Climate-Change Mitigation Potential of Biochar: A Review and Framework for Carbon Accounting

by

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Abstract

Climate change presents one of the greatest challenges facing humanity. The anthropogenic emissions of heat-trapping greenhouse gases are widely considered to be the primary driver of global warming and climate change. Climate change mitigation strategies are being considered and implemented by government and non-government organizations worldwide. One practice that has attracted attention as a tool to offset and reduce emissions of greenhouse gases is the manufacture and application to soil of charred biomass, commonly referred to as biochar. As a soil amendment, biochar can stabilize carbon belowground and potentially increase agricultural and forest productivity. It is also resistant to decomposition when incorporated in soil, and can serve as a significant carbon sink. Researchers have examined the potential of biochar to produce multiple environmental benefits including energy production and agronomic improvements, while simultaneously sequestering carbon and reducing net greenhouse gas emissions. This paper reviews current scientific literature to evaluate biochar's potential to stabilize carbon belowground, all while producing a number of other environmental and economic benefits. The feasibility of implementing biochar systems is considered in the context of carbon-market incentives that may be adapted to motivate investment in biochar production. A framework for carbon accounting of biochar projects is also presented.

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Prologue

Climate change is one of humanity's greatest challenges. Based on a substantial array of scientific evidence, there is a general agreement in the scientific community that: 1) the earth's lower atmosphere and oceans are warming (NASA 2013), 2) the increase in temperature is forcing changes in global climate systems, including sea level rise and extreme weather events (Bernstein et al. 2007), and 3) human activity is a primary cause of these changes (National Research Council 2010). Climate is a function of human and natural forcings. Climates have always presented a risk to human society. The situation today is new as humanity has become a geological force affecting not only climate but all global-scale Earth systems. Both natural and anthropogenic phenomena affect average surface temperatures and associated climate patterns through "radiative forcing." Short-term natural variability leads to fluctuations in temperature and weather patterns both regionally and temporally, and the physical and chemical criteria affecting long-term climate characteristics are complex. However, there are no observed natural occurrences (e.g. changes in solar irradiance) that can explain the observed changes in average surface temperatures over the last 150 years (IPCC 2002). Among anthropogenic causes, the combustion of fossil fuels (coal, petroleum and natural gas) has had the most significant effect on climate, although industrial processes and agriculture contribute significantly. Analyses of such factors have determined that the observed increases in the tropospheric concentrations of heat-trapping "greenhouse gases" (GHG), primarily carbon dioxide (CO_2), methane (CH_4), and to a lesser degree nitrous oxide (N_2O) and halocarbons, have had the most significant effect on global warming over the last century (Forster 2007).

Among the anticipated effects of climate change are continued sea level rise, human health risks, adverse economic impacts on human habitation near coastlines, disruption of natural habitats and agricultural systems, and species extinctions. Scientists and policy analysts have developed proposed response actions to reduce net GHG emissions and limit the effects of climate change. These proposals include the use of alternative energy sources, energy efficiency measures for residential and industrial demand and transportation, and the sequestration of carbon in living biomass (forestation) or below ground as stored gases or in the form of increased soil carbon content. Such strategies are intended to reduce or offset the GHG emissions from human activity and stabilize the concentration of GHG in the atmosphere.

Introduction

In recent years, the production and application of charred or "carbonized" biomass has received increased interest as a technique that may have significant climate change mitigation potential. Charred biomass that is deliberately incorporated into soil for long term carbon stabilization and soil amendment is typically referred to as *biochar*.

Biomass from harvested plant matter, wood and mill waste, agricultural waste, manure, or biosolids has long been used as a source of energy. When biomass is combusted to produce electricity or heat (or to dispose of organic waste material), the energy released can be considered "carbon neutral," because there is no net gain of carbon to the atmosphere; the organic carbon in the biomass fuel was captured from the atmosphere through photosynthesis, and would return to the atmosphere as methane and/or carbon dioxide if the biomass were left to decompose. Conversely, fossil fuel utilization removes paleocarbon sequestered below ground for thousands or many millions of years, and through the process of combustion, adds carbon to the atmosphere in the form of carbon dioxide and methane. If technologies such as pyrolysis or gasification are used, instead of combustion, to generate useable energy from biomass, biochar can be produced simultaneously. During biochar production, a portion of the biomass carbon is removed from the photosynthesis and decomposition cycle and can be stored for centuries to millennia in soil. As such, biochar-generating projects are considered carbon-negative energy systems (Lehmann 2007), because carbon in the atmosphere is reduced, while simultaneously producing useable energy.

Biochar has the potential to yield additional environmental benefits. Biochar additions enhance soil's desirable physical and chemical characteristics by retaining water and nutrients, which may reduce fertilization and irrigation requirements (Sohi 2009). Biochar may also adsorb pesticides, nutrients and minerals in soil, preventing the movement of these chemicals to surface water or groundwater, and the subsequent degradation of these waters from agricultural activity. Biochar has also been demonstrated to reduce methane and nitrous oxide emissions from agricultural soils (Zhang et al. 2010), which could have additional climate mitigation effects, as these are potent GHG. These environmental benefits have potential economic value in the form of increased agricultural productivity, water quality protection, and reduced GHG emissions, in addition to the sequestration of carbon. Due to its potential to yield multiple benefits, biochar has acquired attention from climate and policy analysts in recent years. Recent assessments indicate that increased and well-managed biochar generation with subsequent application to soil could play a significant role in mitigating GHG emissions and climate change (Lehmann et al. 2006, Woolf et al. 2010). However, despite recent research, the environmental and economic benefits of biochar are not yet fully characterized, and they vary depending on location, soil, and crop to which biochar is applied, the material used as the biochar feedstock, and pyrolysis conditions used to generate biochar including temperature and exposure time.

The purpose of this paper is to evaluate existing information about biochar's environmental benefits and its potential for climate mitigation, and to analyze these characteristics in the context of existing carbon markets that are intended to financially motivate investment to ameliorate climate change. Comparisons of this type will continue to inform decision-making regarding the benefits and feasibility of biochar manufacture and application operations. Such information may also be useful in the development of appropriate public policies that encourage investment in biochar projects. Based on available information, a framework for carbon accounting is introduced to assess the climate change mitigation effects of biochar, which may be especially relevant in the event that biochar production becomes common outside monitoring programs of carbon market systems.

Methods

The methods for this study included an examination of existing scientific literature on biochar's history, characteristics, and potential as a tool for offsetting GHG emissions. This study also provides an analysis of the incentives and structure of existing carbon markets and the degree to which they are useful for biochar projects. Additionally, recommendations for further data collection on biochar projects and a suggested framework for carbon accounting for biochar systems are provided to inform future analysis of biochar's role in influencing GHG concentrations in the atmosphere and its potential to mitigate climate change.

