

Evaluation of the Opportunities for Generating Carbon Offsets from Soil Sequestration of Biochar

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List of Acronyms

Acronym	Definition
AFOLU	Agriculture Forestry and Other Land Use
AG	Aboveground
A/R	Afforestation/Reforestation
ASTM	American Society for Testing and Materials
BC	Black carbon
C	Carbon
CEC	Cation Exchange Capacity
CER	Carbon Emission Reduction
CDM	Clean Development Mechanism
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
CO ₂ e	CO ₂ -equivalent
DOC	Dissolved Organic Carbon
EPA	United States Environmental Protection Agency
GHG	Greenhouse gas
GJ	Gigajoule
Gt	Gigaton
H ₂	Hydrogen gas
H ₂ O	Water
Ha	Hectare
IC	Inorganic carbon
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
km	Kilometer
m	Meter
Mg	Mega gram
MIR	Mid Infrared
MJ	Mega joule
MRT	Mean Residence Time
MSW	Municipal Solid Waste
MT	Metric Ton
N	Nitrogen
NH ₄ ⁺	Ammonium
N ₂ O	Nitrous oxide
NIR	Near Infrared
NMR	Nuclear Magnetic Resonance
NPP	Net Primary Productivity
OC	Organic carbon

OM	Organic matter
PAH	Polycyclic aromatic hydrocarbon
RFS	Renewable Fuels Standard
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TOC	Total Organic Carbon
TIC	Total Inorganic Carbon
µm	Micrometer
USDA	United States Department of Agriculture
MRT	Mean Residence Time
MSW	Municipal Solid Waste

Executive Summary

The production and application of biochar into the soil offers solutions to a number of important problems:

- Mitigation of climate change by reducing GHG emissions and sequestering carbon from biomass
- Production of energy from the pyrolysis process in which biomass is transformed into biochar
- Soil improvement through the application of biochar as a soil amendment
- Management of waste streams from agriculture, forestry, and municipal sources

This paper looks at important issues related to the production and application of biochar and how a protocol can be developed that can account for carbon sequestration from its production and use for the purpose of offsetting GHG emissions. To keep this review and analysis manageable, the scope of the paper is limited to:

- Only biochar produced from plant biomass, such as agricultural residues, bio-energy crops, yard waste, or forest slash or mill waste, but not from municipal solid waste, manures, or paper waste.
- Only carbon offsets from soil biochar incorporation, and not carbon offsets from fuel displacement associated with the energy potentially co-generated during pyrolysis.
- United States as the primary geographical scope of the discussion.

The key factors that have been identified for consideration in the creation of a Biochar protocol are:

Measurement and Accounting of Sequestration for Carbon Offset Purposes

- GHG accounting of carbon sequestration through biochar soil incorporation is complex but not impossible to manage.
- The complexity does not originate so much from a lack of scientific understanding, or technical capacity to measure GHG removals and emissions, but from the enormous number of possible scenarios in which plant biomass can be used and the numerous ways biomass is converted into biochar, and subsequently, incorporated into an agricultural soil.
 - This complexity makes it challenging to comprehensively account for secondary emissions and possible activity-shifting leakage effects through land-use change.
 - In addition, to meet additionality criteria for crediting sequestration from biochar, it is necessary to determine what would have happened to the biomass used in the production of biochar in the absence of a project.
 - In most cases, it will be challenging for a third-party verifier to verify any statements made by project proponents on the exact feedstock of biochar, and the level of emissions associated with production and transportation of biochar.
 - To address these concerns, a carbon offset protocol should focus on a limited set of project types for which the baseline disposition of feedstocks can be

determined with sufficient certainty. Suggested project types are listed below, under “Recommendations.”

- Biochar accumulation can be relatively easily monitored compared to other types of soil carbon sequestration.
- However, there may be considerable uncertainty about how much biochar will remain in soil over long periods (e.g., 100 years), which is critical for determining how much credit should be given for offsetting GHG emissions.
 - Longevity will depend on the chemical composition of the original biomass used to produce biochar; production parameters during pyrolysis; soil type where the biochar is incorporated; micro-climate of the agricultural system where biochar is incorporated; and the cultivation system used.
 - Longevity can be predicted with sufficient accuracy using a mathematical decomposition model combined with monitoring data on the fraction of labile and resistant matter in biochar material (Section 2.3). However, there is currently no generally accepted methodology to quickly, accurately and robustly measure this fraction.
 - Rapid, accurate and robust techniques must be developed to test the fraction of resistant matter in biochar that do not take years or months but weeks or days so that some kind of certification can be provided and producers and consumers of biochar alike can know what they are using.
 - A set of generalized coefficients to predict the effect of microclimate and soil type on biochar decomposition for ex-ante use must also be developed.
 - A maximally allowed amount of biochar that can be incorporated, expressed as tons per acre, must be established.
- GHG emissions from the production, processing, transportation, and incorporation of biochar need to be examined to fully account for the net effects of any project activity on GHG emissions.
- Once sequestered, biochar carbon has a low risk of unintentional reversal (i.e., re-emission to the atmosphere). Intentional reversal risk should be mitigated through project and landowner eligibility requirements.

Benefits of Biochar

- Lifecycle Analysis (LCA) shows clearly that there are GHG emissions reductions of various magnitudes, depending upon the feedstock used, and the pyrolysis system employed.
- LCA demonstrates that there is net energy production from any kind of pyrolysis system.
- Research has demonstrated there is a wide range of potential non-GHG benefits resulting from biochar use in agricultural systems. These include: enhanced soil fertility, improved soil physical properties, higher plant productivity, reduced leaching of nutrients, reduced GHG emissions, tighter nutrient cycling in resource poor agricultural systems, better water infiltration, and lower irrigation costs.

Science

- Biochar feedstocks and the pyrolysis process need to be thoroughly characterized in order to accurately determine the carbon sequestration potential of various types of biochar systems.
- Biochar stability in soils is central to its effectiveness in sequestering carbon and delivering other important benefits. A fraction of studied biochar is very stable over very long time periods, with a Mean Residence Time (MRT) from hundreds of years to millennia. For the purposes of a carbon offset protocol, the proportion of stable biochar would need to be determined for each manufacturing process and feedstock type.
- Further studies are needed on the influence of biochar on the decomposition of soil organic matter.
- Research indicates that there is little risk from dioxin production via biomass pyrolysis due to the thermochemical reactions of pyrolysis. Polycyclic aromatic hydrocarbon (PAH) contamination of biochar is also low risk at most biochar production temperatures. Heavy metal contamination of biochar is minimal if MSW, sewage sludge and other potentially contaminated material are avoided. Biochar ash content is highly variable and dependent on the type of feedstock used. Interactions between high ash content biochar and high pH soils needs to be better understood prior to application.

Industry and Technology

- The biochar industry is in its infancy. Companies have developed slow pyrolysis, fast pyrolysis and gasification systems for biochar production but there are very few commercially operational manufacturers of equipment or producers of biochar. Some companies are concentrating on biochar production- particularly those with slow pyrolysis systems, while others are producing bio-oil and biochar together, intending to make most of their profits from the production of bio-oil to satisfy requirements of the Renewable Fuels Standard. But many technical issues remain to be resolved with respect to bio-oil production, refining, and use.
- Activity is increasing in the equipment production domain and what we see currently will undoubtedly be different in two, five, or ten years. A variety of systems is or will be available on the market, though no single kind of technology dominates the market. A testing period of several years will be the norm to perfect and fully develop the technological solutions offered by producers.

Economics

- Obtaining reliable cost and return figures for the production of biochar is problematic given the underdeveloped nature of the industry.
- Competition for the use of biomass that biochar production requires may increase as Renewable Fuels Standards come into force and energy and fuel production from biomass becomes more the norm. This could limit the development of the biochar industry.
- Given that the biochar industry is in its infancy, it is reasonable to expect that technological advancements will allow for emergence of several dominant technologies

that will help drive the growth of the industry and will lower costs. One example is a company that is developing an industrial scale microwave oven for biochar production, which has the potential to increase efficiency and reduce costs dramatically.

- The potential value of biochar as a source of sequestration is superior to the potential value of producing biochar for energy production. The sequestration potential is enormous, and so its potential value is quite significant. Other benefits such as bio-oil production are so far unproven.
- Changes in technology and the ability to generate carbon offsets from biochar will affect biochar production facilities differently: large-scale plants may be less profitable and biomass might be more profitably turned into energy, bio-coal or used for ethanol or electrical energy production.

Market Development

- Given current biochar technology and production costs, current prices in the voluntary carbon market are unlikely to provide sufficient incentive for biochar production and incorporation in soils in the absence of other revenue streams. Projects may be viable, however, if they are able to monetize the multiple co-benefits and by-products that biochar production and use can generate.

Recommendations

- At first, a biochar protocol should focus on high-priority circumstances where accounting and baseline uncertainties can be managed, with the possibility of expansion of the protocol when more research is available for a more comprehensive inclusion of biochar systems.
- The most challenging parts of the GHG accounting for biochar soil incorporation projects are the secondary emissions and potential activity-shifting leakage effects through land-use change. Thus, for the first phase of protocol development, we propose to only allow carbon credits from biochar produced under the following conditions:
 - Case 1 - Biochar from slow pyrolysis of corn stover that is left on agricultural fields under the baseline scenario
 - Case 2 - Biochar from slow pyrolysis of switchgrass produced on marginal or degraded land with limited current land use with potential cogeneration of energy
 - Case 3 - Biochar from slow pyrolysis of yard waste that is deposited in land-fills or composted under the baseline scenario
 - Case 4 - Biochar from slow pyrolysis of forest waste that is left to decompose under the baseline scenario
- Before the more complex project circumstances can be integrated in a protocol, more understanding is needed to comprehensively quantify potential emissions and emission reductions at multiple sources, sinks, and reservoirs.
- Challenges of indirect land use change due to feedstock production are similar to those found in any bioenergy approach. Therefore, it is recommended to build upon the experience regarding estimation of indirect land use change from the bioenergy sector.

1 Introduction and Background

1.1 Objectives and Limitations

Biochar is the product of the thermal transformation of organic matter such as crop residues, wood or grasses, in a process called pyrolysis (Lehmann 2007a, 2007b). When incorporated into a soil, biochar is more resistant to microbial decomposition than the original organic materials used to produce the biochar. In addition, biochar additions may improve soil fertility by improving soil nutrient retention capacity and by enhancing water infiltration (Lehmann et al. 2006). Therefore, the production of biochar and its subsequent incorporation in agricultural soils has been proposed as a potentially effective way to sequester carbon while improving soil fertility. As with any land-based carbon sequestration strategy, income streams from biochar carbon sequestration could partially alleviate the ever-increasing pressure on rural land users to generate sufficient income from their land while keeping production techniques sustainable, minimizing off-site pollution and soil degradation (De Gryze et al. 2009).

However, before a system can be developed in which carbon offsets are generated from biochar soil incorporation, many aspects of the process need in-depth analysis. It is essential to ask where the feedstock for biochar will come from. Many sources have been proposed: municipal green waste, forest slash waste, biomass waste from removing invasive plants, agricultural residues, saw mill residues, or other forest product waste streams. Many of the same sources of biomass as the ones considered for biofuel or bio-energy production are suggested, or are proposed to enlarge bio-energy production streams. Each of these feedstocks has its advantages and limitations.

For the purpose of quantifying net carbon sequestration and GHG reductions from biochar production, it is necessary to consider what would have happened to the feedstock biomass in the absence of such production. Such a scenario might be different for every type of feedstock, or even within types of a particular feedstock. In addition, secondary emissions from the production, incorporation, and transportation of the feedstock and the biochar must be subtracted to obtain the net greenhouse gas benefits from biochar. These secondary emissions are highly dependent on the distances between feedstock production and biochar production, and between the biochar production plant and the field into which the biochar is eventually incorporated. Also, since in many cases the biomass feedstock for biochar could be used for the production of renewable energy, it is also necessary to consider the net effect on GHG emissions of diverting the biomass to biochar, which would decrease the availability of renewable energy, and potentially cause leakage.

Consequently, calculating the actual net GHG benefits from incorporating biochar in a soil is a complex task. This complexity does not originate so much from a lack of scientific understanding, or technical capacity to measure GHG removals and emissions, but from the enormous number of possible scenarios in which plant biomass can be used and the numerous ways biomass is converted into biochar, and subsequently, incorporated into an agricultural soil.

This paper aims to provide a comprehensive review of the issues involved in generating carbon offsets from the production and incorporation of biochar into soil. Due to the complexity of the subject at hand, the discussion is deliberately kept within the following constraints:

- Only biochar produced from plant biomass is considered, and not from municipal solid waste (MSW), or from paper waste.
- Only carbon offsets from soil biochar incorporation are considered, and not carbon offsets from fuel displacement associated with the energy potentially co-generated during pyrolysis.
- The primary geographical scope of the discussion is the United States, even though we will integrate findings from foreign studies and production processes pioneered in different countries.

1.2 Fundamental Principle of Biochar Carbon Sequestration in Soils

Pyrolysis is a chemical process that converts decomposable organic matter into biochar, a relatively inert organic material. In other words, the process of biochar production changes the chemical composition of the organic material so that it more slowly converts back into atmospheric CO₂ compared to the feedstock from which it is derived under comparable environmental conditions. Even though both the original feedstock and the resulting biochar will eventually convert back to atmospheric CO₂, the timeframe of when this will happen for biochar is thousands of years, while the timeframe is only a couple of years for the original feedstock. Since it is believed that incorporating biochar material into agricultural soils also improves soil quality and productivity, soils are considered to be ideal sinks for biochar. This concept is illustrated in Figure 1. The thick line represents the baseline decomposition of the original biomass, which contains up to 90% labile carbon (C). The thin lines represent scenarios of conversion of biomass into biochar, with different levels of chemical recalcitrance, ranging from 50% labile C to 10% labile C. Carbon losses by pyrolysis average approximately 68% at high temperature and 30% at low temperature (depending upon feedstock and production conditions).

