydrocarbon content in the biochar production process by traditional kilns.

Table 1. Comparison Between Commercial (Modern) Pyrolysis Machines and Traditional Kilns

	Commercial (Modern) Pyrolysis Machines	Traditional Kilns
Syngas produced (e.g. carbon gases)	Recycled as fuel or chemically processed	Released into the air
Bio-oil produced	Harvested as fuel	Discarded
Residual hydrocarbon content in biochar	Can be regulated by controlling heating rate and maximal temperature	Cannot be regulated precisely
Manufacturing cost	Very high	Materials available locally
Prevalence	Very scarce, due to cost	Found in many countries

Proposed Hypotheses

The potential adverse effects of utilizing biochar for carbon sequestration have not yet been extensively studied. Such a study has two goals (Figure 1). The first is to measure carbon emissions from commercial pyrolysis machines and traditional kilns. The second is to determine the effects of biochar on soil toxicity, after determination of hydrocarbon content in the biochar produced by different production methods using different heating rates and maximum temperatures. These goals are depicted in a schematic (Figure 6):

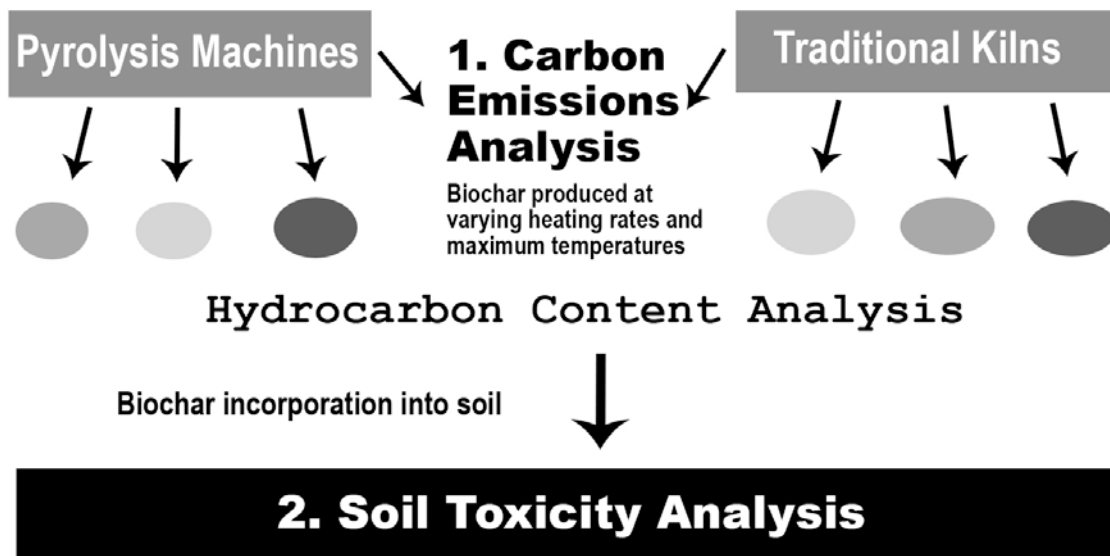


Figure 6. This schematic demonstrates the experimental procedure aimed at measuring carbon emission effects of biochar production and soil toxicity effects stemming from residual hydrocarbon content in biochar, which we identified as two unintended consequences from the global application of biochar as a geoengineering scheme.

With respect to Goal One, we hypothesize that traditional kilns (without a syngas-cycling system) will produce disproportionate amounts of carbon emissions, enough to completely or nearly completely counteract the amount of carbon sequestration potential by the biochar produced. On the other hand, we hypothesize that commercial hydrolysis machines with a syngas-cycling system will generate minimal carbon emissions, making carbon sequestration via biochar possible.

With respect to Goal Two, after the hydrocarbon content of biochar products formed at varying temperatures and heating rates are determined, different biochar samples will be placed in tropical soil tracts to measure soil toxicity induced by the hydrocarbon content contained in the added biochar. We hypothesize that soil toxicity effects (measured through crop productivity) will be less in fields containing biochar containing smaller hydrocarbon concentrations, making the residual hydrocarbon content of biochar a key element in the implementation of biochar burial as a geoengineering scheme. If there is a correlation between residual hydrocarbon content

and reduced crop productivity due to soil toxicity induced by the hydrocarbon, then the global application of biochar may not be feasible if the residual hydrocarbon content is too high.