Biochar Background

Charred material is generated when biomass is thermally oxidized especially in an oxygen-deficient atmosphere, which prevents complete oxidation of the biomass. Perhaps the most familiar forms of charred material are char and charcoal, which has historically been manufactured for use as a secondary fuel. Historically, charcoal has had some advantages over wood as a fuel, due to its high-temperature combustion (which facilitates metalwork), its ease of transport compared to woody biomass, and its resistance to decomposition. Charcoal has been produced using pits or kilns to generate fuel for cooking, heating or industry. Char is a naturally occurring product of fire and is found in most soils due to its resistance to microbial breakdown (Liang et al. 2008). Soils contain various levels of naturally occurring char. For example, North American prairie soils are estimated to contain 5%-15% char from historical wildfires (Laird 2008).

Studies of historical char content in soil suggest that carbonized biomass is far more stable than its original biomass source, with persistence in soil of hundreds to thousands of years (Lehmann et al. 2006). In Australia, estimates of the age of naturally occurring biochar carbon are 1,300 – 2,600 years (IBI 2010). Liang et al. (2008) found char in Amazonian Anthrosols ranging from 600 to 8,700 years old, and also noted that no significant difference in CO_2 respiration per unit carbon (C) was observed between Anthrosols with varying ages of black carbon (BC) and soil textures (0.3 to 36% clay). Liang also found that the Anthrosols with high BC content had 61–80% lower CO_2 evolution per unit C over 532 days in a laboratory incubation compared to adjacent soils with low BC contents. These studies demonstrate biochar's extraordinary recalcitrance in soil in two ways: its presence and relative age in existing soils (up to 8 millennia), and a lower rate of carbon decomposition to CO_2 when naturally occurring soils with higher and lower char contents are compared under controlled conditions.

Biochar differs from charcoal in that the term biochar has come to represent charred material that is deliberately applied to soil to sequester carbon and to amend the soil to improve plant productivity or other desired soil characteristics (as opposed to combustion of the char for energy). Biochar can be produced using modern technology and processes such as pyrolysis or gasification. This type of controlled char production can be carried out with fewer emissions of particulates (smoke) than less advanced kilns or pits. Pyrolysis is achieved when biomass is heated to a range of 400 to 900 degrees F in the near or total absence of oxygen. Gasification utilizes a limited amount of oxygen and typically higher temperatures to drive off and burn combustible gases (known as "syngas") from the biomass, which produces less char. Both processes, once initiated, are exothermic and can be used for energy generation. Other, similar processes that can produce char include torrefaction, hydrothermal carbonization, and flash carbonization. Table 1 (from Meyer et al. 2011) exhibits these process types, their typical process parameters, and characteristics of the produced char material.

Table 1

Process type	Typical process temperature (approximate temperature or range)	Typical residence time	Typical solid product yield (dry wood feedstock basis – mass percent)	Typical carbon content of solid product (mass %)	Typical carbon yield (mass of carbon product/mass of carbon feedstock)
Torrefaction	290 C	10 to 60 minutes	61-84%	51 – 55%	0.67 to 0.85
Slow pyrolysis	400 C	Minutes to days	About 30%	95%	About 0.58
Fast pyrolysis	500 C	About 1 second	12 to 26%	74%	0.2 to 0.26
Gasification	800 C	10 to 20 seconds	About 10%	Not determined	Not determined
Hydrothermal carbonization	180-250 C	1 to 12 hours	Less than 66%	Less than 70%	About 0.88
Flash carbonization	300-600 C	Less than 30 minutes	37%	About 85%	About 0.65

Biochar Project Types

Interest in biochar in recent years has been stimulated by the discovery that biochar is the primary reason for the highly fertile dark earths in the Amazon Basin known as Terra Preta de Indio, or simply *terra preta* (Lehmann & Joseph 2012). These soils have been studied and it is now generally agreed that Amerindian populations began deliberately enriching broad areas of the Amazon basin that were used for agricultural production with char and ash prior to the arrival of Europeans. Some records indicate that prior to the introduction of western microbial diseases, the Amazon basin populations could have numbered in the tens of millions, supported by large areas of agriculture (Bates 2010). Soils of the Amazon are acidic and nutrient poor, due to rapid plant growth and microbial decomposition from high moisture and temperature in the region. Researchers speculate that pre-Columbian natives learned that additions of charcoal (and perhaps human and animal waste and compost) increased the fertility of these soils and the longevity of production that could be obtained from an area cleared of natural vegetation. The fact that this ancient technique may have allowed these populations to prosper, and that these soils 1,000 years hence retain both their enhanced fertility and their charcoal material, has spurred great interest in studying and recapturing the benefits of this land management approach. By adapting and applying the knowledge obtained by ancient civilizations we may be able to address current environmental issues.

Various modern techniques can produce different amounts of char. As noted above, pyrolysis is defined as the thermal decomposition of organic matter in an atmosphere with limited oxygen and is also the initial stage for both combustion and gasification (Roberts et al. 2010). One can manage the temperature and exposure time or "residence time" of the biomass to the heat to achieve desired ratios of three end products: syngas (a combustible mixture of hydrogen, hydrocarbons, and other gases), bio-oil and char. Slow pyrolysis is typically performed with lower temperatures and longer residence times than fast pyrolysis. Fast pyrolysis produces about 13% syngas, 75% oil, and 12% char (Sohi et al. 2010). Slow pyrolysis typically produces about 35% syngas, 30% oil, and 35% char (Roberts et al. 2010) but can be optimized for char production at up to 50% char. Gasification produces about 85% syngas, 5% oil and 10% char. Syngas and bio-oil are considered renewable fuels, and can be used for bio-energy applications (although a portion of the syngas is typically combusted to facilitate the biochar production process). Syngas can be combusted to generate electricity for on-site use or connection to a power grid. The bio-oil generated from pyrolysis can be combusted or refined for use as transportation fuels. This use of pyrolysis bio-oil has been estimated to have a high potential for off-setting the use of petroleum transportation fuels (Laird 2008), but the refining process for this oil is atypical compared to petroleum oil, and has cost implications that affect its feasibility as a fossil fuel substitute. Additionally, the location of bio-oil facilities, the accessibility of pyrolysis feedstock materials, and the locations where there is demand for transportation fuel, present life-cycle emissions issues for bio-oil production and transport, when comparing the environmental costs of various projects. More research in this area may provide innovations that address these problems.