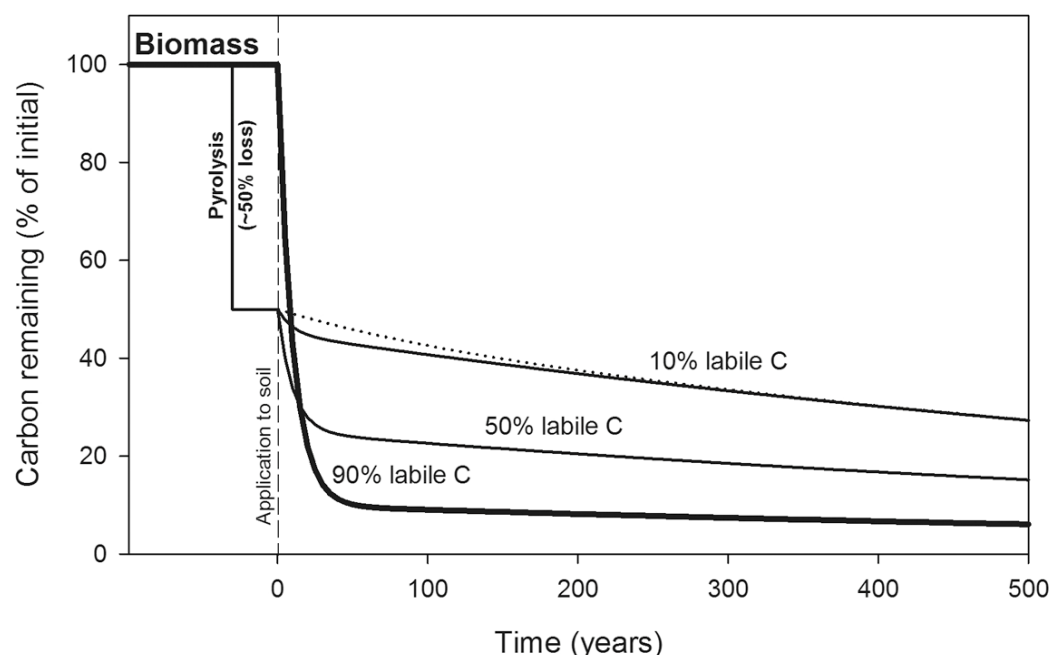


Figure 1. Conceptual model of C remaining from biomass using a decay model with a MRT of 10 years for the labile C pool and 1000 years for the stable C pool, but different proportions of labile C. Source: Lehmann and Joseph 2009

Despite the partial biological decomposition of biochar upon incorporation into the soil, the long-term stability of biochars that were pyrolyzed under the right circumstances appears to be at least one order of magnitude greater than that of non-pyrolyzed organic matter that was incorporated into soils under the same environmental conditions (Baldock and Smernik 2002; Cheng et al. 2008a; Liang et al. 2008). The stable fraction of biochar has an approximate mean residence time (MRT) of greater than 1,000 years (Cheng et al. 2008a; Lehmann et al. 2008; Liang et al. 2008; Zimmerman, 2010). The potential GHG benefits of biochar projects fundamentally relates to this greater long-term stability of carbon. However, to comprehensively assess the GHG benefits, the complete lifecycle of biochar production and use must be taken into account and compared to baseline scenarios.

Lifecycle of Soil Biochar Systems

A comprehensive greenhouse gas accounting methodology for the net emissions benefits from incorporation of biochar in soils should not only account for the amount of biochar C incorporated in the soil, but also for any other greenhouse gas that was produced or removed from the atmosphere to get the biochar in the soil. Such an accounting requires the biomass to be followed from the point it was produced to the point when it is incorporated as biochar into soils, accounting for all three of the major greenhouse gases (CO₂, CH₄, and N₂O) that were produced or removed from the atmosphere.

1.3 Typology of Feedstock

Feedstocks can come from a large number of sources of biomass. A distinction is made between primary sources of biomass and secondary sources of biomass, because it will impact the carbon accounting. **Primary sources** of biomass are grown for the purpose of producing bio-energy or biochar, while **secondary sources** consist of biomass that is already available and is co-generated during a different process. Producers of biochar and bio-oil have indicated they are technically able and willing to use any of the following kinds of biomass.

Primary Sources

- **Woody bio-energy crops** are fast-growing tree varieties such as poplar hybrids or willows grown in short-rotation systems. New varieties and culture techniques offer the capability for high yielding, sustainable production systems similar to grasses. Biomass from these systems is currently being used commercially for fiber and as dedicated biomass crops for bio-energy demonstration projects.
- **Agricultural bio-energy crops** are grown exclusively for energy production, potentially for biofuel. Plant species mostly consist of deep-rooting perennial warm-season grasses characterized by high nitrogen-use efficiencies (at least in the first year) such as Switchgrass (*Panicum virgatum*), which is a native prairie tallgrass, or *Miscanthus x giganteus*. There is potential for large-scale production of these species in the Mid-West. In many areas, there are serious concerns about the introduction of these species into agricultural systems because of their invasive nature. Furthermore, the success of the first generation of corn-ethanol production due to tax credits, import tariffs on raw sugar or bio-ethanol, and the reduction of the conventional Conservation Reserve Program (CRP), as part of the 2008 Farm Act, indicates the need for a policy decision to support the production of bio-energy crops.

Secondary Sources

- **Secondary forest biomass** from forest maintenance, forest fuel-load reduction, and harvesting procedures on forest and timber-land excluding urban areas. This includes sawdust, twigs, leaves, mill residues, pre-commercial thinnings, slash, brush, or non-merchantable material. Figure 2a indicates that productive timberland, and hence, the source of secondary forest biomass from forest management, is primarily located in the Pacific Northwest, the Mid-West, the Northeast, and some parts of the Southeast. Fuel-load management is a growing concern for the Western United States as fire severity and frequency increases each year (Figure 2b). Regular low-intensity forest fires are a natural and beneficial process that frequently removes dead wood and prevents the build-up of fuel wood, reducing the risk of high-intensity fires. However, the common practice of fire suppression has eliminated these natural low-intensity fires, and therefore increased the fuel load of forests to dangerous levels, which has led to severe fires. The US Forest Service now spends over a billion dollars in fire suppression each year. Often the secondary effects of wildfires, including erosion, introduction of invasive species, poor water quality, and adverse effects on human health are more

disastrous than wildfires. Currently fuel-load reduction is the most cost-effective way to combat wildland fire in the West.

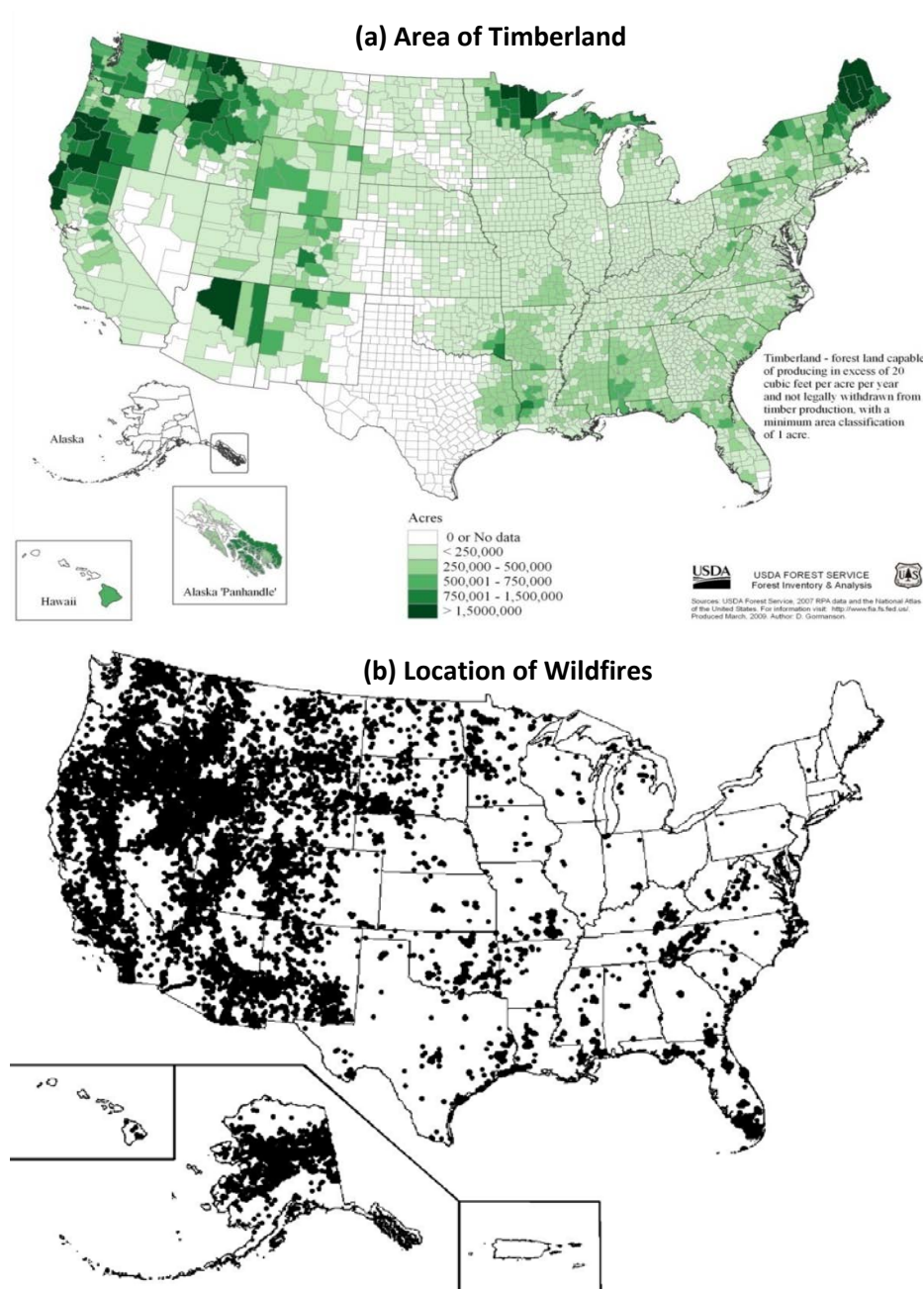


Figure 2. (a) Location of productive timberland in the U.S. in 2007. Source: USDA Forest Service. (b) Locations of wildfires greater than 250 acres, from 1980 to 2003. Sources: BLM, USFS, USFWS, BIA, NPS, and the USGS

- **Other solid wood waste** including waste pallets, crates, dunnage, manufacturing and construction wood wastes (other than pressure-treated, chemically-treated, or painted wood wastes), and landscape or right-of-way tree trimmings.
- **Secondary agricultural biomass** including straw, corn and rice husks, hulls, cherry pits, coconut shells, seeds, vineyard biomass trimmings, orchard tree crop biomass, and livestock and poultry waste. Crop residues that are harvested, baled, and used in the livestock and dairy industries such as corn stover and cereal straw are excluded from this feedstock category.
- **Municipal green waste and biomass from wastewater treatment.** Biomass from domestic green waste, which is often high in nitrogen, can be composed of garden or park waste, such as grass or flower cuttings and hedge trimmings, as well as domestic and commercial food waste. Sludge, a product from wastewater treatment, can also be used as a feedstock for biochar. The liquid sludge is often converted on-site to a more solid form. Most modern wastewater plants will maximize the on-site extraction of energy from the sludge, which makes the use of sludge for biochar less likely. Note that there is no risk of bacterial contamination if biochar derived from sewage sludge is incorporated in a soil since the pyrolysis process will completely sterilize the sludge.

Alternative Sources and Uses of Secondary Biomass

The fate of secondary biomass depends not only on the economics of its various alternative uses, but also on ecological and policy conditions. A change in these conditions can shift the biomass usage and alter the supply of biomass for biochar. For example, if a change in policy would promote – either financially or legally – the thinning of forests to reduce fire hazards (an option which is under study by the U.S. Forest Service), a significant volume of biomass would become more readily available. Alternatively, these fuels would remain in forests causing a significant fire risk, costing millions of dollars. The list below outlines other uses or fates of secondary biomass that may impact the availability of secondary biomass for biochar production.

- **Production of timber.** Timber from commercial thinning operations that are executed to promote forest health, manage fire risk, or to remove hazardous trees in urban areas, will be milled if the timber has any commercial value. However, given the economic value of timber, it is unlikely that biochar will be produced from sawmill-quality wood, unless costs to transport the wood to a mill are significantly higher than costs to transport the wood to a biochar production plant.
- **Decomposing on the soil.** Forest slash that is left during tree harvesting is usually left to decompose within the forest since it is too expensive and mechanically challenging to remove from the forest. Similarly, biomass from thinning operations that is of a pre-commercial size is often chipped and left in the forest. Most of this biomass decomposes within some years, and some of it will be converted into recalcitrant organic matter. In agricultural systems, certain components of the biomass of agricultural residues are currently left on the field. The proportion of the biomass that is left on the field varies depending on soil type, climate, and agronomic practices. This

biomass performs a critical ecosystem function by maintaining soil carbon levels, which promotes soil structural stability, improves infiltration and reduces the loss of soil to wind and water erosion. The sustainability of further removing this residue off-site is contested.

- **Conversion to a soil amendment such as compost or mulch.** The product left from sewage sludge and wastewater treatment plants is frequently turned into fertilizer pellets due to its high nitrogen content. Waste from urban forestry management is sometimes chipped and used as mulch. Municipal green waste is often used for compost production, which has commercial value.
- **Transportation to landfill and subsequent decomposition.** Biomass that is neither composted nor anaerobically digested may be disposed of in a landfill. Biodegradable waste in landfill breaks down to biogas containing methane and nitrous oxide, which is an environmental liability. Many municipalities and counties face environmental and economic constraints as landfills have become full and they are forced to find other waste disposal solutions. Although the burning of biomass is done under certain circumstances in urban as well as in rural settings, in most cases this is not a sustainable solution.
- **Invasive species or pest control.** A US Senate bill on weed and pest control is forthcoming. Instead of incinerating detritus such as woody and herbaceous invasive species or pest-affected biomass, such as pine bark beetle trash, the detritus could be pyrolyzed and converted to biochar. Note that biochar sterilizes all biomass.