Experimental Design

The analysis of unintended consequences in biochar application used as a geoengineering scheme (Figure 1) may be broken down into three different smaller experiments: analyzing carbon emissions, analyzing hydrocarbon content, and analyzing soil toxicity. Although the analysis of hydrocarbon content does not address a direct unintended consequence of the application of biochar, it is a key element that precedes the soil toxicity experiment and still merits its own experimental procedures.

Analyzing Carbon Emissions of Conventional Kilns and Pyrolysis Machines

In this experiment, we will compare the carbon emissions stemming from the biochar production process by conventional kilns and modern pyrolysis machines. Conventional kilns do not recycle the syngas released in the pyrolysis reaction, and the resulting carbon-rich gas is released into the atmosphere following a pyrolysis cycle, when biochar is harvested. Modern pyrolysis machines capture the syngas and either treat the gas through catalysts and chemical scrubbing (Austin, 2009) or recycle the gas to be used as an energy source, such as in fuel cell systems (Arni et al., 2009). Because most models of pyrolysis machines that utilize syngas recycling produce little to no emissions, the focus will be placed on measuring carbon emissions produced by a typical kiln in the production of biochar.

The experiment will comprise the measurement of carbon emissions by conventional pyrolysis kilns, including the pit kiln, the mound kiln, the brick kiln, and the transportable metal kiln, as detailed in Lehmann (2009). Each kiln will be placed in a distinct, sealed chamber for the duration of the experiment. Ten kilograms of elephant grass (*Pennisetum purpureum schum*) will undergo pyrolysis in each of these four kilns at a heating rate of 10 degrees Celsius per minute. The pyrolysis reaction will be capped at 720 degrees Celsius, because we want to include the peak right after 600 degrees Celsius – the point of maximal gas production in the pyrolysis process (William and Besler, 1996). Elephant grass is chosen as the biomass source for this experiment (as well as the following experiments) because the plant is abundant, rapidly propagating, and holds promising potential as a biochar source for the future (Strezov et al., 2008). During the pyrolysis process (defined from the initiation of the pyrolysis reaction to the removal of biochar from the chamber), the amount of the gases released and contained in the sealed chamber will be measured. Gases will be characterized via column gas chromatography, with a special emphasis on identifying carbon monoxide, hydrogen gas, methane, carbon dioxide, and hydrocarbons produced.

The experiment will be repeated three times with each kiln to ensure accuracy and validity of the gas measurements. After error analysis, the amount of carbon emissions produced by each kiln in the process of biochar production will be compared against the calculated carbon sequestration potential of the biochar produced by the kiln, using estimates derived from Lehmann (2006). We hypothesize that the carbon emissions produced by each conventional kiln will far outweigh the carbon sequestration potential of the biochar generated.

Analyzing the Hydrocarbon Content of Biochar

In the second experiment, we will measure the amount of residual hydrocarbon contained in biochar obtained from pyrolysis. Since temperature and the rate of heating both influences the composition of produced biochar, we will control for these two variables (William and Besler, 1996). Using a syngas-recycling pyrolysis machine and a brick kiln (as the representative of conventional kilns), ten kilograms of elephant grass will undergo pyrolysis trials following the experimental conditions given by William and Bessler (1996) (Table 2).

Table 2. Experimental Design of Hydrocarbon Content Analysis

Rate of Heating (°C per minute)	Maximum Temperature (°C)
5	300
	600
	720
20	300
	600
	720
40	300
	600
	720
80	300
	600
	720

In Table 2, the rate of heating refers to the rate of temperature increase in the pyrolysis chamber, given in degrees of Celsius per minute. The maximum temperature refers to the maximum temperature attained during the pyrolysis cycle before the pyrolysis reaction is terminated. Both the syngas-recycling pyrolysis machine and the brick kiln runs through all the trials, yielding a total of twenty-four trials.

Although the experimental set-up may seem to repeat William and Besler’s pyrolysis experiments, we aim instead to take the solid char generated through the pyrolysis process for each trial and analyze for hydrocarbon content. Hydrocarbon content will be assessed through the gas chromatography / mass spectrometry (GC/MS) method. From William and Besler’s experimental outline, biochar generated at the

experimental conditions where the greatest amount of bio-oil is produced is expected to contain the minimum amount of residual hydrocarbon content. The reasoning behind this is that the hydrocarbon content originally contained in the biomass is largely transferred to the bio-oil.