The Climate Change Mitigation Potential of Biochar Projects

Several studies estimate the potential climate mitigation benefits of biochar projects. These model the maximum and/or conservatively realistic quantities of GHG offsets from biochar projects that are possible in terms of the mass of CO_2 carbon equivalents (CO_2-Ce) in avoided emissions, or as sequestered carbon (C), annually. The modeled scenarios are based on assumptions regarding carbonization efficiency of a chosen system, mass of sustainable biomass feedstocks available, and presumed presence or absence of offset benefits in addition to the carbon sequestration of the biochar (e.g. reduced nitrous oxide emissions from agricultural fields to which biochar is applied). For example, the International Biochar Initiative (IBI 2008) has prepared an analysis using a simple model, and using assumed values for a set of parameters including the fraction of global net primary production available to make biochar, the carbonization efficiency of the biochar production technology selected, the increase in productivity from land to which biochar is applied, and other assumptions. Under four baseline scenarios, which they considered in the range of "conservative" to "very optimistic," the annual offset potential of biochar systems ranged from 0.25 to over 2 Pg C/yr (1 petagram, or Pg, is equal to 1 billion metric tons). The IBI model "conservative" scenario assumed that only agricultural and forestry residues that "had no use" (i.e. were left to decompose), representing about 27% of total residues from these sources, comprised the available feedstock. Woolf et al. (2010) also analyzed global "sustainable" potential for biochar systems using a variety of literature based assumptions, and estimated that 1.8 Pg/yr CO_2-Ce could become avoided emissions if biochar systems were maximized globally. Woolf's criteria for feedstock availability were suggested to be conservative and included the following: no crop residue currently used as animal fodder, no current agriculture taken out of food production, no wastes with a high likelihood of contamination, and biomass crops limited to abandoned agricultural land that has not been converted to other uses.

In addition to analysis of the potential for gross biochar production and related climate benefits, other studies have considered the rates at which biochar could be applied to soil without adverse impacts to plant growth. In addition to biochar's recalcitrance in soils, recent studies of terra preta exhibited the capacity of these soils to sequester additional carbon when biochar is added. One analysis by Glaser et al. (2001) of Amazonian terra preta produced an estimate of 250 Mg/ha of soil C storage (1 Mg is equal to 1 metric ton) in terra preta soils compared to 100 Mg/ha of C storage in similar soils that are outside the terra preta area. The historical additions of biochar in this case also demonstrate that the terra preta soil can sequester more carbon than that observed in above-ground tropical forest biomass, which was estimated by Lehmann et al. (2006) at 110 Mg/ha. Lehmann et al. (2006) also cited literature confirming high-char soils that increased soil productivity. Lehmann and Rondon (2006) demonstrated increased crop yields with biochar addition rates of up to 140 metric tons per hectare. However, the physical and chemical reactions of soil to biochar additions vary depending on soil type and biochar characteristics, and some studies showed no increase, or in some instances decreases, in yields after biochar additions. Thus, the ability of biochar to improve yields when applied to agricultural or forested land is not yet fully characterized. The variability in plant growth response to additions of biochar to soil is presumed to be due to numerous physical and chemical characteristics of the soil and the biochar. The condition of soil prior to biochar additions, the local climate, the type of vegetation grown on the amended soil, and the biochar feedstock material and process conditions are also expected to affect the plant growth response to biochar. This is one area where researchers agree that additional study is needed to characterize and model the anticipated effects of biochar additions upon plant growth under variable circumstances.

Additional studies demonstrate biochar's potential as a mitigation strategy when compared to other management practices. A study conducted by the Nicholas Institute for Environmental Policy Solutions (Eagle et al. 2010) compared literature on GHG mitigation potential of various agricultural land management practices in the United States, to evaluate how various techniques might be used as carbon offsets. This analysis examined 37 agricultural land management practices with regard to their potential to achieve a net reduction in CO_2e emissions by sequestering carbon or preventing emissions. The methods included nutrient management, rice field water management to control methane emissions, and tillage modifications among other high-potential options that have been studied. The review determined that biochar application had the highest offset potential among the practices considered for GHG mitigation, when both average net impact per hectare and the maximum number of applicable hectares available for each technique were considered. Based on available acreage and expected net impact, the study suggested that up to 0.18 Pg/yr of sequestered carbon or avoided C emissions are possible just within the United States. The literature review did note that research was limited for several of the evaluated methods, including biochar, and that the methods with limited research produced mitigation estimates with greater uncertainty. Nonetheless, the potential for GHG mitigation from biochar was significant compared to alternative mitigation strategies.

Public Policy and Market Incentives

Currently, as of 2013, there are no carbon markets that offer carbon offset credits or other financial compensation for the carbon sequestration or soil emissions suppression of biochar applied to soil. Major regulatory carbon market systems include the Clean Development Mechanism (CDM) of the Kyoto Protocol, the European Union Emissions Trading Scheme (EU ETS), and the California Cap and Trade market. Significant voluntary markets also exist, including the Verified Carbon Standard, the American Carbon Registry (ACR), and the Climate Action Reserve (CAR), but these, likewise do not accept biochar projects as a carbon offset protocol at this time. At least one offset protocol for biochar projects has been developed and published for consideration (Weisberg et al. 2010), and some biochar advocates promote the benefits and feasibility of further developing and approving biochar protocols for use within these established carbon markets. In particular, the CAR and ACR have ongoing evaluation and approval programs for new protocols, and have a demonstrated willingness to adopt additional methods. Approved protocols within these market programs typically include criteria for establishing the permanence, verifiability, additionality, monitoring, and ownership of carbon offsets. Proposed offset protocols for biochar would need to address these criteria.

Other than afforestation, the CDM does not currently allow any carbon sequestration projects as offsets. However, under CDM, avoided fossil fuel emissions, including those from biomass electricity generation projects, are tradable. This creates a potential for using biomass energy produced from biochar projects as a CDM offset, but creates no incentive for the application of biochar. In fact, it creates an incentive to combust the biochar as a renewable fuel. The EU ETS accepts all methods approved under CDM except nuclear energy projects, afforestation and reforestation activity (with some exceptions), and after 2013, the destruction of industrial gases (e.g. some halocarbons) with high global warming potential (GWP). Thus, the ETS also does not currently include biochar as an offset category. The California market currently accepts only four offset types – forestry, urban forestry, dairy manure digester projects, and the destruction of high GWP gases – all of which have specific protocol requirements and limitations. The California market has indicated a willingness to consider adopting additional project types, and usually bases their protocols on those developed through the CAR. Currently, coal mine methane reductions and rice field management to reduce methane emissions are under consideration as additional California market offsets (Stevenson et al. 2012). However, biochar production is not currently being considered as an offset option, and would likely face difficulty in being accepted as an approved method due to concerns over additionality. All carbon offset protocol programs consider additionality, in which offset projects must demonstrate that generated offsets would not have occurred under "business- as-usual" circumstances, that is, without the financial incentive received from the offset market.