1.4 Production of Biochar

Production Technology

The conversion of biomass into charcoal and/or energy is as old as civilization. It is well understood that controlling aeration during burning optimizes the process for energy versus charcoal production. Modern pyrolysis and carbonization technology offers significant improvements in terms of energy efficiency and levels of pollution over traditional charcoal production technologies. In modern plants, different quantities of heat, bio-gas, bio-oil, and biochar are produced depending on the technology and key production parameters such as temperature and aeration. Even though a number of advances have been made in the pyrolysis process, and there are a number of companies working on perfecting their technologies, the technology is far from mature, and there is no dominant technology or design as of yet. This makes the characterization of biochar problematic because it can be made by many different kinds of pyrolysis systems, and from any number of sources of biomass. This is why the life cycle analysis (LCA) presented in this paper has been limited to three scenarios, as a starting point for protocol development. Furthermore, as described by Brown (2009), the characteristics of modern pyrolysis systems are:

- **Continuous feed systems** that improve energy efficiency and reduce pollution emissions associated with batch kilns.

- **Exothermic operation** without air infiltration, which improves energy efficiency and biochar yields.
- **Co-generated products and energy** which reduce pollution emissions and improve process economics. The following products can be co-generated during pyrolysis:
 1. Primary outputs from the pyrolysis process are **biochar** for soil applications or pelletized for use as **bio-coal** that can be used for electricity production.
 2. **Bio-oils** that contain water and organic acids in addition to hydrocarbons. The acidic nature of such bio-oils renders them unsuitable for direct use as a fuel in diesel or gasoline engines. Bio-oil produced from cellulosic biomass does not burn efficiently without pre-heating, and can only be burned in industrial boilers.
 3. **Co-generated heat** may be used to dry incoming feedstock.
 4. **Syngas** is primarily a mixture of H_2 and CO , but also typically contains CH_4 , CO_2 , H_2O , and several low molecular-weight volatile organic compounds. Even though the heating value of syngas is relatively low compared to natural gas (6 vs. 50 MJ kg^{-1}), syngas can be used to replace natural gas or propane, or burned to produce heat energy for drying and electricity generation (Lehmann 2009), perhaps even to run the pyrolyzer itself (Laird et al. 2009).
- **Control of operating conditions** to improve biochar properties and allow change in co-product yields. Given the on-going research and development in the science of biochar and the production technology, it might be possible to further optimize the pyrolysis process for biochar C sequestration applications, and for better use of the co-products of pyrolysis. Table 1 summarizes the product yields from various modes of pyrolysis, to illustrate the variations possible on a very general level.

Table 1. Typical Product Yields (Dry Basis) for Different Modes of Pyrolysis

Pyrolysis Mode	Conditions	Liquid/Oil (%)	Char (%)	Gas (%)
Fast	Moderate temperature $\sim 500^\circ C$ Short vapor residence time ~ 1 sec	75	12	13
Moderate	Moderate temperature $\sim 500^\circ C$ Moderate vapor residence time $\sim 10\text{--}20$ sec	50	20	30
Slow	Moderate temperature $\sim 500^\circ C$ Very long vapor residence time $\sim 5\text{--}30$ min	30	35	35
Gasification	High temperature $>750^\circ C$ Moderate vapor residence time $\sim 10\text{--}20$ sec	5	10	85

Source: Brown 2009.

It is apparent that fast and moderate temperature pyrolysis produces relatively more liquid and gas than char. Thus, to optimize the production of biochar, slow pyrolysis

would seem to be the most appropriate choice. However, producers are attempting to use fast pyrolysis technology in the hope that the production of bio-oils and syngas could become economically viable, thus helping to make biochar production economical.

- **Feedstock variability** of using both woody and herbaceous biomass, including corn and wheat stover, forestry byproducts, urban yard wastes, industrial byproducts, animal manures, and sewage sludge to be converted to biochar will have an impact on the typical product yields for different modes of pyrolysis. The high temperature of the pyrolysis process neutralizes any organic toxins (e.g., aflatoxin) and pathogens in the feedstock. However, any heavy metals present in the feedstock will be concentrated in the biochar fraction after pyrolysis (Laird et al. 2009). This may be a problem, particularly when the source of the feedstock cannot be well controlled, such as for municipal green waste.

Note that chemical properties of the feedstock have a significant influence on both the yield and quality of the produced biochar and co-produced bio-oil and syngas. For example, bio-oil yield decreases with increasing ash content, while the average molecular weight of the bio-oil fraction increases with increasing lignin content of the feedstock. Likewise, the decomposability of biochar will be dependent on the chemical nature of the initial feedstock (Nguyen and Lehmann 2009; Zimmerman, 2010). Figure 3 illustrates the effect of feedstock type on the degradation rate of the resulting biochar in soils, and the evolution of the degradation rate with the duration of the incubation, as reported by Zimmerman (2010).

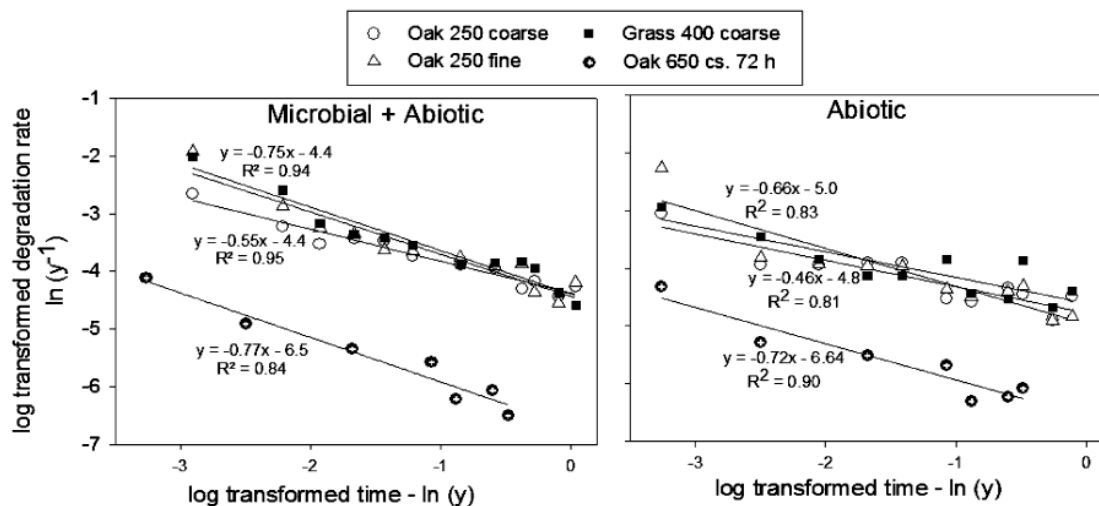


Figure 3. Natural log-transformed time versus C mineralization rate during 1 year total (microbial and abiotic) and abiotic incubations of four representative biochars and linear correlations. Degradation rate in units of mg of C (g of char)⁻¹ year⁻¹ was divided by 1000 to yield units of year⁻¹ in which degradation rates are often expressed. Figure from Zimmerman (2010).

- **Technologies for biochar production** that currently exist are: drum pyrolyzers, rotary kilns, screw pyrolyzers, the Flash Carbonizer, fast pyrolysis reactors, gasifiers, hydrothermal processing reactors, and wood-gas stoves. Pyrolyzers can be scaled from small to large to optimize the balance between economies of scale that are associated with processing biomass at a large centralized facility, and reduced biomass transportation, storage and handling costs that accrue from processing biomass through a distributed network of small facilities that are located close to the biomass source. The largest fast pyrolyzers in North America are capable of processing 200 and 250 dry tons of biomass per day. Slow pyrolyzers are less complicated and can be built at smaller scales than fast pyrolyzers. Several companies are currently marketing or soon will be marketing industrial-scale pyrolyzer systems. See Appendix A for an overview of the company's marketing industrial-scale pyrolyzer systems.

1.5 The Science of Biochar Stability and Decomposition

Once biochar is incorporated in a soil, it is subject to a number of biotic and abiotic factors which will lead to its gradual disappearance (Figure 4). This section explores the extent to which biochar is stable in soils, the mechanisms that control its decay and stability, and the implications of these factors for carbon projects.

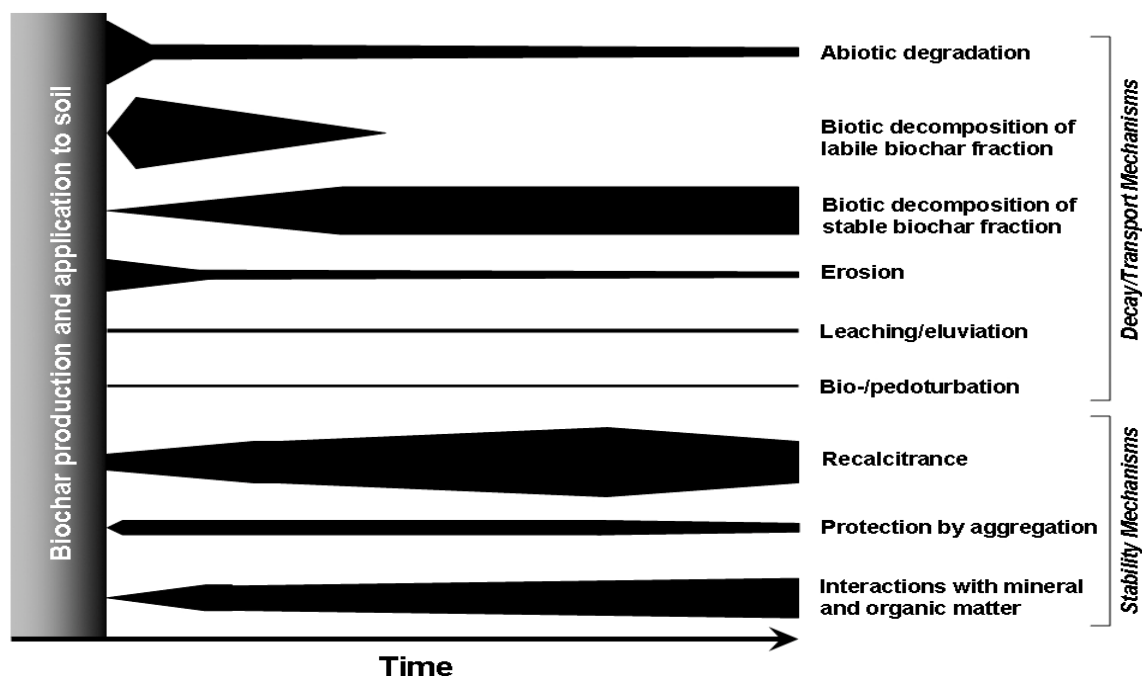


Figure 4. Schematic representation of the factors that may influence stability or decay and transport of biochar, and their proposed importance over time (indicated by thickness of the bars). Source: Lehmann and Joseph, 2009

Why is Biochar Stable?

The exceptional stability of biochar against biotic and abiotic factors is due to a number of characteristics of biochar. The following section provides the main reasons and mechanisms associated with the stability of biochars.

- Chemical recalcitrance.** The conversion of organic matter to biochar by pyrolysis significantly increases the inertness or recalcitrance of C, meaning that it is more resistant to chemical, biological and physical decomposition. The composition changes through destruction of cellulose and lignin and the appearance of aromatic structures, a specific class of organic chemical structures which are fundamentally more biochemically resistant (Paris et al. 2005, Baldock and Smernik 2002). The presence of these aromatic structures is the reason why biochar is biochemically inert. For example, after conversion to biochar, the mineralization rates of wood decreased by one order of magnitude (Baldock and Smernik 2002, Czimczik et al. 2002). Biochar is characterized by unordered structures that create high stability (Paris et al. 2005). Increasing temperature often increases recalcitrance (Nguyen and Lehmann 2009) but even biochar produced at relatively low temperatures (less than 600°C) possesses organic structures that have great stability. The differences in crystal structures, their changes in soil, how they react with the soil and the impacts of these changes on recalcitrance are, however, poorly understood.
- Spatial separation.** After soil application, biochar is predominately found in fractions of soil organic matter (SOM) that reside in small clusters of soil particles, or soil aggregates,

rather than as free organic matter (Liang et al. 2008). Aggregates, which are loosely bound together by worm secretions and/or soil microbes, make up the overall structure of the soil. It is hypothesized that the presence of biochar in aggregates reduces the accessibility of biochar to decomposers, especially because biochar particles are abundant within stable micro-aggregates (soil aggregates between 53 and 250 micrometers), which protect soil carbon from decomposition and results in a much longer residence time for carbon in the soil. However, Liang et al. (2008) found no difference in mineralization between biochar rich soils with 27, 10 and 0.3 % clay. This suggests that greater aggregation in the finer-textured soils had no influence on biochar mineralization. Laird et al. (2008) demonstrated that microorganisms can be spatially associated with biochar in soils. Reduced accessibility by aggregation may be significant in controlling biochar decomposition but less important than chemical recalcitrance. Biochar may promote aggregation by forming an initial center of biological activity around which organic matter forms, as occurs with plant litter (Six et al. 2002, Tiessen and Stewart 1988). This may lead to coating of biochar particles with minerals (Lehmann 2007b). Associations between biochar and the hyphae of mycorrhizal fungi (Warnock et al. 2007) may also increase aggregation. Ingestion and excretion of biochar by earthworms may help to mix biochar with soil and form stable aggregates (Topoliantz et al. 2006). However, these mechanisms are poorly or not at all quantified for biochar.

The particulate nature of biochar may be important in decreasing decomposition rates of biochar. Oxidation of biochar particles starts at its surfaces (Cheng et al. 2006) and remains restricted to the near-surface regions (Lehmann et al. 2005, Liang et al. 2006, Cohen-Ofri et al. 2007, and Nguyen et al. 2008). The outer regions of a biochar particle protect the inner regions from access by microorganisms and their enzymes; this particulate nature gives biochar enhanced recalcitrance and, thus, stability.

- **Interactions with mineral surfaces.** A significant portion of biochar was found in the organo-mineral fraction of soil (Brodowski et al. 2005, Laird et al. 2008, Liang et al. 2008), suggesting that biochar interacts with minerals. Spectroscopic evidence for large particles showed biochar to be embedded within the mineral matrix (Glaser et al. 2000, Brodowski et al. 2005), but biochar can also be present as very fine, particulate material within aggregates.

Rapid association of biochar surfaces with aluminum (Al), silicon (Si) and iron (Fe) happens during the first decade after addition of biochar to soil (Nguyen et al. 2008). It is not clear what type of associations these are or to what extent these processes are lending more stability to biochar. Coating of biochar particles with mineral domains is frequently visible in soils (Lehmann 2007b) suggesting interactions between biochar surfaces and oxides or phyllosilicates.