Soil Toxicity Analysis

The biochar produced in the hydrocarbon content analysis experiment will be utilized in the soil toxicity experiment, where we aim to uncover a correlation between soil toxicity and hydrocarbon content in biochar. Three biochar samples produced from the hydrocarbon content analysis will be used in this experiment, including the sample with the lowest hydrocarbon concentration, a sample with a mid-range hydrocarbon concentration, and the sample with the highest hydrocarbon concentration. As controls, we will include samples of natural fertilizer with the same hydrocarbon concentration (through chemical additions of hydrocarbon) as those found in the biochar samples. These controls help to delineate the specific effects of biochar on the soil by comparing it against regular fertilizer, when hydrocarbon content is controlled for.

The soil toxicity analysis will be conducted in tropical soil to mimic the native environment in which terra preta is found. Experiments will be conducted in square plots of 10 meters by 10 meters, which have similar initial soil profiles determined before the experiment. The plots will be located in a contiguous tract of land, to control against environmental differences stemming from geography. Each plot is cleared of existing plant vegetation and sufficiently aerated and irrigated in preparation for planting.

The same amount of biochar by weight of the different samples (three low, medium, high hydrocarbon content biochar and the corresponding natural fertilizer controls) will be applied to the plots, for a total of three experimental and three control

plots. The biochar added will be pelletized and distributed in a uniform fashion across the experimental fields, buried half a meter underground. Natural fertilizer control will be distributed in a similar fashion in the control fields. Radish (*Raphanus sativus*) will be chosen as the experimental plant subject, and twenty germinated young plants will be added to each plot following biochar or fertilizer application. Radish is chosen as the experimental plant subject for several reasons: its small size, fast growing time (24-30 days under ideal conditions), and the formation of distinct shoot and root systems that clearly indicate carbon source and sink (Kostka-Rick and Manning, 1993). Young plants are chosen in order to eliminate any background effects relating to seed germination. Three replicates of the experimental and control plots will be created in order to ensure better experimental accuracy.

Radish growth will be conducted for a period of 6 weeks over the late spring to early summer, during the months of May and June. The plots will be watered three times a week with tap water but will otherwise be subject to normal weather conditions during the test period. After 6 weeks, the radish plants will be harvested by carefully uprooting existing plants, the plants will be cleaned with tap water, and the lengths of the shoot and root systems will be measured for each plant. The plants will then be oven dried at 80 degrees Celsius for 48 hours, and the dry weight of the shoot and root systems measured separately. The above harvest protocol is adapted from soil fertility experiments conducted by Chidumayo (1994).

The measurements will be collated separately for each experimental and control sample, and the three experimental replicate results will be incorporated. We hypothesize that the field with the least concentration of hydrocarbons will result in the best radish productivity, measured through shoot and root measurements and the resulting dry weight yield of the plants. The differences in soil toxicity between biochar samples and natural fertilizer controls with the same amount of hydrocarbon content is

unclear, so we will be also testing for this by noting the productivity between fields containing the same amount of hydrocarbon concentration.

Expected Results, Conclusions, and Further Recommendations on Biochar as a Geoengineering Scheme

Expected Results

Through the carbon emissions analysis experiment, we would expect that traditional kilns would generate a disproportionate amount of carbon emissions that will make the carbon sequestration potential of the biochar generated quite minimal or nonexistent. On the other hand, we would expect that commercial pyrolysis machines would generate a minimal amount of carbon emissions, since the emitted gases are recycled or chemically treated.

Through the soil toxicity experiment, we would expect that tracts containing biochar with the least amount of residual hydrocarbon content would produce the greatest crop yield (as measured by the dry weight and the length of the radishes produced). On the other hand, we would expect that tracts containing biochar with the most amount of residual hydrocarbon content would produce the smallest crop yield. In regards to the control with chemical fertilizer with added hydrocarbon, we would expect there to be little difference between the biochar and the fertilizer samples.

Future Recommendations

From the carbon emissions analysis experiment, we would recommend the implementation of commercial pyrolysis machines to be used in the generation of

biochar, as opposed to traditional kilns because of the difference in carbon emissions during the biochar production process.