Some biochar projects may not be able to meet the additionality criteria of some offset programs, because the projects may be financially viable and self-sustaining without the financial incentives of payments from the offsets market. An example of this situation would be biomass gasification systems that generate electricity profitably, while also producing biochar.

Also, offset programs typically include a monitoring aspect to demonstrate the real and permanent nature of the offset. With regard to carbon sequestration, it could be difficult for some biochar projects to demonstrate this criterion, unless the final location of the applied biochar was known and monitored, or if the persistence of the biochar material in the environment was affirmed through reliable and robust models.

Both CAR and ACR have developed agricultural offset protocols incorporating the management of soil carbon and soil GHG emissions in agricultural systems. For example, reduced tillage and nutrient management are both protocol types with approved methods for registered offsets under these voluntary markets. Presumably, biochar protocols could be developed that would meet the necessary offset criteria of the ACR or CAR, at least for some biochar projects for which the disposition and permanence of the applied biochar could be effectively established. These considerations suggest that some types of biochar-generating projects could garner acceptance as approved offset protocols, and some could not.

Even if biochar project protocols are developed and approved for these markets, there are financial limitations to the total amount of biochar that could be counted under an offset program. To evaluate the maximum potential of these regulatory and voluntary carbon markets, we can assume that biochar protocols that meet the programs' offset criteria for usability would be developed. The regulatory carbon markets require covered entities within their programs (emitters of GHG) to significantly reduce their emissions, and the programs limit the amount of carbon offsets that can be used for compliance under the programs' emissions caps. For example, in the California market, individual covered entities are allowed to use offsets to comply with up to 8% of their total emissions limit. Based on the California cap-and-trade market, this limits the total amount of offsets allowed to be used for compliance between 2013 and 2020 to about 200,000,000 tons of CO2e, or about 0.055 Pg/yr CO2e as C, on average. The EU ETS has allowed 1.7 Pg CO2 (.46 Pg C) in total offsets to be used between 2008 and 2020. About one-third of this EU ETS limit has already been used. If the remaining approximately 0.31 Pg C were divided among the remaining years, it would amount to about 0.039 Pg/yr between 2013 and 2020 within the European market. Together, these two markets (California and Europe) could absorb a total of about 0.094 Pg/yr C in approved carbon offsets.

We can compare this rate to estimates of the potential for biochar carbon projects to sequester carbon or offset emissions. In this comparison we would assume that all offsets, hypothetically, were obtained from biochar projects, although biochar projects would be competing with other approved offset project types that might be achieved with greater economic efficiency. Even if maximized for biochar projects only, in our hypothetical comparison, the two markets combined would support only five percent of the estimated global maximum offset potential of sustainable biochar projects, estimated by Woolf et al. (2010) at 1.8 Pg/yr C. This does not mean that biochar offset protocols, if approved, could not play a role in climate change mitigation by incenting projects and increasing the actual sequestration of carbon as biochar. However, it does indicate that the financial incentives of existing markets are limited, and these markets alone cannot maximize the global potential of biochar to offset GHG emissions. To maximize biochar's potential, many projects would have to be economically self-sustaining, or obtain revenue from alternative policy incentives.

These comparisons demonstrate that even under the most conservative assumptions, the known carbon market offset opportunities could provide financial incentives for only a fraction of the global maximum carbon offset potential for sustainable biochar projects. Other public policy incentives could play a role in stimulating investment in biochar technology and the analysis of associated costs and benefits. Tax incentives and subsidies have been used for other "green" energy investments like solar, wind, and biomass combustion-generated electricity, and similar programs could be extended to biochar-production. If public or private funds are used for investment in biochar systems, it would be beneficial to quantify and analyze the individual financial and environmental costs and benefits of these systems. However, there is little discussion in the literature to date regarding the use of financial assistance for biochar projects, outside the consideration of developed carbon trading systems and markets.

Potential Risks to Human Health, the Environment, and Social Responsibility

As interest in the potential benefits of biochar production increases, possible adverse impacts of biochar manufacture and application need to be addressed. Potential negative effects of biochar systems include human and environmental health risks from cogenerated chemical constituents, unintended adverse agronomic consequences that may occur upon application of biochar to soil, and social injustices that could result from land use changes based on potential large-scale commercialization of biochar systems to acquire revenue from carbon markets.

The high-temperature decomposition of organic matter can result in the formation of polynuclear aromatic hydrocarbons (PAH) and chlorinated dioxins. Both classes of compounds carry health risks to humans and other organisms. Some PAH are known or suspected carcinogens, and dioxins can be toxic at very low concentrations. Hale et al. (2012) assessed chemical analysis of biochars for PAH and dioxin constituents and found that PAH concentrations in biochar were generally below existing environmental quality standards for PAH in soils. However, fast pyrolysis and gasification did produce some concentrations (up to 45 µg/g or parts per million) that exceeded soil quality standards. PAH concentration generally decreased with increased pyrolysis temperature. Total dioxins were detected at low concentrations of up to 92 picograms per gram (parts per trillion or ppt). Bioavailable fractions of the total concentrations of PAH and dioxins were also analyzed in the study. Bioavailable PAH from slow pyrolysis were below background concentrations found in urban soils, and bioavailable dioxins in this study were below analytical detection limits.

In a separate study, PAH concentrations in biochar were found to be lower than PAH in char obtained from the residue of a prescribed burn (Brown et al. 2006), further indicating that PAH contamination from biochar application is possible, but unlikely to increase human health risks beyond naturally occurring background levels in soil. Likewise, unhealthy dioxin levels in soils as a result of biochar prepared from plant biomass are unlikely, but the chlorine levels in biochar feedstocks and in biochar should be considered to prevent dioxin contamination. Regarding dioxin formation, the use of synthetic materials, especially polymers and plastics that contain chlorine atoms (e.g. polyvinyl chloride) as biochar feedstocks, would probably present chemical risks, and should be discouraged or closely monitored. This situation is possible if municipal solid wastes are used as a feedstock. Overall, the available literature on biochar prepared from woody biomass feedstocks seems to suggest little risk from PAH and dioxin contamination. Nonetheless, formation of dioxins and PAH are possible and concentrations are likely to fluctuate with various feedstocks and process conditions.

Metals at toxic concentrations are an additional concern, especially for biochars prepared from feedstocks that contain high concentrations of metals. Biochar generation from sewage sludge is one known source that may yield biochar with metals in concentrations that may present a threat to human health (Lehmann & Joseph 2012). Manure is another potential source of metals. The organic portions of municipal solid waste and tires are also potential biochar feedstocks with high metals content. However, manure and sludge that have not been charred are often applied to agricultural soil, and biochar preparation from these feedstocks would not be expected to increase metals content over and above what was in the feedstock to begin with. In general, application of biochar with metals content that presents a threat could and should be avoided by monitoring feedstocks, analyzing biochar to monitor for metals, and excluding contaminated char from being applied to agriculture.