Laird et al. (2008) found particulate biochar could be physically separated in the coarse clay fraction whereas the finer fractions were low in biochar yet rich in biogenic organic matter. Short-term mineralization normalized by organic C content was 48 to 78 % slower in coarse than fine-clay fractions (Laird et al. 2008). This evidence may suggest that either stabilization by the particulate nature or chemical recalcitrance of biochar is

more important than by interaction with clay (Liang et al. 2008) or that there is a lower size limit of biochar. However, other edaphic interactions may also play a role. For example, coarse clay particles formed into very small aggregates can protect organic C within the aggregate, resulting in slower mineralization.

The decrease in the mineralization rate of biochar with additions of free Al^{3+} to organic matter is well known (Sollins et al. 1996). Nakamura et al. (2007) found large amounts of Fe and Al^{3+} in biochar humic extracts. This indicates that metal ions that bind to the surface of biochar particles increase biochar stability. In other words, adsorption of metals reduces bio-availability and stabilizes biochar.

Biochar particles interact with organic matter in soil in various ways that increase its stability. Surfaces of biochar are coated by organic matter (Lehmann et al. 2005), mixed with biogenic organic material in soil fractions (Laird et al. 2008), associated with microbial matter (Hockaday et al. 2007, Laird et al. 2008) and complexed with dissolved organic carbon (DOC) (Pietikäinen et al. 2000). These processes must affect both the stability of biochar and of adsorbed organic matter.

Aged biochar (i.e., biochar that has gone through an initial peak in decomposition) is less prone to enzymatic degradation than newer biochar as a result of organic or mineral interactions (Hockaday 2006). Yet, these protection mechanisms may not be as important as the rapid decomposition of a labile fraction of biochar that leaves behind recalcitrant fractions with lower mineralization rates. These interactions between mineral material and organic matter begin soon after application to the soil and gain importance over time (Figure 4).

Mechanisms that Cause Biochar Decay

Despite the above-discussed properties of biochar that make it resistant to decomposition, biochars will slowly decay. Different biochar products will decompose to varying extents, depending on the physical and chemical properties of a specific biochar (Brodowski 2004, Hamer et al. 2004, Nguyen and Lehmann 2009, Zimmerman 2010). Not only does the organic and molecular structure differ among biochars (Czimczik et al. 2002, Bourke et al. 2007), but the mineral content and chemical composition varies as well, all affecting the potential for carbon sequestration. This section outlines the science behind the different mechanisms by which biochars are broken down once it is incorporated in a soil.

- **Biological decomposition.** The organo-chemical and physical (Harris 2005, Paris et al. 2005, Bourke et al. 2007) structure of biochar are the main reasons for the high stability of biochar (Schmidt and Noack 2000) (Figure 4). However, microorganisms will slowly break down biochar and convert the biochar carbon back to atmospheric carbon dioxide through heterotrophic decomposition, meaning that the microorganisms directly attack the chemical compounds of the biochar and survive using the energy gained from the decomposition (Shneour 1966, Baldock and Smernik 2002, Brodowski 2004). Conversely, when microbial activity is suppressed, biochar mineralization does not readily occur (Schneour 1966, Brodowski 2004).

- **Co-metabolism and priming.** Soils contain many other organic compounds apart from biochar; these compounds may influence biochar decomposition. Microbial utilization of available sources of organic C may cause concomitant decomposition of biochar, a process termed co-metabolism (Willmann and Fakoussa 1997). Additions of glucose, alone or with nutrients (Hamer et al, 2004, Kuzyakov et al. 2009, Brodowski, 2004), caused double to six fold increases of short-term (one month or less) decomposition of biochars from different residues in the lab. Without direct evidence, we cannot assume that priming of aged biochar decay occurs to a significant extent in soils because: (1) added organic matter, e.g. manures or crop residues, are still much more recalcitrant and chemically complex than glucose and could have a different effect on biochar; (2) a range of recalcitrant organic compounds besides biochar are present in soil and may be co-metabolized first if they are less resistant to decay than biochar (Liang et al. 2009); (3) aged biochar may behave very differently than fresh biochar; and (4) interactions with both labile organic matter and mineral particles may change biochar behavior in soils. In fact, additions of organic C (sugar cane residue) caused a greater increase in the mineralization of uncharred soil organic matter compared to the mineralization of biochar over 550 days (Liang et al. 2009). Nevertheless, priming of biochar decay by added labile organic matter (OM) may occur in soils and might be more important for the easily decomposable fraction of biochar.
- **Abiotic processes.** Surfaces of fresh biochar are hydrophobic and have relatively low surface charge, but can be rapidly transformed in soil environments. Hydrolysis and oxidation, initially abiotic, of biochar surfaces creates negatively charged organic C groups after a few months of incubation (Cheng et al. 2006) (Table 7). Degradation of biochar appears to change its crystal structure first by oxidation (Cohen-Ofri et al. 2007). Abiotic oxidation may not be associated with a significant loss in C (Decesari et al. 2002). However, abiotic oxidation may facilitate the microbial metabolization of the otherwise highly recalcitrant structures and hydrophobic biochar surfaces. Biochar produced at higher temperatures oxidized on surfaces more vigorously than biochar produced at lower temperature. It is plausible that abiotic oxidation is a necessary step towards microbial mineralization of biochar.
- **Physical breakdown of biochar.** Biochar particle size may have a significant effect on microbial decay by increasing the accessible surface area and facilitating the surface reactions necessary to initiate decomposition. Over time, biochar particles do reduce in size—30 year old biochar particles larger than 50µm had disappeared in a Kenyan field study (Nguyen et al. 2008). Tillage effects on the physical breakdown of biochar may be minimal, although evidence is still limited. Soil fauna breakdown of biochar has not been reported—rather, soil fauna processing of biochar may increase stability (Topoliantz et al. 2006). Freeze-thaw actions may be important since aged biochar has significant fine pores and internal pore space that may be water filled and subsequently ruptured, transported and mineralized. Swell–shrink dynamics of dryland clay-rich soils might cause breakage (Gouveia and Pessenda 2000). However, there is no evidence for greater biochar decomposition from these processes, and Kuzyakov et al. (2009) discounted the

importance. Some of the processes that stabilize organic matter and biochar require small particle size and large exposed surface area so physical breakage may be beneficial.

External Factors influencing Biochar Decay

Once incorporated in soil, biochar will decompose at a slow but significant rate. The mechanisms by which this occurs are discussed above. A number of external factors and management practices influence the rate of decomposition of biochar.

- **Temperature.** The decomposition of any organic matter increases with increasing temperature - a phenomenon that also affects biochar. If biochar is to be used to mitigate global warming, the influence of temperature on biochar decay needs to be better understood (Lehmann et al. 2006). A proposed reason why rising temperatures do not affect decomposition to the same degree that temperature affects organic matter protected only by chemical recalcitrance, is that organic matter embedded within stable micro-aggregates or adhered to mineral surfaces becomes physically less accessible to microbial decomposition (see Davidson and Janssens 2006). Biochar's mineral interactions may make it less temperature sensitive than decomposition studies of isolated biochar suggest.
- **Depth of Burial.** The oldest black C (biochar is biomass-derived black C) was found in ocean sediments up to 13,900 years older than the age of other organic C (Masiello and Druffel 1998). It is found in sediments that are several million years old, showing little trend in sizes with age, which indicates a low rate of decomposition over time (Herring 1985). Black C makes up a significant portion, from 15 to 31%, of total organic C in these sediments (Masiello and Druffel 1998, Middelburg et al. 1999). With an increase in the presence of oxygen, decomposition of uncharred organic matter in ocean sediments was 83% over a period of 10,000 to 20,000 years in comparison to only 64% for black C (Middelburg et al. 1999). In the absence of oxygen, the biochar probably remains unchanged in deep ocean sediments over geological timescales. These results indicate that once biochar is buried in sediments under low oxygen or anoxic conditions, the turnover time significantly increases in comparison to terrestrial environments, although the biochar will be of less use for soil improvement.
- **Soil Cultivation.** Cultivation typically increases decomposition of SOM, but this effect may be less important for biochar than for other organic matter. In fact, long-term cultivation of two Australian soils left the size of a biochar dominated fraction of SOM unaffected (Skjemstad et al. 2001). As a result, the proportion of biochar carbon relative to the total amount of soil carbon increased from 33% and 7% in two native savannah soils up to 53% and 27% in the same soils during 50 years of cropping with mainly wheat and sorghum. This observation suggests that biochar was the most stable C fraction during cultivation. Kuzyakov et al. (2009) found only a two week increase in C respiration in a three-year biochar-soil incubation with periodic mixing. This was attributed to cometabolic decomposition rather than breakage of biochar-soil aggregates. High proportions of biochar in SOM after long-term cultivation were also

observed in the US (Skjemstad et al. 2002), Germany (Schmidt et al. 2001), Russia (Rodionov et al. 2006) and Kenya (Nguyen et al. 2008). These results do not imply that cultivation has no effect on biochar mineralization, but rather indicate that the effect is less than for other organic matter in soil.

Nutrient management during cultivation may also affect biochar stability. Application of nutrients, such as nitrogen (N) added to organic material with a high C/N ratio, typically increase its mineralization (Hobbie 2003). Since biochar shows high C/N ratios, N fertilization could conceivably increase decomposition of applied biochar. Current experimental evidence, however, does not support this. On the contrary, an application of commercial fertilizers was not found to affect the contents of biochar-type organic matter (Brodowski et al. 2007). Further studies are needed to evaluate nutrient effects on biochar stability.

Conclusion and Relevance for Protocol Development

Exactly how much biochar will remain in the soil at the end of a carbon project varies, and is dependent on a large number of factors (some of which relate to the application conditions and some to the production process):

- Chemical composition of the original biomass used to produce the biochar
- Production parameters during pyrolysis, most notably oxygen content and temperature of the kiln
- Soil type of the agricultural system where the biochar will be incorporated
- Micro-climate of the agricultural system where the biochar will be incorporated, especially average rainfall and temperature (Cheng et al. 2008a; Nguyen and Lehmann, 2009)
- Cultivation system of the field in which the biochar was incorporated.

Given the complexity of the mechanisms and factors involved in biochar decomposition, it is impossible to predict how much biochar will remain at the end of a carbon project for a given biochar and in a given situation. Therefore, a carbon protocol must rely on field measurements to calculate the actual GHG benefits from biochar soil application, and not be based on standard coefficients. In addition, a carbon protocol can set out a number of “good practice” eligibility criteria to ensure that such projects maximize the GHG benefits. These applicability criteria are further discussed in section 6.

1.6 Predicting the Carbon Sequestration Potential of Biochars

Studies demonstrate that microbial mineralization of biochar to CO₂ does occur eventually, converting any biochar back to atmospheric CO₂ (Schmidt 2004, Czimczik and Masiello 2007). However, this process occurs very slowly and may take thousands of years. Therefore, the potential for offset crediting is determined by the amount of biochar that is left at the end of the project’s commitment period (i.e., the period of time over which a project is required to

maintain carbon storage in order to receive full credit for offsetting CO₂ emissions). To understand how much of the biochar is left at the end of a commitment period, it is necessary to predict the rate of decomposition of biochar once it is incorporated in the soil.

The Two-pool Kinetic Model to Describe Biochar Decomposition

Traditionally, the decomposition rate of plant biomass is determined by measuring the disappearance of the biomass after it is added to the soil (Melillo et al. 1982) and fitting the resulting data with a model that assumes a *labile fraction* with a short turnover time (usually days to weeks) and a *resistant fraction* with a longer turnover time (usually several months to years). Since the decomposition rate of plant biomass is quite rapid, model parameters can be fitted with sufficient accuracy to extrapolate biomass stability beyond the duration of an experiment of a few months. Biochar, however, has a slower decomposition rate than plant biomass, and therefore, much longer experiments in which biochar disappearance is measured in soils are necessary to model biochar's decomposition rate over longer time periods. Timescales of months to years are often insufficient, and ideally, experiments would be carried out at a timescale of centuries or millennia (Baldock and Smernik 2002, Brodowski 2004, Hamer et al. 2004, and Kuzyakov et al. 2009). Note that the two-component kinetic model of decomposition still holds for biochar--the validity of the two-component kinetic model for describing biochar decomposition is corroborated by the observation that aged biochar in soils does not change appreciably in chemical structure and recalcitrance against microbial decay compared to younger biochars¹. The difference with regular plant biomass is that for biochar, the two-component kinetic model must be calibrated using different tools, or much longer decomposition experiments compared to plant biomass.

The importance of duration for measuring biochar stability is depicted in Figure 5. The calculated mean residence time (MRT), which is inversely related to the decomposition rate, and can be interpreted as the average time biochar will be present in a soil, increases if data are available for longer periods of time for the calculations. If data were only available for two years, the MRT obtained by a model is merely 57 years for the data shown in Figure 5. In this example, the MRT of the stable pool of the modeled decay (MRT₂ in Figure 5) continued to increase significantly, from 1,625 to 2,307 years, depending upon whether 50 or 100 years of data were available (Figure 5). This example illustrates that long-term decomposition data are necessary to predict biochar decay and that extrapolations from short-term decomposition experiments are misleading.

¹ Liang et al. (2008) found no differences in chemical structure for Amazonian Dark Earths biochar particles with ages ranging from 700 to 7,000 years. Also, mineralization of organic matter in these biochar-rich soils was identical regardless of biochar age (Liang et al. 2008). Nguyen et al. (2008) found a similar phenomena in biochar exposed to soil for 100 years in Kenya. The surface of biochar particles oxidized rapidly in less than five years (there was no ability to quantify mineralization losses). However, beneath the surface layer of the biochar particles, the Oxygen-to-Carbon (O/C) ratio remained unchanged, indicating that no chemical transformations occurred beneath the surface over a period over 100 years.