Furthermore, from the soil toxicity experiment, we see that residual hydrocarbon content in the biochar plays a major role in the resulting crop productivity in tracts containing buried biochar, due to soil toxicity effects. This reinforces our recommendation for the implementation of commercial pyrolysis machines because they can control for maximal temperature and heating rate during the pyrolysis process accurately, which directly affects the hydrocarbon content in the biochar produced. In traditional kilns, these experimental conditions are very hard to control accurately, and consequently hydrocarbon content in produced biochar is also highly variable.

Previously, we have presented the prohibitive cost of commercial pyrolysis machines, which logistically causes shortages of these machines in developing countries. A proposed solution is for governments to purchase a certain number of these commercial pyrolysis machines and circulate the machines amongst farmers in different parts of the country on a regular schedule for biochar creation. This reduces the burden of a small group of individuals purchasing and owning pyrolysis machines, and makes biochar more accessible for normal farmers. As described above, in addition to its carbon sequestration properties, biochar has demonstrated fertilizer capabilities, and if applied in the right amount with the hydrocarbon content controlled for, biochar may be able to improve crop yields by maximizing nitrogen assimilation efficiency (Chan et al., 2007). This may prove to be further incentive for the introduction and the propagation of biochar for the future, aside from purely carbon sequestration purposes.

Biochar and the Future

Critics of implementing biochar burial on a global basis as a geoengineering scheme have cited difficulties such as large-scale deforestation in anticipation of the creation of massive biochar burial tracts used to sequester carbon. In addition, critics have also questioned the logic of creating crop plantations where the crop yield is used solely for the production of the biochar. However, we believe that these two major problems can be circumvented easily.

Through the proposed soil toxicity experiment outlined in this proposal, we can definitively determine biochar's unintended side effects on crop productivity and soil toxicity, and subsequently there will be no need for large-scale deforestation projects to clear land for biochar burial. Biochar can be buried in farmland that are already productive, perhaps even serving as fertilizer similar to the terra preta that has existed in the Amazon basin for centuries.

Furthermore, biochar can be created from agricultural waste very easily, and there is no need to plant new plantations to provide biomass for the generation of biochar. Of the estimated 60.6 billion tons of NPP that is produced by the planet every year, about ten percent turns into agricultural and forestry waste, such as corn stalks and leaf litter (Kleiner, 2009). If all this waste was regenerated as biochar through pyrolysis, 3 billion tons of biochar will be produced annually, which would lead to a reduction of atmospheric carbon emissions by approximately also 3 billion tons (Amonette et al., 2007). Considering 4.1 billion tons of excess carbon dioxide accumulates in the atmosphere every year, this will help to offset a significant portion of that imbalance.

There is still a large amount of research ongoing in the use of biochar in carbon sequestration, but we remain optimistic on the outcome. We strongly endorse and recommend further research on biochar as a possible method to address the rising carbon dioxide concentrations in the atmosphere.

Geoengineering and the Future

With the advances that humankind has witnessed in the last two hundred years, it may seem ironic that we are turning again to technology to remedy the global problems that have been created as a byproduct of our technological progress. The concept of geoengineering has become a revolutionary concept in ecology in recent years, but as this experimental proposal has demonstrated, there are multiple sides to the problem and we must proceed cautiously.

Our Earth is an ecosystem that is tightly interlinked in a web of life – one species leading to another, one cycle influencing another. Any disruption in this environment causes the whole system to shift in a different direction to compensate for the disturbance. Keeping this in mind, our experiments with this system need to be guided with reason and prudence. However, the results can also be informative and rewarding – geoengineering experiments at the Hubbard Brook National Forest through the 1960s produced a landmark study in 1968 that focused national attention on the effects of acid rain on soil, forest, and lake ecosystems, directly leading to the Clean Air Act and additional amendments enacted through the 1970s to the 1990s.

In conclusion, we would like to come back to the fundamental definition of applied ecology as given by Remmert in 1980, “In its applied form, ecology faces the problem of discovering how the conditions essential for present-day life can be maintained.” As our world begins to tip out of balance, it is our duty as citizens of the world – as more than just ecologists – to discover how to reverse those adverse effects. Although geoengineering may not (yet) be the perfect solution, it is a step in addressing this unique challenge – to ensure that our planet will continue to be hospitable for our children, our children’s children, and so on till posterity.

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