Regarding social risks due to land use change, the same risks that apply to biofuels production apply to biochar production. Large plantations used to produce biochar feedstock, and the substitution of bioenergy crops on land historically used to produce food crops carry social justice, environmental and economic risks. Although biochar advocates may recommend practices to prevent land use change or exploitation of resources that present unintended social or environmental impacts, the financial incentives of biochar manufacture have the potential to motivate project managers to overlook such factors. For example, Leach et al. (2012) point out that anthropogenic dark earths have historically been, and are currently being developed within agricultural communities in African countries like Liberia. This activity is cultural and is not motivated by international carbon markets. This raises concerns that indigenous practices in developing nations could possibly be subsumed by increased investment in carbon markets. Such possibilities raise the concern that people and land in developing countries could be exploited by market investors, at the expense of the health and well-being of local populations that actually manage the land where biochar practices are implemented. This could lead to environmental justice issues. Leach further asserts that biochar research and development investment may be directed toward carbon market needs and interests at the expense of agronomic, ecological, social and political understanding. Given the current state of biochar's incorporation into carbon markets, these issues appear speculative, but they are valid concerns that should be incorporated in public policy discussions, especially where international markets are concerned.

Other organizations that are skeptical or openly critical of bioenergy systems have also extended those concerns to biochar systems. For example, Biofuelwatch is an organization that specifically rejects carbon trading and other programs that "commodify nature," (Biofuelwatch 2013), and has critiqued the development of biochar systems as a public policy tool. These issues of social and environmental justice are important, but are not analyzed further here. Such concerns should be considered when developing public policy, especially where large, international capital markets are involved.

Discussion

Based on the foregoing information, increases in managed biochar systems would appear to be a useful tool in the fight against climate change. Lehmann et al. (2006) discusses the global carbon cycle with estimates of global carbon sinks that were published in the IPCC third assessment report from 2001. In this assessment, the capacity of available sinks were considered to be the atmosphere (730 Pg), vegetation (500 Pg), the soil (1,500 Pg), the oceans (38,000 Pg), and geological reservoirs (5,000 to 10,000 Pg). That assessment also estimated fluxes of carbon between sinks due to natural and anthropogenic causes. The net increases due to anthropogenic activity from this analysis can be considered as 1.9 Pg/yr C from atmosphere to ocean, and a net 3.3 Pg/yr C from geologic reservoirs (fossil fuels) to the atmosphere. However, emissions have increased globally since then. An estimate from Friedlingstein et al. (2010) suggests global emissions in 2009 were 9.1 Pg C. Lehmann et al. (2006), Woolf et al. (2010) and others have projected "sustainable" potential offsets from biochar ranging up to 2 Pg/yr C. Lehmann et al. (2006) notes that if published projections of year 2100 biofuel use were all derived from pyrolysis systems, the offsets could conceivably reach over 5.5 Pg/yr, which would exceed 2006 fossil fuel emissions rates. As a wedge against climate variation, biochar seems to be a tool worth pursuing. However, to place biochar in context, we must consider its costs and benefits with alternative actions. The economics of biochar systems are not yet clear, and actual implementation will depend greatly on energy prices, government or other incentives, and other financial factors.

These estimates of maximum biochar benefits are likely to be overly optimistic for economic reasons. As discussed, no carbon market systems currently offer compensation for biochar production as an offset alone. Roberts et al. (2010) analyzed projected costs of biochar production and found a wide range of economic results under scenarios utilizing various feedstocks and considering the costs and revenue likely to be achieved with pyrolysis systems. These scenarios included projected revenue per ton of biochar from offsets as well as revenue streams from produced energy, etc., and some were profitable with offsets priced as low as $2 per ton. However, others would only be profitable at prices of $80 per ton or higher. EU ETS prices for carbon emissions and offsets have ranged from over 20 euros per ton down to about 6 euros per ton between 2008 and 2012. The California market achieved an initial auction price just over $10 per ton in 2012.

The economic feasibility of biochar projects are likely to vary greatly. Biochar is a marketable commodity, and recent prices for biochar sold as a garden amendment range up to $1,000 per ton. This of course, will change over time as supply and demand change, and may be based largely on characteristics of the char. As the economic impacts of climate change continue to increase, increased demand for mitigation will also increase, and the search for economically feasible responses will flourish. These economic uncertainties will reveal themselves over time. However, it is clear that biochar systems, to some degree, will be profitable from a cost/benefit perspective that includes the monetized environmental costs of climate change.

Alternative climate responses include reductions in fossil fuel emissions which can be achieved through efficiency or alternative energy programs. Additionally, there are carbon sequestration efforts such as afforestation and carbon capture and storage (CCS), which is the collection of combustion emissions as gasses with deep underground storage. These techniques are certain to be pursued, but they only have the potential to stabilize (not reduce) GHG concentrations in the atmosphere, and stabilization is not anticipated for many decades due to our dependence on fossil fuels for energy. The carbonization of biomass is the only current, feasible strategy that uses natural photosynthesis and managed biochar production to reverse the process of fossil fuel combustion, and store mineralized carbon underground. This technique has been practiced in the past and is currently practiced in rural agricultural systems due to the process' agronomic benefits. Current energy systems that are operating profitably and producing biochar (albeit on a small scale) also currently exist. In summary, as climate change progresses and biochar research advances, it seems likely that the magnitude of biochar producing systems will increase to a large, but yet unknown, extent.

A Framework for Carbon Accounting for Biochar Systems

Lehmann & Joseph (2012) asserts that adoption of biochar production systems may occur across multiple sectors and to varying extents, because biochar projects will address different objectives and operate on different scales. For example, the results of ongoing biochar research and development may encourage a large number of small, widelydistributed electrical generation stations that produce biochar, using locally-available biomass in pyrolysis or gasification systems. Also, new projects could emerge in the form of larger-scale, grid-connected bioenergy plant operations using, for example, biomass from forest thinning, municipal green waste collected and centrally-located at a landfill or waste transfer station, or manure from large animal management operations such as feedlots. Increased activity might also result in commercial sales of biochar for greenhouse potting operations, sales for individual farm operations or for residential or urban landscapes, or in the form of rural small-scale agricultural systems. Biochar also has the potential to be used to remediate soils that are degraded from mining or previous agricultural use, or even as a filtration medium to prevent contamination of water from agricultural chemicals. Some of these possibilities result from a likelihood that biochar will have significant value as an end product, in and of itself. Biochar-producing systems can also sustainably produce bioenergy at rates that match or exceed biofuel combustion systems.