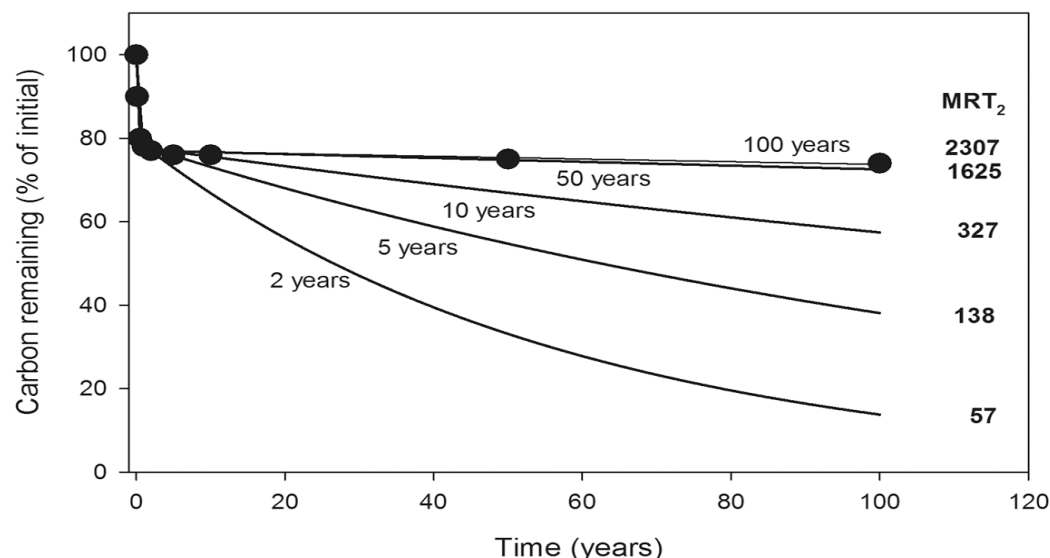


Figure 5. Theoretical models (continuous lines) fitted to experimental data (closed circles) of biochar decay after 0.1, 0.5, 2, 5, 10, 50 or 100 years. The different theoretical models assume data availability for either the first 2, 5, 10, 50 or 100 years. The model assumes that the biochar is a mixture of labile and stable carbon constituents. The modeled mean residence time of the stable pool is noted as MRT₂ and is given in years (right of the graph). Source: Lehmann and Joseph 2009

Assuming a two-component kinetic model of biochar decomposition, the carbon sequestration potential of biochar can be completely described if the following factors are known:

- Decomposition rate of the labile fraction of biochar
- Decomposition rate of the resistant fraction of biochar
- Fraction of labile vs. resistant matter in biochar

Each of these factors must be known if one wants to predict how much biochar will remain for any time after incorporation. However, the fraction of labile vs. resistant matter is most important if one wants to predict how much biochar will be left at the end of the commitment period, presumably 100 years after incorporation of the biochar in a soil² (Lehmann and Joseph, 2009).

Quantifying the Decomposition Rate of the Labile Fraction of Biochar

Hamer et al. (2004) found that 0.3 and 0.8% of initial C is emitted as CO₂ for two biochars produced at different temperatures. Baldock and Smernik (2002) reported a C loss of less than 2% from wood biochar over 120 days. Kuzyakov et al. (2009) determined a decomposition rate of 0.5% of biochar added to soil and lost over 3 years in an incubation experiment. Most of the loss occurred during the first 2 months. Major et al. (2010) found that 2.2% of biochar was lost

² The decomposition rate of the labile fraction is of less importance since most of the labile organic matter will have disappeared by 100 years after incorporation. The decomposition rate of the resistant fraction is of less importance since only a small fraction of the resistant fraction will have decomposed over 100 years.

by respiration in a 2 year field experiment. Furthermore, in a five year study, Cowie and Singh (2008) observed bio-char decomposition, across different biochar types, as between 0.15 % to 7.7 % of the biochar carbon they applied to soil within the first 66 weeks of incubation. They observed the highest increase in decomposition with low temperature biochar amended with poultry litter. In conclusion, about 0.2-8% of fresh biochar decomposes within months after soil application.

Quantifying the Decomposition Rate of the Resistant Fraction of Biochar

Ample evidence suggests that, after the initial peak in decomposition described in the previous section, biochar is very stable in the environment. Biochar that has been subject to the initial decomposition is referred to as aged biochar. Evidence from various sources invariably indicates that aged biochars have a long-term mean residence time of thousands of years. The exact value of decomposition rates is dependent on the technique used to measure them, and the site-specific circumstances.

- **Evidence from incubation studies.** Mineralization is lower for aged biochars collected from 130-year-old charcoal storage sites and amounted to 0.05% to 0.4% of initial C after 50 days (Cheng et al. 2008b). Cheng et al. (2008b) estimated average MRT of these biochars as 1,335 years at a 10°C mean annual temperature (MAT). Similarly, Liang et al. (2008) calculated a mean residence time of 4,035 years for the stable pool of the old biochars in the Amazonian Dark Earths projected for a MAT of 10°C. These decomposition rates are very low compared to uncharred organic matter which has a mean residence time (MRT) of a few years (Baldock and Smernik, 2002).
- **Evidence from radiocarbon dating.** In soil, biochar typically has the greatest average age of any C fraction (Pessenda et al. 2001) but is not always the only form of very old C (Krull et al. 2006). Biochar as residue from forest fires is frequently found to be more than 10,000 years old in various soil ecosystems (reviewed by Preston and Schmidt 2006). Biochars in the so-called 'Terra Preta' soils of the Amazon region (Glaser et al. 2001; Liang et al. 2008) have been radiocarbon dated³ to 500 to 7,000 years BP (Neves et al. 2003). The Terra Preta soils testify to the longevity of biochars.
- **Evidence from large scale C budgeting** of biochar (also termed biomass-derived black C) indicates that natural biochar⁴ has a much greater stability than plant litter. Global biochar production of only 0.05 Gt C yr⁻¹ to 0.3 Gt C yr⁻¹ (Forbes et al. 2006) is less than 0.5 per cent of the 60 Gt C yr⁻¹ estimated for global NPP (Sabine et al. 2004), yet biochar

³ Radiocarbon dating gives the average time from photosynthesis to biomass growth to burning (pyrolysis) to biochar entry in the soil, but it provides no information about the decay rate. In addition to this uncertainty, decay of biochar inputs has to be understood in terms of the amount of biochar deposited. In all known cases, archived samples or historical records are absent. Therefore, it is not possible to calculate a mass balance (Hammes et al. 2008). However, the old ages of biochar found in soil studies and archaeological sites as determined by radiocarbon dates is proof of high stability despite the aforementioned constraints for obtaining decay rates.

⁴ Even though such large-scale budgeting studies are based on natural biochar, the properties of natural biochar are similar to anthropogenic biochar, and the conclusions from these studies can be extrapolated over all biochars.

concentrations are often above 10% of total organic C in soils (Skjemstad et al. 1996, 2002). These studies show that decomposition rates differ by at least one order of magnitude between biochar and other organic material.

- **Evidence from areas where steady-state conditions occur.** On smaller spatial scales, estimates of turnover time of biochar are possible if steady-state conditions of natural char production and disappearance are present over long time periods. For example, the annual production of char by natural savannah fires in Australian woodlands has been relatively constant over thousands of years. By relating the input to the measured char stocks in soils⁵, mean residence times of chars were (conservatively) estimated at 1,300 to 2,600 years (Lehmann et al. 2008). Measurements of biochar stocks from soil chronosequences are limited. Preston and Schmidt (2006, using data from Gavin et al. 2003) calculated an average half-life for black carbon stocks of 6,623 years in a temperate Canadian rainforest. In contrast, using archived soil profiles, Hammes et al. (2008) calculated a turnover time of 293 years for black carbon stocks in a Russian steppe that is subject to periodic fire. Both studies can be questioned based on how spatial variability affected calculations of black carbon stocks.

Note that mineralization is not the only process by which biochar can disappear from a system with set boundaries. Biochar stocks can also decrease due to erosion, leaching, and re-burning. These processes are further discussed in section 2.5.

Quantifying Labile vs. Resistant Fraction of Biochar

Due to the importance of determining the labile vs. resistant fraction for assessing the carbon sequestration potential of biochar, methods to quantify this fraction are covered in section 2.3.

Conclusion and Relevance for Protocol Development

A two-component kinetic model, where it is assumed that an easily decomposable portion of the biochar is mineralized very quickly and the stable portion is mineralized very slowly, can be used to mathematically describe the decomposition behavior of biochar once it is incorporated in a soil. This model requires three factors:

- Decomposition rate of the labile fraction of biochar
- Decomposition rate of the resistant fraction of biochar
- Fraction of labile vs. resistant matter in biochar

To predict how much biomass will remain after a period of about 100 years, the most critical factor is an accurate assessment of the proportion of labile vs. resistant C (Lehmann and Joseph, 2009).

This mathematical model can only be calibrated through decomposition experiments of at least 10 years, or through complex analytical approaches. Therefore, for biochar projects at least 10

⁵ More specifically, these estimates assumed proportionality between char produced per unit of biomass burned and the extent and frequency of biomass burning as well as biomass production.

years of monitoring data would likely be necessary to estimate the final sequestration potential of biochar with some certainty.

2 Lifecycle Analysis and Elements of GHG Accounting

A number of factors will determine the net GHG reduction potential for the biochar, including: (1) source of feedstock, (2) types of feedstock, (3) biochar production process, and (4) soil application procedure. A GHG accounting system for biochar must take into account all emissions and emission reductions from production, storage (including gaseous emissions during landfill or composting), and transport of the biomass along with the secondary emissions from the transport and application of the biochar to the soil. In addition, emissions from leakage and displacement of activities must also be included in the accounting. More specifically, the displacement of a potential reduction in energy production because biomass is pyrolyzed and not solely used for energy production must be accounted for. Therefore, all the potential uses and co-generated products of biomass/feedstock during both pyrolysis and energy production must be carefully analyzed. Figure 6 outlines the possible uses for biomass/feedstocks. If biomass is used for energy production and not for pyrolysis, it goes to producing electricity or biofuels. If on the other hand, it is used for pyrolysis, it generates the various by-products delineated here. This bifurcation of uses demonstrates the alternatives for which biomass can be used. The actual relationship will be driven by the economics of biofuel and electricity generation versus the economics of the biochar production and the creation of carbon credits.

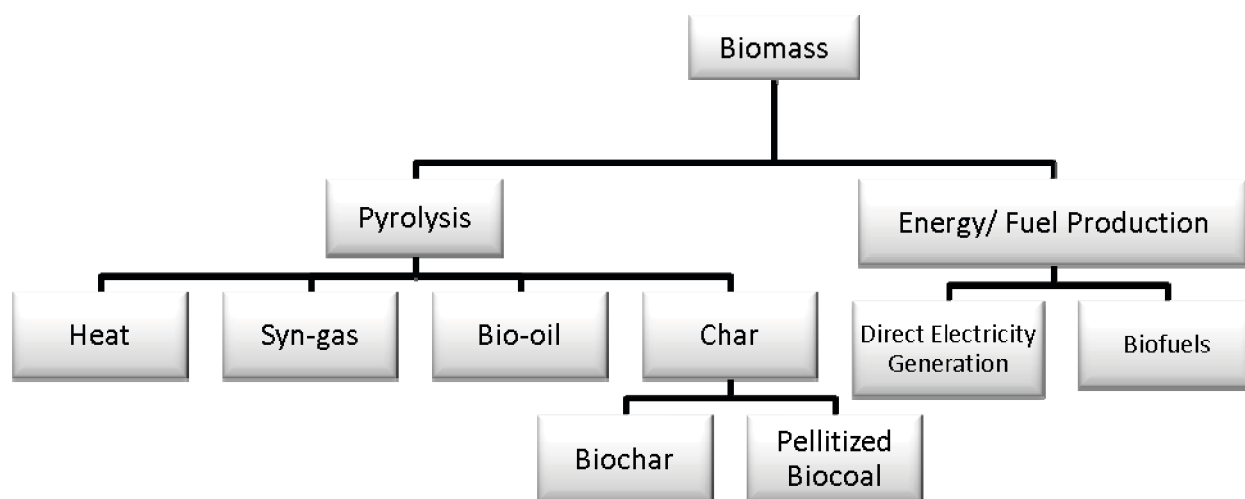


Figure 6. Uses and co-generated products from pyrolysis and energy production of biomass and feedstock.

2.1 Lifecycle Analysis

Overview

The accounting of emissions from any particular GHG producing activity is the subject of lifecycle analysis and can be done for any number of industrial processes. A full lifecycle analysis is a complex undertaking. Within the framework of developing carbon offsets, the focus of a lifecycle analysis-based comprehensive GHG accounting must be based on conservative and verifiable assumptions. Therefore, complex calculations may be replaced by simplified procedures, such as those based on standard coefficients, when it can be demonstrated that the procedure is conservative.

Each of the three greenhouse gases carbon dioxide, methane, and nitrous oxide has a different warming effect on the atmosphere. Project activities will often have opposite effects on the different greenhouse gases. Therefore, the net global warming effect is calculated by summing the contributions of each GHG after they are multiplied by their respective global warming potential, and expressed as CO₂ equivalents. Table 2 summarizes the potential sources and sinks of each of the three greenhouse gases related to production and incorporation of biochar in agricultural soils. Even though methane may be produced during pyrolysis, it is assumed that the production process is set up so that this methane is further combusted into carbon dioxide, which is about 25 times less powerful as a greenhouse gas than methane, either through the co-generation of bio-gas, or during biochar production. Therefore, effects on methane are assumed to be insignificant.

Table 2. Overview of Sources and Sinks Related to Biochar Soil Sequestration per Greenhouse Gas

Gas	Radiative Forcing	Sources (Emissions to the Atmosphere)	Sinks (Removals from the Atmosphere)
CO ₂ (carbon dioxide)	1	<ul style="list-style-type: none"> Fuel used during transportation/ incorporation Displacement of alternative energy to fossil fuels 	Increase in soil carbon
CH ₄ (methane)	25	Not significant	Uncertain
N ₂ O (nitrous oxide)	310	Not significant	Potential decrease in emissions on fields amended with biochar

The total net GHG balance depends on the pyrolysis system, the initial feedstock, and the fuel used for transportation between biomass production, biochar production plant, and the agricultural field. A number of authors have calculated GHG balances for different assumptions, with feedstock source as the main variable (Gaunt & Lehmann 2008, Gaunt & Cowie 2009, Roberts et al. 2010, and McCarl et al. 2009). Although the net sequestration balance was positive for all scenarios, GHG balances are highly dependent on the particular scenario. For example, incorporation of switchgrass-based biochar led to a lower sequestration rate than corn stover-based biochar (Roberts et al. 2010).