In light of these many opportunities, it is likely that significant quantities of biochar will be produced. However, due to the limitations of carbon market incentives upon biochar production, it is probable that a large percentage of biochar projects will not be accounted for and monitored within the protocols of carbon market mechanisms. Therefore, alternative carbon accounting methods and databases may become important to reasonably evaluate and quantify the climate mitigation effects and other environmental costs and benefits of these biochar systems.

A brief review of current California biomass plants that are potential biochar-generating systems supports the view that biochar projects will multiply with or without offset incentives. According to one analysis, there are currently in California five gasification biomass energy projects, including three small demonstration projects, one small (500 kilowatt) grid-connected active gasifier, and one larger (3 megawatt) plant under development (Mayhead et al. 2011). The company that operates the small, active gasifier currently markets the biochar produced for sale online (Phoenix Energy Systems 2013). None of these plants currently contributes or is expected to contribute data on produced biochar amounts or specific data on offset characteristics to carbon offset databases or programs. In situations such as these it would be useful to gather information to estimate the effects of these and similar systems on atmospheric carbon balance and climate. This is especially true if such projects multiply rapidly in number.

Ideally, to capture biochar information across all project types, a registry with prescribed data collection methods and project parameters would be established. The specific parameters that would be necessary for evaluation may vary across projects, but the critical information needed to adequately assess the climate impacts of a biochar project include (but may not be limited to) the following:

- The amount of biochar produced over time.
- Information on the carbon content of the biochar, and the labile (volatile or easily decomposed) and recalcitrant fractions of the biochar (which could be measured or potentially modeled).
- The disposition of the biochar after production (combusted, landfilled, or applied to soil in known or unknown locations).
- Information on the feedstock to assess the lifecycle emissions of the produced material. This would include information on the composition, source, location of origin, and sustainability of the feedstock stream.

- Quantitative information on the disposition of the energy produced (kilowatt hours of electricity, BTU of useful heat, etc.) and the source(s) of energy that would be offset by the produced energy (to measure fossil fuel offsets).
- Ideally – if available – information on the lifecycle energy inputs used to produce the feedstock (for life cycle emissions analysis).
- Ideally – if available – the characteristics (before and after) of the soil to which biochar is applied, and ongoing monitoring of the soil to assess soil carbon stocks over time, increases in productivity, and other analytical data that may be used to evaluate the additional offset characteristics or economic benefits of the project, such as improved water quality

Tables 2a through 2d exhibit a proposed set of data that could be used to populate a database for such a tracking system. Many of the data fields in Table 2 are taken from the publication entitled "A Guide to Conducting Biochar Trials," a document prepared by Julie Major (Major 2009) for the International Biochar Initiative. The document was intended as a recommended set of parameters to consider for data collection for biochar research trials, intended to assess various aspects of biochar research efforts. I have adapted and expanded the list of parameters here to include additional aspects that could be used to assess climate mitigation impacts across multiple projects.

Table 2a. Chemical analysis of biochar

Biochar chemical parameter	Value	Units	Method reference	Method description
General Chemistry Parameters				
pH in water		pH units		
pH in KCl		pH units		
pH in CaCl		pH units		
Total C		Percent		
Volatile C		Percent		
Fixed C		Percent		
Labile C		Percent		
Total N		Percent		
C/N		Ratio		
H/C		Ratio		
O/C		Ratio		
Ash		Percent		
Available Ca		mg/kg		

Biochar chemical parameter	Value	Units	Method reference	Method description
Available Mg		mg/kg		
Available P		mg/kg		
Available K		mg/kg		
Dioxins				
Chlorinated Dioxins		µg/kg TEQ		
Polynuclear aromatic hydrocarbons				
Acenaphthene		µg/kg		
Acenaphthylene		µg/kg		
Anthracene		µg/kg		
Benz(a,h)anthracene		µg/kg		
Benzo(b)fluoranthene		µg/kg		
Benzo(k)fluoranthene		µg/kg		
Benzo(g,h,i)perylene		µg/kg		
Chrysene		µg/kg		
Dibenz(a,h)anthracene		µg/kg		
Fluoranthene		µg/kg		
Fluorene		µg/kg		
Indeno(1,2,3-cd)pyrene		µg/kg		
Naphthalene		µg/kg		
Phenanthrene		µg/kg		
Pyrene		µg/kg		
Other		µg/kg		
Metals				
Arsenic		µg/kg		
Beryllium		µg/kg		
Cadmium		µg/kg		
Chromium		µg/kg		
Copper		µg/kg		
Manganese		µg/kg		
Molybdenum		µg/kg		
Nickel		µg/kg		
Lead		µg/kg		
Selenium		µg/kg		
Thallium		µg/kg		

Table 2b. Biochar physical parameters

Biochar physical parameter	Value	Units	Method reference	Method description
Surface area		m^2/g		
Cation Exchange Capacity (CEC)		$mmol_c/kg$		
Pore volume		cm^3/g		
Pore size range	/	nm min/max		
Bulk density		kg/m^3		
Earthworm avoidance test				

Table 2c. Biochar production characteristics

<table>
<tr><th>Production characteristic</th><th colspan="3">Characteristic description</th></tr>
<tr><td>Feedstock</td><td colspan="3"></td></tr>
<tr><td>Feedstock source/location</td><td colspan="3"></td></tr>
<tr><td>Feedstock pretreatment</td><td colspan="3"></td></tr>
<tr><td>Peak temperature</td><td colspan="3"></td></tr>
<tr><td>Residence time</td><td colspan="3"></td></tr>
<tr><td>Process type</td><td colspan="3">Gasification, etc.</td></tr>
<tr><td>Equipment description</td><td colspan="3"></td></tr>
<tr><td>Batch manufacture start date</td><td></td><td>Electricity produced (kWh) – batch</td><td></td></tr>
<tr><td>Batch manufacture end date</td><td></td><td>Disposition of electricity</td><td>(Used on-site, sold to, etc.)</td></tr>
<tr><td>Syngas produced</td><td colspan="3">Amount produced, disposition</td></tr>
<tr><td>Bio-oil produced</td><td colspan="3">Amount produced, disposition</td></tr>
</table>

Table 2d. Biochar disposition and application

Parameter	Data
Was biochar combusted for energy?	Yes/No/Unknown/% of batch combusted
Were carbon market offsets allocated?	If yes, program, protocol, serial numbers of offsets

Parameter	Data
Was biochar sold/delivered to multiple locations?	Yes/commercially marketed/application location(s) are unknown
Was biochar landfilled?	
Is location of soil application known?	
If application location is known, additional soil measurement parameters if available	
Location of application (if known)	Latitude/longitude in decimal degrees; area (m^2) to which biochar was applied, description
Application rate	kg/ hectare
Date(s) of application	
Soil taxa	Soil order, suborder, and great group.
Soil texture	
Depth of application	
Describe method of application and incorporation	
Physical and chemical characteristics of soil to which biochar is applied, before and after application	Sampling locations, dates, and results for total carbon, organic carbon, pH, CEC, etc.