The four studies cited above are the most relevant for biochar, though other studies exist for ethanol production and other kinds of chemical industrial processes. They each use a variety of feedstocks as the starting point and different methods to calculate GHG emission reductions, and therefore come to slightly different conclusions, though this is largely a matter of degree (See Table 4). It should be added that although studies calculating energy balances and GHG emissions reductions are useful and quite illustrative, they are not wholly consistent with the needs of a protocol for carbon sequestration such as that which is under consideration here. For example, all the emissions reductions that are claimed, such as reduced fertilizer use and related emissions cannot be easily quantified and standardized in a protocol. Similarly, the energy that is produced and which can offset fossil fuel use and thereby lower emissions and reduce actual energy costs, while real and documented, would not necessarily be credited in a greenhouse gas offsets protocol. Since the work presented in Roberts et al. (2010) is the most relevant to the present discussion, we have focused the analysis on three scenarios presented in this study: (1) Late Corn Stover, (2) Switchgrass, and (3) Municipal Yard Waste. Table 3 below summarizes the findings from the LCA undertaken by Roberts et al. (2010).

Table 3. Summary Table of LCA of Different Feedstocks

Feedstock	Energy Balance	GHG Emissions Balance	Economic Analysis	
	(MJ t ⁻¹ Dry Feedstock)	(kg CO ₂ e t ⁻¹ Dry Feedstock)	High ¹	Low ²
Corn Stover	+4116	-864	\$35	\$17
Switchgrass	+4899	-442	\$18	\$-8
Yard Waste	+4043	-885	\$69	\$16

¹ High revenue scenario: \$80 t⁻¹ CO₂e with Syngas product

² Low revenue scenario: \$20 t⁻¹ CO₂e with Electricity product

The figures in Table 3 demonstrate that each source of feedstock presents a different response relative to energy balance, GHG emissions, and the economic returns. Of course, the economics presented here are dependent on the price of carbon. (This is dealt with later in section 3.3)

Energy Use

The net energy balance incorporates all energy inputs to the system as well as the energy that is produced by it. Energy produced includes syngas energy and energy from avoided processes such as fossil fuel production, fertilizer production, and composting. The “net GHG reductions” are the sum of the “CO₂e sequestered” and the “avoided CO₂e emissions”. The C sequestration is a direct result of the stable C in the biochar, while the avoided emissions are from the avoided processes such as fossil fuel production and combustion, soil N₂O emissions, fertilizer production, and composting (Roberts et al. 2010).

For all crops, the net energy production is positive. Energy use covers drying, agrochemicals and field operations in production, plus transportation. Syngas production from the pyrolysis process contributes the most to the resulting energy surplus. As in most systems this is used to operate the system, can be stored for future use and can offset fossil fuel use. Use of agrochemicals also contributes to much of the energy use for the corn stover and the switchgrass scenarios. Drying consumes much of the energy in the corn stover, the majority of energy for yard waste and the most energy in all three systems for switchgrass. The pyrolysis system used will dictate the energy consumption. Some fast pyrolysis systems are more efficient in that they have minimal drying costs because they grind and dry in a single operation.

GHG Emission Reductions

Greenhouse gas reductions of biochar must include emissions and removals from biomass transport, biochar transport, chipping, plant construction and dismantling, farm equipment, biochar application and avoided fertilizer production. Of all the feedstocks, yard waste has the highest net GHG reductions because there are no emissions associated with its production that are accounted for in the analysis, except for those associated with its transport. Higher levels of emissions are associated with the other feedstocks because more sources must be accounted

for. Note that the amount of stable C sequestered in biochar was largest when stover was used as a feedstock (Roberts et al. 2010).

Biomass and biochar transport of 9 miles (15 km) each contribute < 3% of the total GHG reductions. The stable C sequestered in the biochar contributes the largest percentage (~ 60%) of emission reductions. Avoided use of natural gas also accounts for a significant portion of reductions (~30%). Reduced soil N₂O emissions from biochar application to the soil, contributes only 2-4% of the total emission reductions (Roberts et al. 2010).

Table 4. GHG Emissions Balance with Slow Pyrolysis Units

Feedstock	t CO ₂ e per t of dry feedstock			
	Gaunt & Lehmann	Gaunt & Cowie	Roberts et al.	McCarl et al.
Corn Stover	10.7		6.8	1.1
Switchgrass	12.6		1.6	
Late Corn Stover (lower moisture content)			2.8	
Yard Waste		7.4 – 12.5	3.0	

Table 4 demonstrates that for corn stover, estimates of carbon emissions avoided when using slow pyrolysis vary from 1.1 to 10.7 tons of CO₂e per ton of dry feedstock depending on the methodology to calculate emissions. Avoided emissions using switchgrass vary from 1.6 to 12.6 tons of CO₂e, and for yard waste from 3.0 to 12.5 tons of CO₂e. The carbon stored in the biochar, i.e., the stable C, is what accounts for these levels of avoided emissions. As explained above, to a lesser extent, emission reductions also result from reduced fossil fuel use, less fertilizer use, and other GHG reductions in cropping systems once biochar is applied to fields. This table indicates the broad magnitude of net GHG emission reductions, although the degree to which these calculations vary relate to the methods used in accounting for the reductions, to the systems presumed to be used, and to all of the associated costs.

The economic analysis in the LCA shows differing levels of returns, which vary according to the estimated value of the carbon credit. This part of the analysis is prospective in that it does not reflect actual cost for pyrolysis systems and biochar production or for carbon sequestration credits and returns. Since there are no units in commercial production that are relevant for the current discussion and for which actual costs and returns are available, the presented costs and returns are purely illustrative. Note that the carbon credit values assumed in the LCA are unrealistically high in the current carbon market, particularly at the upper limit where a value of \$80 per ton of CO₂e is specified. Thus, the projected costs and returns for each of these feedstocks should not be taken as evidence that biochar production is only profitable with such high values for carbon credits. Carbon prices are most assuredly likely to rise from their current low levels, but probably not to the levels reported in this LCA table, at least for the foreseeable future. Some value for carbon credits needs to be assigned, but such values should not be the factor that determines whether or not biochar production and application are economically feasible.

2.2 Overview of GHG Accounting for Soil Biochar Incorporation

The GHG benefits from biochar soil sequestration can be calculated by summing on-site leakage and secondary emissions using the same basic equation that is used for any GHG accounting from land-based carbon projects.

$$GHG_s = \overbrace{(GHG_{project} - GHG_{baseline})}^{on-site} + \overbrace{(GHG_{project} - GHG_{baseline})}^{leakage} + GHG_{secondary} \quad [1]$$

Where $GHG_{project}$ refers to annual or cumulative changes in soil carbon stocks over time. Note that in this equation a removal of GHGs from the atmosphere is always positive and any emissions towards the atmosphere are always negative.

2.3 Testing the Carbon Sequestration Potential of Different Biochars

This section reviews possible approaches to measure and monitor carbon sequestration in soils as a result of applying biochar. Once incorporated in the soil, biochar will be subject to decay. If 10 tonnes of biochar are incorporated, only about 7 tons may remain after 100 years. However, the exact amount of biochar that will remain after 100 years is variable and dependent on the properties of the specific biochar. As introduced in Section 1.5, a mathematical decomposition model can be used to: (1) predict how much biochar will remain at the end of a commitment period, and (2) extrapolate the results of monitoring data to quantify how much carbon is left in biochar at the end of a commitment period and the uncertainty around predictions. Even though this two-component model is a simplification of the actual decomposition behavior of biochar, it is a sufficiently accurate description within the context of biochar soil incorporation carbon projects.

As explained in section 1.5, an accurate assessment of the proportion of labile vs. resistant C is important for quantifying the potential emissions reductions from biochar soil incorporation projects. Therefore, to estimate carbon sequestration it may be sufficient to measure the relatively labile fraction of biochar and use this to calculate the proportion of stable C in biochar. Instead of measuring the decay of biochar over time within a soil, a chemical test to quantify the proportion of labile organic matter within a biochar sample could suffice. However, since biochar is new as a class of materials, no commonly accepted test is available to date, and predictions of biochar decomposition will have to be approached using rough and conservative estimates.

This section provides an overview of potential tests that have been suggested as useful for determining the fraction of labile vs. resistant matter in biochar.

Testing Biochars using Analytical Techniques Established for Other Materials

One standard set of tests is the ASTM (American Society for Testing and Materials) procedures, which are intended for the characterization of solid fuels, especially coals (McLaughlin et al. 2009). The two ASTM tests typically used for coals are known as “Proximate and Ultimate Analyses”, and measure how a specific coal or coal-like sample will perform when utilized in a solid fuel combusting process. Though these tests are intended for a rapid characterization of materials to be used in combustion, they do have some relevance in characterizing biochars. For the analysis of biochar characteristics, they can be adapted with some minor modifications, and are known as “Modified Proximate” and “Modified Ultimate” Analyses.

- A **Modified Proximate Analysis** separates the biochar into fractions related to combustion such as:
 - (1) **Moisture content**
 - (2) **Resident matter**, the solid material left after the volatile matter is driven off upon combustion of the biochar. For coal, the term “fixed matter” is used for this fraction. Some researchers use the term “labile matter” for this fraction. Results of these modified tests reveal different levels of resident matter from a variety of biomass sources.
 - (3) **Mobile matter**, the fraction that is driven off upon short-term heating of the biochar. For coal, the term “volatile matter” is used.
 - (4) **Ash content** is the incombustible matter and consists of silica, iron, alumina, and other metals.
- A **Modified Ultimate Analysis** is an elemental analysis of the biochar and determines the amounts of:
 - (1) **Resident carbon, hydrogen, and oxygen** portions of the resident matter
 - (2) **Mobile carbon, hydrogen, and oxygen** portions of the resident matter (fraction 3 from the Modified Proximate Analysis)
 - (3) **Acid-soluble and acid-insoluble parts of the ash content** (fraction 4 from the Modified Proximate Analysis)
 - (4) **Resident and mobile nitrogen** can also be detected, but are often in amounts too small to be of significance in plant and soil science.

The different proportions of these constituents most likely represent differences in biological stability that may be important for determining the carbon sequestration potential. It is assumed that the resident matter of a Modified Proximate Analysis, and the resident carbon of a Modified Ultimate Analysis is related to the proportion of the biochar that will remain inert during biological decay. In a comparison of 16 biochars differing in original feedstock material and conditions during pyrolysis, McLaughlin et al. (2009) reported values of 55-90 % of resident matter in the biochars, compared to 25-30% of resident matter in the original feedstocks. The rest of the biochar material was made up by mobile matter (2-8%), ash content (5-25%). A

Modified Ultimate Analysis on the same samples revealed resident carbon percentages of 50-75%, compared to 10-25% in the original feedstock, with the rest of the material being made up by resident hydrogen and oxygen (5-20%), mobile carbon (0-10%), and some minor constituents. While it is not known what the exact relation is between the results of these analyses of biochars and the carbon sequestration potential of the biochars, it is clear that the variability in the results of the proximate and ultimate analyses reflect true differences in carbon sequestration potential among biochars. Much more research is needed to show how useful the results of such analyses are in determining the carbon sequestration potential of different biochars.

Testing the Carbon Sequestration Potential of Biochars in Incubations

The carbon sequestration potential of biochars can also be determined in soil incubations. A set amount of biochar is mixed with soil and water and put into a closed container in a controlled temperature. The decay of the biochar is either measured directly, by measuring the difference in carbon dioxide emissions between a biochar-amended soil and a soil without biochar, or indirectly, by measuring the total amount of biochar remaining after different time intervals. In a series of incubations across biochar types, pyrolysis temperatures and sizes of biochar particles, Zimmerman (2010) extrapolated results from a one-year incubation and reported an average loss of carbon in biochar due to microbial decay of 10.3 ± 6.2 % after 100 years, and 28.4 ± 20 % after 1000 years. The average long term carbon loss attributable to abiotic processes was quite similar to the values found for microbial incubations, but with higher standard deviations, i.e., -11.1 ± 10.9 % after 100 years and 28.8 % after 1000 years. However, these results are extrapolated from one-year incubations and should be used with caution. The values likely represent realistic biochar decay characteristics within an order of magnitude. Note that to obtain an approximate value of the carbon sequestration potential, expressed as tonnes of CO₂e per tonne of biochar, the carbon proportion remaining at the end of the crediting period must be multiplied by total carbon content of a particular biochar and the 44/12 factor which relates the mass of carbon to the mass of carbon dioxide.

Measuring Biochar Content in Soils after Application

A large number of techniques are available to measure the biochar content in soils after incorporation. In some approaches, the biochar is first physically separated from the mineral soil. In other approaches, the soil and biochar mixture is measured in one step and different fractions of organic matter are measured simultaneously.

Manning and Lopez-Capel (2009) point out that most of investigative work on biochar measurements has focused on laboratory conditions and not on biochar produced under industrial or field conditions. Ultimately, the majority of methods will be utilized in research or for audit applications and not for the quantification of biochar in the soil. Given the lack of experience for using these measurements under industrial conditions and for auditing reasons, we suggest not prescribing one specific method within a carbon protocol, but to instead require that a method quantify changes in biochar content with a minimal set accuracy, e.g., 10%. Note that standard considerations for soil measurements apply. Any C determination requires consideration of soil texture, soil depth and bulk density. Thus, equivalent masses of soil must

be collected across and within sites, and the sample must relate to the soil profile (Ellert and Bettany 1995, Lee et al. 2009). In addition, in all situations, sampling must represent system diversity (Havemann 2009). Appendix B contains an exhaustive list of all the analytical approaches available to measure biochar in soil. These approaches can be divided into ones that measure changes in total soil carbon and ones that measure changes in black carbon content.