The measurement parameters and associated descriptive data presented in the tables 2a through 2d are not meant to represent a comprehensive set of data for tracking biochar projects, but rather a starting point for further consideration. If such information were incorporated into a database, the information available from multiple projects of various types could conceivably be assimilated and used in the development of models, or analyzed to produce estimates of GHG mitigation effects of multiple projects. A registry with the data indicated above could be developed and maintained to facilitate these analyses, in the absence of other tracking programs. Not all parameters will necessarily be tracked by all projects, because there is no centralized oversight entity for all biochar projects. However, if such a database was created and maintained, the data that are available could be gathered and used to analyze relationships across project parameters, or the data could be applied, as appropriate, to models that are developed from additional research. For example, if the recalcitrance of biochar associated with specific measured conditions is demonstrated, estimates of the sequestration potential over time, across multiple, registered projects could be calculated. Again, this is not a comprehensive set of possible parameters that is adequate to model all types of biochar production systems. Rather, it is a starting point, or basis, that could be used and expanded upon, to begin data collection on multiple projects with a goal of developing methods to quantify the GHG offset potential of projects that are not otherwise characterized by researchers or climate analysis organizations.

Conclusions

In light of the foregoing information, I offer the following conclusions.

Biochar production and incorporation in soil must play a role in climate change mitigation. The stabilization of biomass carbon to carbonized biochar under sustainable protocols is not only an interesting idea; it is likely that this approach will be an imperative component in a multi-phased strategy to reduce and offset GHG emissions on a global scale. Biochar production is arguably the *only* currently known, economically feasible method for reducing carbon dioxide concentrations in the atmosphere on centennial to millennial time scales. GHG concentrations that may cause serious or even catastrophic climate change impacts are likely to be reached, or may already be present (Molina et al. 2009). In addition to reductions in fossil fuel emissions, the removal of carbon from the atmosphere, and its sequestration on centennial or millennial time scales will be required if climate impacts are to be mitigated. Carbon capture and storage (CCS) from stationary fossil fuel combustion is a carbon-neutral strategy, but does not reduce concentrations already in the atmosphere. CCS is also not currently feasible for transportation fossil fuel combustion, and is only beginning to be practiced on a small scale for stationary combustion. Sequestration of carbon in living biomass (trees) can temporarily reduce CO_2 from the air on decadal time scales, and is an important component of climate mitigation. However, on centennial or millennial time scales, it is likewise a carbon neutral strategy. Carbon in managed forests will ultimately be returned to the atmosphere through decomposition over time. The photosynthesis/decomposition cycle of biomass will continually approach an equilibrium that includes the addition of anthropogenic fossil fuel carbon contributions, such that atmospheric concentrations of CO_2 and methane will likely not attenuate over centennial time scales based on afforestation alone.

At scale, biochar projects have the potential to feasibly and sustainably sequester/offset over 1 Pg of CO2-carbon equivalents annually. This represents a significant reduction of current anthropogenic GHG emissions (CO_2, CH_4 and N_2O as carbon equivalents). The percentage of the fossil fuel GHG emissions that could be offset with biochar systems is likely to increase if these anthropogenic emissions are reduced over time. If the use of biofuel systems increases beyond current estimates, the role of biochar sequestration could have an even larger impact.

Current carbon market incentives are not sufficient to rapidly increase or maximize the initiation and development of biochar project implementation. The CDM, EU ETS, and California carbon trading markets do not currently offer offset payments for carbon sequestration via biochar production. Major voluntary markets likewise do not currently recognize biochar directly as an offset mechanism. Carbon offset protocols for biochar have been proposed and drafted, and biochar may become a significant carbon offset mechanism within established markets, if approved biochar protocols are added to existing market systems. However, existing carbon markets will not provide sufficient incentive to maximize biochar's climate change mitigation potential, due to limitations on the volume of offsets allowed for use within established markets, competition among offset project types, and the magnitude of biochar's global potential to mitigate emissions.

Other financial instruments such as subsidies and grants from carbon market proceeds, or tax incentives could be used to accelerate biochar implementation, especially by reducing start-up costs for new projects. If the economic benefits of biochar as an agricultural soil amendment become well established, or if biochar's other external environmental benefits such as water quality protection are monetized, biochar projects can and likely will become economically self-sustaining, and the industry will grow. Some biochar-producing energy projects could also be self-sustaining. However, this growth could be increased by public financial support for project initiation costs. If the economic benefits of these additional advantageous biochar aspects are not realized, it is likely that financial incentives will continue to be needed to spur investment in projects. This is due in part to the incentive to extract all of the economic value of biomass carbon as a fuel by burning it, in the absence of other financial streams to promote the production of biochar.

From a policy perspective, incentives for biochar systems should be prioritized for projects that maximize carbon sequestration benefits, and for projects with the greatest economic feasibility. The potential climate change mitigation effects and economic benefits of biochar projects are not equal across all project types and circumstances. Systems that carry the greatest carbon offset potential based on reasonable project life cycle analyses, and those projects that are likely to achieve sustainable environmental and economic co-benefits should receive the highest prioritization with regard to distribution of limited financial assistance for project initiation.

Uncertainty regarding the recalcitrance of biochar in soil should not inhibit efforts for project initiation and development. Instead, the ongoing acquisition of data from multiple projects should inform biochar project carbon accounting. It is relatively certain that biochar additions to soil will sequester significant amounts of carbon for >100 years. If developed for existing carbon markets, biochar offset protocols will include methodology for the quantitative modeling and/or monitoring of sequestered carbon and avoided emissions. As biochar projects are likely to increase in frequency outside of carbon market protocols, databases and models should be developed and used to estimate the carbon sequestration and offset benefits of biochar production with regard to GHG concentrations and climate effects. The framework presented in this paper could be expanded upon to develop such accounting methodology.

Biochar projects should be pursued despite economic and logistical conditions that may favor biomass combustion. Biomass combustion for thermal energy and electricity generation or other useable energy may achieve considerable emissions offsets, approaching those of biochar systems, and economic and logistical considerations may favor these systems. However, biomass combustion does not achieve the biochar co-benefits of 1) soil amendment (increased agricultural productivity), 2) potential reduction in emissions from soil of CH_4 and N_2O, 3) surface and groundwater quality improvement due to adsorption of N and pesticides that may be achieved by biochar, 4) indirect reductions in GHG emissions associated with lowered agricultural irrigation and fertilizer use, and avoided deforestation for additional agricultural acreage that may be achieved with biochar use, and 5) most importantly, removal of carbon from the atmosphere, reducing GHG atmospheric concentrations over time.

A comprehensive carbon-accounting framework and analysis of biochar systems (including biochar systems that are not part of a carbon-trading market) should be established to evaluate the ongoing global impact of biochar production upon net GHG emissions.

Biochar may become a significant wedge against climate change. Some biochar systems have been implemented and many more may be developed that will not be represented by the methods and metrics of carbon trading systems. Public policy should include an effort to characterize as many biochar systems as possible, and quantify the global impact of these systems. Biochar systems should continue to be pursued and the impacts studied to characterize the overall environmental and economic benefits of biochar, in light of the great potential of its multiple benefits.

References

Bates, A. (2010). *The Biochar Solution: Carbon Farming and Climate Change*. New Society Publishers.

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., & Davidson, O. (2007). Climate change 2007: synthesis report. Summary for policymakers.

Biofuelwatch. (2013). Biofuelwatch policy. Retrieved March 23, 2013 from http://www.biofuelwatch.org.uk/?s=commodify+nature

Brown, R. A., Kercher, A. K., Nguyen, T. H., Nagle, D. C., and Ball, W. P. (2006). Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. Org. Geochem. 37, 321–333.

Eagle, A. J., Henry, L. R., Olander, L. P., Haugen-Kozyra, K., Millar, N., & Robertson, G. P. (2010). Greenhouse gas mitigation potential of agricultural land management in the United States. *A Synthesis of the Literature. Technical Working Group on Agricultural Greenhouse Gases (T-AGG) Report*. Nicholas Institute for Environmental Policy Solutions. Duke University. Retrived March 23, 2013 from http://nicholasinstitute.duke.edu/sites/default/files/publications/TAGGDLitRev-paper.pdf

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., ... & Van Dorland, R. (2007). Changes in atmospheric constituents and in radiative forcing. *Climate change*, *20*.

Friedlingstein, P., Houghton, R. A., Marland, G., Hackler, J., Boden, T. A., Conway, T. J., ... & Le Quéré, C. (2010). Update on CO2 emissions. *Nature Geoscience*, *3*(12), 811-812.

Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The'Terra Preta'phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, *88*(1), 37-41.

Hale, S. E., Lehmann, J., Rutherford, D., Zimmerman, A. R., Bachmann, R. T., Shitumbanuma, V., ... & Cornelissen, G. (2012). Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. *Environmental science & technology*, *46*(5), 2830-2838.

International Biochar Initiative. (IBI). (2008). How much carbon can biochar systems offset-and when. Retrieved March 18, 2013, from http://www.biochar-international.org/sites/default/files/final%20carbon%20wpver2.0.pdf

International Biochar Initiative. (IBI). (2010). IBI Research Summary: Biochar Recalcitrance in Soil. Retrieved March 18, 2013, from http://www.biochar-international.org/sites/default/files/IBI-RS-recalcitrance-2-Apr-2010..pdf

IPCC. (2002). Watson, R. T. (Ed.). *Climate change 2001: Synthesis report: Third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Laird, D. A. (2008). The charcoal vision: A win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, *100*(1), 178-181.

Leach, M., Fairhead, J., & Fraser, J. (2012). Green grabs and biochar: revaluing African soils and farming in the new carbon economy. *Journal of Peasant Studies*, *39*(2), 285-307.

Lehmann, J., & Rondon, M. (2006). Bio-char soil management on highly weathered soils in the humid tropics. *Biological approaches to sustainable soil systems. CRC Press, Boca Raton, FL*, 517-530.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems–a review. *Mitigation and adaptation strategies for global change*, *11*(2), 395-419.

Lehmann, J. (2007). A handful of carbon. *Nature*, *447*(7141), 143-144.

Lehmann, J., & Joseph, S. (Eds.). (2012). *Biochar for environmental management: science and technology*. Routledge.

Liang, B., Lehmann, J., Solomon, D., Sohi, S., Thies, J. E., Skjemstad, J. O., ... & Wirick, S. (2008). Stability of biomass-derived black carbon in soils. *Geochimica et Cosmochimica Acta*, *72*(24), 6069-6078.

Major, J. (2009). A Guide to Conducting Biochar Trials. International Biochar Initiative. Retrieved March 23, 2013, from http://www.biochar-international.org/sites/default/files/IBI_Biochar_Trial_Guide_final.pdf

Mayhead, G., & Tittmann, P. (2012). Outlook: Uncertain future for California's biomass power plants. *California Agriculture*, *66*(1), 6-6. Retrieved March 23, 2013 from http://ucanr.org/repository/CAO/landingpage.cfm?article=ca.v066n01p6&fulltext=yes

Meyer, S., Glaser, B., & Quicker, P. (2011). Technical, economical, and climate-related aspects of biochar production technologies: a literature review. *Environmental science & technology*, *45*(22), 9473-9483.

Molina, M., Zaelke, D., Sarma, K. M., Andersen, S. O., Ramanathan, V., & Kaniaru, D. (2009). Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO2 emissions. *Proceedings of the National Academy of Sciences*, *106*(49), 20616-20621.

National Aeronautics and Space Administration (NASA). (2013). Global Climate Change: Vital Signs of the Planet. Retrieved March 18, 2013, from http://climate.nasa.gov/causes

National Research Council (US). Panel on Advancing the Science of Climate Change, & National Research Council (US). Board on Atmospheric Sciences. (2010). *Advancing the science of climate change*. National Academy Press.

Phoenix Energy Systems. (2013). All Biochar Products. Retrieved March 23, 2013, from http://www.phoenixenergy.net/shop

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environmental Science & Technology*, *44*(2), 827-833.

Sohi, S., Lopez-Capel, E., Krull, E., & Bol, R. (2009). Biochar, climate change and soil: A review to guide future research. *CSIRO Land and Water Science Report*, *5*(09), 02.

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A review of biochar and its use and function in soil. *Advances in Agronomy*, *105*, 47-82.

Stevenson, S., Morris, B., Martin, N., Grady, M., (2012). Compliance offset supply forecast for California's cap-and-trade program (2012-2020). American Carbon Registry. Retrieved March 23, 2013 from http://americancarbonregistry.org/acr-compliance-offset-supply-forecast-for-the-ca-cap-and-trade-program

Weisberg, P., Delaney, M., Hawkes, J., (2010). Carbon Market Investment Criteria for Biochar Projects. Public Interest Energy Research (PIER) Program. Retrieved March 23, 2013 from http://www.biochar-international.org/node/2426

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature communications*, *1*, 56.

Zhang, A., Cui, L., Pan, G., Li, L., Hussain, Q., Zhang, X., ... & Crowley, D. (2010). Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agriculture, Ecosystems & Environment*, *139*(4), 469-475.