- **Changes in Soil Organic Carbon.** There are a number of techniques for the measurement of organic carbon. The techniques can be broadly classified as destructive methods (dry and wet oxidation) and non-destructive methods (NIR or MIR) (Bisutti et al. 2004 and Havemann 2009). All of the methodologies have advantages and disadvantages whether in terms of accuracy, limitation, or cost. We expect that, because of cost prohibitions and the need for inexpensive, robust, accurate and mobile testing devices, spectroscopic technologies based on MIR will be the primary method for quantifying biochar in the field.
- **Changes in Black Carbon Content.** Biochar is part of a continuum of pyrolytic products that are called black carbon. Some of these carbons may already be present in soil and can be mistaken for added biochar. A number of methods are available to measure the sum of the various black carbon products, such as soot, char, and charcoal. These methods fall broadly into a category that determines the organic carbon residue after oxidation of other carbon and the direct spectroscopic quantification of biochar (Hammes et al. 2007, Manning and Lopez-Capel 2009). Even though these methods are not very selective in separating different forms of black carbon, they can be used to measure biochar if a reliable measurement is made of non-biochar black carbon before biochar application is carried out. Given the time frame of carbon projects, all changes in black carbon after biochar applications can be assumed to be due to changes in biochar. Appendix B contains a brief overview of all methods available to measure black carbon in general with observations, unless otherwise noted, from Hammes et al. (2007) and Manning and Lopez-Capel (2009).

2.4 Secondary Emissions from Collection, Production and Transportation of Biomass and Biochar

Emissions from Biomass Production for Primary Sources of Feedstock

In cases where feedstock is produced specifically for the production of biochar, i.e. a primary source, the emissions from feedstock production must be accounted for in the biochar GHG accounting. Use of fertilizers and farm equipment contributes to the energy use for all types of feedstocks. Note that nitrogen (N) requirements for most perennial grasses, such as switchgrass and *Miscanthus*, are low. Even though the N content of switchgrass and *Miscanthus* are low, N requirements may be substantial, given the volume of biomass that is produced. As with the effects of biofuel production on food-crops, very favorable economics of biochar soil carbon incorporation may affect global land-use change, and increase emissions due to displacement

of agriculture or by bringing forest and grassland systems into cultivation. If the complete lifecycle were to be included in the GHG accounting, one would need to account for land-use changes in other areas that cut down forests to grow foodcrops as a result of U.S. cropland being converted to production of biofuel crops. However, for the time being, given the current economics of carbon offsets and the costs related to biochar production, this is an unlikely feedstock scenario for biochar.

Emissions from Biomass Collection and Transportation

Emissions from biomass collection and transportation can be substantial. However, in some cases the feedstock is already collected in the baseline scenario, and emissions from biomass collection and transportation do not have to be subtracted from the final GHG benefits of a biochar soil incorporation project. For example, for green domestic waste, emissions related to pick-up of the waste, should not be accounted for by project participants since this source is already present in the baseline scenario. In such cases, only emissions related to the transport of the waste from the collection point to the biochar production plant should be included in the net GHG reductions (see Table 5).

Table 5. Emissions from Collection and Transportation to be Included in the GHG Accounting

Feedstock Source	Emissions from Collection and Transportation to be included in the GHG accounting
Green domestic waste	Already collected at a central location, only emissions from transportation between the collection point and the biochar production unit must be included in the GHG accounting.
Yard waste	Already collected at a central location, only emissions from transportation between the collection point and the biochar production unit must be included in the GHG accounting.
Corn stover	Majority is left in field to decompose. Emissions from baling and bale collection must be included in the GHG accounting, as well as transportation from field to biochar production unit.
Switchgrass grown for the purpose of producing biochar	All emissions from harvesting, collection, and transportation must be included in the GHG accounting.
Sawdust from milling	Sawdust is already available at one central location, the saw mill. Only emissions from transportation to the biochar production unit must be included in the GHG accounting.
Forest slash	Not collected on a regular basis; usually left to decompose in the forest. All emissions from collection, hauling, chipping, and transportation to the biochar production unit must be included in the GHG accounting.
Biomass from forest fire load reduction	Not collected on a regular basis. All emissions from collection, hauling, chipping, and transportation to the biochar production unit must be included in the GHG accounting.

In general, biochar producers (or those intending to produce biochar) reported that, given the cost and density of the biomass, its weight, and the cost for transporting it, the upward limit for transport of biomass from agricultural residues was about 20-25 miles (35-45 km). Beyond this distance, transport is assumed to be too expensive. Forest processing of biomass will likely be done with portable units, and biomass will be secured from within a 5-10 mile radius (10-18 km). In cases where woody/forest biomass or mill by-products are transported to a central processing plant, the distances might range from 30 to 50 miles (50-80 km). No information was available on the transport distances for domestic green waste.

An emission factor for the transportation of feedstock (and biochar) from a single location connected to the road network can be calculated if it is assumed that biochar is transported on trucks in batches of standard cargo containers of around 3200 cubic ft (90 m³), or 8 ft wide x 50 ft long x 8 ft height (2.44 m x 15 m x 2.44 m). A conservative maximal bulk density of biochar is 0.6 Mg m⁻³; the 3200 cubic ft (90 m³) therefore would equate to 59.5 short tons, or 54 metric tonnes. Assuming a mileage of 5.1 miles per gallon for combination trucks⁶, and a carbon content of 2.778 kg per gallon⁷ (0.73 kg per l) of diesel, the emission factor for a full truck is:

$$\frac{44}{12} \cdot \frac{2.778}{5.1} \cdot \frac{1}{1000} = 1.997 \cdot 10^{-3} \text{ [MTCO}_2\text{e per mile]}$$

Expressed per weight of biochar, the emission factor is 33.6×10^{-6} MTCO₂e per mile per short ton (2.30 MTCO₂e per km per metric tonne) of biochar.

Roberts et al. (2010) calculated theoretically that the GHG emissions associated with the collection and transport of biomass and biochar together account for less than 3% of the total GHG balance, when the radius between feedstock collection and biochar delivery was smaller than 9.3 miles (15 km).

Emissions from Biochar Production

Some energy is required to operate a biochar production plant. Most of the energy is needed for drying feedstocks, especially for dedicated grassy or herbaceous biomass, animal manures and domestic green waste. Other feedstocks such as crop residues or woody biomass have low drying requirements. Some fast pyrolysis systems have minimal drying costs because they grind and dry in a single operation. In most systems, the syngas produced from the pyrolysis is used to operate the system and process heat is used for pre-drying. A protocol should require these emissions to be monitored, quantified, and accounted for through established methods.

⁶ http://www.bts.gov/publications/national_transportation_statistics/html/table_04_14.html

⁷ <http://www.epa.gov/oms/climate/420f05001.htm#carbon>

2.5 Risk of Reversal from Erosion, Fire and Development

When it comes to measuring the sequestration potential for biochar, one must determine within which boundaries the biochar content should be monitored. These boundaries must also include a fixed lower depth below the soil surface, and therefore represent a three-dimensional volume. Only the carbon from biochar that remains within this volume during the project duration can be accounted for as an offset. Given that it cannot be verified, all biochar that leaves the geographical boundaries after incorporation in either a vertical or horizontal direction must be considered a loss, even if it is transported through runoff, deposited lower in the landscape, and not converted back into atmospheric CO₂.

In many field experiments, decreases in biochar content are attributed to decomposition, although erosion, eluviation and leaching may be the main causes. Significant amounts of biochar observed at depth in various ecosystems (Skjemstad et al. 1999, Dai et al. 2005, Rodionov et al. 2006, Brodowski et al. 2007, Leifeld et al. 2007) suggest that biochar can be transported downwards in soil (Preston and Schmidt 2006). In some cases, biochar distribution in a soil profile may not be the result of transport by water, but of either deposition during times when the respective depth was at the surface, e.g. anthropogenic soils, or of redistribution by biotic and abiotic means (Gouveia and Pessenda 2000, Bormann et al. 1995, Ping et al. 2005).

Loss due to Erosion

Erosion of biochar can be a significant export pathway from a watershed (Rumpel et al. 2006), especially on sloping terrain. Erosion is likely more important than leaching, especially in the initial period following application to soil, although direct evidence is still sparse. Even though erosion should not be equated with C loss - work by Berhe et al. (2007), Van Oost et al. (2007), and others show that erosion probably creates a terrestrial carbon sink. As indicated in the previous section, once biochar leaves an agricultural field through erosion it may be considered lost since it is not verifiable anymore and this is the most conservative assumption. Biochar accumulates in depressions (Bassini and Becker 1990), or is transported within aqueous systems (Guggenberger et al. 2008) and deposited in fluvial or oceanic sediments (Masiello and Druffel 1998). The extent of mineralization of biochar during transport in water is not known. However, the contribution of biochar to total C along the transport pathway from soils to sediments appears to increase rather than decrease, which suggests a decreasing turnover rate (Mitra et al. 2002). In estuary sediments in Australia, biochar made up a large proportion of the total organic C (Golding et al. 2004), thereby manifesting the slow turnover and enrichment in sediments.

Loss Due to Development

If an agricultural field where biochar was applied is subsequently developed, and soil is removed during construction, the remaining biochar for which credits were already issued is no longer verifiable.

Loss of Biochar due to Downward Movement of Biochar in the Soil Profile

The identification of biochar structures in leachates, soil pore, and ground and river water provides direct evidence for leaching of biochar in the dissolved phase (Kim et al. 2004, Hockaday et al. 2007). Direct quantification of portions of biochars derived from forest fires demonstrated a slightly preferential export of biochar from a watershed in comparison to other organic matter (Guggenberger et al. 2008). Oxidation of biochar may not only be connected with gaseous losses of biochar as CO₂ but also with transport by leaching and lateral export within stream networks. Less information is available about the transport of particulate biochar.

2.6 Secondary Emissions Post-application

Once incorporated, biochar may affect the biogeochemistry of an agricultural ecosystem, and thereby affect emissions of CO₂, CH₄ and N₂O resulting from underlying biological process. Potential GHG emissions post-application must be accounted for in a carbon protocol.

Effects on CO₂ emissions and decomposition rates

The influence of biochar on the soil organic matter (SOM) decomposition rate is still relatively ill understood. The potential negative effects of biochar on SOM decomposition are most likely quite minor, occurring only in very specific circumstances, if at all. In a 10 year litter study from three contrasting boreal forest sites, Wardle et al. (2008) reported evidence that additions of charcoal mixed with organic matter (OM) resulted in a substantially higher loss of OM mass and C compared to the components separately. These authors also found higher microbial activity within the mixture bags which may indicate that the charcoal particles could act as a hub for microbial activity and absorption of organic compounds, which will in turn enhance decomposition rates and the overall mass loss of the OM. Therefore, the results of Wardle et al. (2008) suggest that charcoal additions can promote the rapid loss of forest SOM during the first decade of its formation, thus releasing CO₂ back to the atmosphere. However, Lehmann et al. (2009) dispute their findings as being unclear as to whether or not the C lost in the OM was lost as CO₂ or as physical export through the mesh of the litter bags used in the study and sequestered elsewhere in the system. The most current work reveals more than Wardle et al. In incubation experiments without plants, Kuzyakov et al. (2009), Liang et al. (2009), and Spokas et al. (2009) show no effect on CO₂ levels or rather a reduction. If plant growth is included in the assessment, even an increase in SOC content was observed (Major et al. 2010). Therefore, the effect of biochar on CO₂ respiration rates may not be a principle concern. However, to be able to rule out any future negative feedback, further studies on the mechanisms of interaction between biochar and organic matter that is already present in soil are required.

Effects on CH₄ and N₂O Emissions

It is hypothesized that biochar soil incorporation increases the efficiency of C and N cycling in agricultural systems and, therefore, reduces emissions of CH₄ and N₂O, which are two powerful greenhouse gases.

- **Effects on CH₄ emissions.** Evidence for reduced methane emissions in biochar amended soils is extremely limited. Only Rondon et al. (2005) have shown complete suppression of methane emissions after biochar additions.
- **Effects on N₂O Emissions.** Direct evidence for a decrease in N₂O emissions due to biochar application is limited. Yanai et al. (2007) found up to 90% lower N₂O emissions with biochar additions at high water saturation levels, although greater saturation overwhelmed emission suppression. Spokas et al. (2009) also found lower N₂O emissions in an incubation trial. Singh et al. (in press) found that biochar additions lowered N₂O emissions 14-73% in Alfisols, a soil type found in semi arid and humid regions, and 23-52% in Vertisols, a high clay content soil type. Sohi et al. (2009) found an emission suppression of 15% in a pot trial. Rondon et al. (2005) cite field trials in Colombia that demonstrate an 80% reduction in N₂O emissions from soil. Sohi et al. (2009) state that the duration of the effect may be limited, that long term effects from biochar are likely to be non-linear with respect to application rates and that biochar effects on soil physical structure, particularly pore space, will be more critical (see a review by van Zwieten et al. 2009).

Even though the mechanisms behind potential CH₄ and N₂O reductions are relatively well understood, the direct quantification and verification of this effect is problematic, partially due to the inherent temporal and spatial variability of N₂O emissions and the high costs of measuring trace gases such as CH₄ and N₂O in the field. Although some studies exist, as cited above, there is a paucity of field-based and quantitative research examining the effect of biochar on gaseous losses (Sohi et al. 2009). As a consequence, the GHG benefits from the potential reduction of N₂O emissions resulting from biochar applications will probably be excluded from carbon offset calculation. Such an omission is conservative and relatively insignificant. Roberts et al. (2010) calculated that reduced soil N₂O emissions resulting from biochar application to the soil contributes only 2-4% of the total emission reductions.

3 Preliminary Economic Analysis of Carbon Sequestration from Biochar Soil Incorporation

The U.S. biochar industry is in its infancy. It is characterized by an array of mostly young companies with new business models, a variety of technologies that are for the most part commercially unproven, and an uncertain regulatory environment. Furthermore, the availability of capital is a constraint for many companies, the economics of this fledgling industry are unclear, and returns to most investments are unpredictable. (See Appendix A for a listing of biochar producers.)

There are no large-scale plants operating in the U.S., although there are several in Canada, which use either municipal solid waste or mill waste from the lumber mills where they are located. Currently, demand for biochar in the U.S. comes primarily from research institutions

and from some early adopting agricultural producers. As there are only a handful of plants in operation, biochar supplies are limited and price is quite high.

Many players, who are just now coming into the market or who are contemplating entering it, are doing so after years of technology development. Figures on costs and returns are very limited and often prospective since the industry is small and new. Technology that is available from companies currently in the market varies greatly, as these companies are taking a host of different approaches to their respective markets. There are no “off the shelf” pyrolysis technologies at reasonable prices. It will take a number of years for certain designs to emerge and become the dominant technologies that drive the market. It is clear, in any case, that whatever we see today will be vastly different in two, five, or ten years.

Assuming that climate legislation on the national level is ultimately passed in the U.S. Congress, offsets from biochar use and carbon sequestration are part of the legislation, and that policies to encourage investment in biochar technology and its deployment and the use of biomass for biochar production are put in place, this industry will begin to scale up. It could then provide a significant supply of carbon sequestration credits, and make use of substantial quantities of biomass.

What is also needed is a regulatory scheme that can certify biochar in a manner that is cost effective and efficient so that users/consumers of biochar can be assured as to the quality and characteristics of the product they purchase and use. The technology needs to mature and be widely tested so that this industry can begin to develop in accordance with the model found to be the most desirable (distributed or centralized). Furthermore, the carbon accounting protocol for biochar use as an offset needs to be in place. Presently, expectations are high, both from a production and a policy perspective.

3.1 Opportunity Cost for Biochar

There are vast quantities of biomass available throughout the American landscape—in forests and sawmills, from agricultural residues and waste, green waste, municipal solid waste, and other sources as discussed earlier (Section 1.3). The biomass that is potentially available for biochar production can also be put to alternative uses that include the direct production of energy for the grid, or the production of biofuels, which will offset fossil fuels (Gaunt and Lehmann 2008). Growth of demand from competing uses for that biomass could push up prices, potentially making procurement logistically more difficult and feedstocks more costly. Gaunt and Lehmann (2008) conclude that more emission reductions can be claimed when the biomass is used as feedstock for biochar and sequestered in soils than when the biomass is used to offset fossil fuel. However, a comparison based purely on emission reductions may not be sufficient. A comprehensive analysis must compare the GHG emissions per unit of energy produced between pyrolysis-biochar and combustion. This analysis has not been conducted yet. The trade-off between turning biomass into energy or fuel, versus the value of creating biochar and applying it to fields, is a question that is at the heart of the development of the biochar industry and research community.

The LCA studies presented earlier indicate that emission reductions from producing biochar and applying it to soil are superior to using that same biomass to offset fossil fuel use.

Undoubtedly, in some situations there could be competition for biomass to be used for fuel or pyrolysis for biochar. However, since the opportunities are so varied with regard to scale, the location of pyrolysis units, type of technology chosen, and the source of feedstock biomass used, it does not mean this would universally be an either/or scenario. Depending on the local supply and demand conditions for available biomass, these choices could be complementary, although prices for feedstock for energy production could affect prices for biochar production. Cross price elasticities would need to be examined in the context of public policy choices and carbon sequestration values.

As a recently published report describes it, “The profitability of any biochar operation will depend mainly on its potential to attract revenue as a soil additive and C sink and will be affected by the type of biomass feedstock and that of production (open vs closed, local vs centralized)... Moreover, the demand for biochar, as a byproduct of pyrolysis, will be influenced by, and will indeed influence, the demand for biofuels, the demand for products such as manure and compost and the price of carbon in the carbon markets” (Verheijen et al, 2010).

Currently, given the alternative uses and potential returns to using biomass for processes other than making biochar, its production would most likely not be part of a business-as-usual scenario. Presuming the market grows and that biochar can be produced relatively cheaply (it does not require the same large capital investments that ethanol plants do), and given its expected agronomic benefits as well as its potential carbon value, it will be used as an effective soil amendment and as a source of carbon offset credits. Furthermore, the notion that it would be part of a business-as-usual situation does not seem likely because there are too many factors that have to be worked out deliberately, in terms of public policy, the growth of markets for pyrolysis units, the production and application of biochar itself, and thus the economics of the industry.

It may be the case that public policies will need to be put in place, perhaps similar to those that supported the ethanol industry—which included tax incentives, investment credits, even subsidies, and public policy choices that fostered the growth of that industry. Such policies will likely have an impact on the use and cost of biomass over the long term, the scale of potential biochar operations, and the returns producers can ultimately reap relative to their investments.

Renewable Energy

The Waxman–Markey bill (and other proposed legislation) provide for a federal renewable portfolio standard (RPS) that would require electricity generated from renewable sources, together with energy efficiency savings, to equal at least 6% of retail electric utilities’ baseload power starting in 2012 and increasing to a 20% target by 2020. The Kerry–Boxer bill does not contain a federal RPS or renewable energy standard, most likely because similar proposals are already under Senate consideration in the separate American Clean Energy and Leadership Act of 2009 (the Bingaman Bill). The Kerry–Boxer bill provides grants through the Environmental Protection Agency (EPA) for projects that increase the quantity of energy that a state uses from renewable resources, with priority given to applicants in states with a binding RPS mandate,

such as California. Demand for energy production under the RPS will no doubt raise demand for biomass.

Biofuels

The Renewable Fuel Standard (RFS) is a provision of the U.S. Energy Policy Act of 2005 that mandated 7.5 billion gallons of renewable fuels by 2012. The U.S. Environmental Protection Agency has proposed revisions to the National Renewable Fuel Standard program to address changes required by the Energy Independence and Security Act of 2007 (EISA). The revised statutory requirements establish new specific volume standards for cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel that must be used in transportation fuel each year. The revised statutory requirements also include new definitions and criteria for both renewable fuels and the feedstocks used to produce them, including new greenhouse gas emission (GHG) thresholds for renewable fuels. The regulatory requirements for RFS will apply to domestic and foreign producers and importers of renewable fuel (U.S. EPA). Under the proposed rule changes to the annual renewable fuel standard (RFS2), the volume standard would increase beginning in 2008, from 5.4 billion gallons (Bgal) to 9.0 Bgal. Thereafter, the required volume continues to increase, eventually reaching 36 Bgal by 2022.

Currently, the U.S. produces around 9 billion gallons of ethanol, and it is expected that ethanol capacity will be around 11.4 billion gallons by the end of 2009. This means that the RFS target may be exceeded nearly four years ahead of schedule. The growing demand for renewable fuels, especially biomass based diesel, and cellulosic ethanol could also push up demand and therefore biomass prices. Though the future of the cellulosic ethanol industry looks somewhat uncertain, if it were to become economically feasible on a large enough scale, corn stover and other sources of biomass could be used for its production, potentially depriving biochar producers of this feedstock, or at least pushing up its price.

Bio-oil

As described in Section 1.3, bio-oil is one of the by-products of the pyrolysis process. Discussions with various companies have indicated that, for the most part, companies that intend to use fast pyrolysis systems expect to produce bio-oil, and that biochar will only be a by-product of lesser value to them. Depending on the pyrolysis technology and the temperature used during the pyrolysis process, varying amounts of biochar, bio-oil and syngas can be produced. The combination of these elements is what producers will alter, as they optimize for production of one versus the other, depending on costs and prices for outputs (See WSU, 2009).

Many of these companies are planning to use the bio-oil as a fuel additive, as a replacement for bunker fuel, or as another type of renewable transportation fuel. Though it has 42% of the energy content of fuel oil (equivalent to 61% on a volumetric basis) and a lower heating value, it has flow characteristics that make it favorable for combustion, and it can therefore be used as a basis for the production of higher value extracts and by-products (Winsley 2007). But the technology for bio-oil seems to be as yet unproven both for refining and for use as a fuel, despite the fact that much research has been done on the refining processes necessary for

sustained fuel use. Much of this research is on-going and includes studies that have looked at the technical and economic issues associated with bio-oil production. Still many issues remain to be resolved, and as a result, the economics of this dimension are unclear (Brown 2009; Laird et al. 2009). Despite these technical constraints, however, several companies are building their business plans on the production of bio-oil. Some of these unresolved technical issues were analyzed in a recent issue of the journal *Scientific American* which summed it up aptly: “Although you can burn biocrude directly in a diesel engine, you should attempt it only if you no longer have a need for the engine” (Huber and Dale, July 2009).

Co-generation of Electricity

Much of the available biomass, such as secondary forest biomass and agricultural residues, by and large, are not near the power plants or the customers who need electrical energy. Transporting the low value and high volume and/or weight material is costly. Thus, pyrolysis units must be located near the sources of biomass so it can be converted into gas, oil, or char, and transported to where it can be used. In 2007, biomass contributed 3.6×10^{15} Btu of energy within the U.S., which is about 5% of total U.S. energy production or 3.5% of the total U.S. energy consumption (U.S. DOE, 2003). This biomass likely is used as fuel for local power boilers to produce heat and steam for industrial processes or electricity. Wood resources contribute the most to biomass that is used in energy production. Saw-dust from milling operations is frequently used in a nearby power plant to co-generate energy to power the milling operation or to provide electricity to the grid. Sawdust may be pelletized and transported to a power plant further away from the mill. Similarly, biomass from forest operations that is removed from the forest system and cannot be used as pre-commercial timber can be chipped and transported to power plants. Biochar can potentially be made of any kind of biomass, making its production possibilities more varied than say ethanol, or other biofuel. The same wood waste that can be used to fire boilers at a mill could be used to produce biochar, or made into pelletized biochar, or “bio-coal”. Such competing uses of the biomass are at the heart of the discussion as was mentioned earlier.

As an example of the current economics of this activity, biochar is currently being pelletized by some Canadian producers. The demand for such “bio-coal” is driven by strict air pollution regulations in countries that need to reduce emissions from coal fired plants and coal mining operations, and limit the use of coal for energy production. This is the case in Canada and Western Europe. There are companies in Canada pyrolyzing sawmill waste into such pelletized bio-coal and shipping it to Western Europe. Based on an interview with a Canadian bio-coal producer, the energy content of such pellets is about 25-30 GJ per ton, which is comparable to the energy content of coal, which is between 27-30 GJ per ton. The bio coal is delivered to Europe at about CAD\$300-400 per ton, of which about 25%-30% is freight costs. This price translates to CAD\$11-13 per GJ for pure bio-coal. Prices of coal delivered in Europe are about CAD\$110 per ton, which translates to about CAD\$3.66 per GJ⁸. Clearly, with a cost per GJ that is

⁸ By comparison, coal from the U.S. delivered to Canada is CAD \$30-40 per ton which translates to an energy cost of CAD\$ 1.10-1.30 per GJ.

three times the energy cost from coal, the use of bio-coal is not economically attractive. Although the regulatory demand to reduce coal use and emissions from the burning of coal may fuel the demand for bio-coal and artificially increase its price, the value of biochar as a sequestration medium would seem to be more compelling than using bio-coal as an energy source. Similarly, with the Renewable Fuels Standards (RFS) proposed for the U.S., energy production from biomass could be stimulated further through various policy incentives. Large-scale electrical generation from biomass may be possible, but will likely require tax incentives, some form of subsidies, and regulatory mandates that make it economically feasible to get such an industry off the ground and sustainable.

3.2 Cost and Returns of Biochar Production and Application

The Lifecycle Analysis (LCA) for biochar (see section 2) analyzes the components of the benefits and costs associated with the production and application of biochar. The magnitude of these costs and benefits, and who actually reaps the economic return, depends on how the feedstock is generated, where the pyrolysis units are located, the scale at which they operate, and who bears the actual cost of production. As Gaunt and Lehmann (2008) point out:

The overall financial justification for investment in a pyrolysis plant will be location specific and depend on the following: revenues for the biochar and energy products (heat and local electricity), market value of any carbon offsets, cost of feedstock, and the costs of installation and operation.

For owners of pyrolysis systems, whether they are strictly commercial producers selling to farmers who are incorporating biochar on their farms, a number of costs and benefits for biochar production and soil incorporation are incurred. These costs can be itemized as follows:

- feedstock production and collection
- feedstock hauling
- feedstock storage and pre-processing
- feedstock processing
- pyrolysis operation (other than labor)
- labor costs of running the pyrolysis unit
- energy use for sales of co-generated bio-oil or electricity
- biochar packaging and hauling
- biochar application
- development costs for the carbon offset
- monitoring of carbon sequestration
- capital costs of purchasing and establishing the unit
- opportunity costs of alternative uses of feedstock and char

For the pyrolysis operators, the benefits can be itemized as follows - the receipt of these benefits depends on whether the operator is a farmer or a commercial producer:

- revenue from sale of biochar or bio-coal (if not used directly by the producer)
- revenue from other products such as bio-oil (for both potentially)

- reduced cost of fertilizer or other agrochemicals (for farmer)
- increased revenue from higher agricultural productivity (for farmer)
- reduced costs from heat and electricity production (for both potentially)
- carbon revenue from offset sales (for both potentially)

Table 6. Costs and Returns for Biochar Production (U.S. Dollars/ton of biochar)

	McCarl et al	Roberts et al						WSU Forest Waste	
	Corn Stover	Corn Stover		Switchgrass		Yard Waste		Transportable	Stationary
	Large Scale	Low C Value	High C Value	Low C Value	High C Value	Low C Value	High C Value		
Cost of Feedstock	-59.44	-43.46	-43.46	-36.89	-36.89			-20.00	-20.00
Cost of Feedstock Transport		-6.24	-6.24	-6.02	-6.02			-16.00	-16.00
Pyrolysis Cost									
<i>Fixed Cost of Facility</i>	-21.28	-16.26	-16.26	-16.26	-16.26	-16.26	-16.26	-60.00	-60.00
<i>Operating Cost of Facility</i>	-31.58	-31.58	-31.58	-31.58	-31.58	-31.58	-31.58	-155.00	-124.00
<i>Total</i>	-52.86	-47.84	-47.84	-47.84	-47.84	-47.84	-47.84	-215.00	-184.00
Total Biochar Production Cost	-112.30	-97.54	-97.54	-90.75	-90.75	-47.84	-47.84	-251.00	-220.00
Value of Energy Produced	25.00	42.81		55.05	55.05	35.20	35.20	163.00	162.00
Value of Biochar	15.75							114.00	114.00
Biochar Transport Cost	-3.07	-1.57	-1.57	-1.53	-1.53	-1.57	-1.57		
Biochar Application Cost		-1.07	-1.07	-1.04	-1.04	-1.07	-1.07		
Estimated Value of C Credit	4.55	17.28	69.12	8.84	35.36	17.70	70.80		
P and K Content		18.39	18.39	9.68	9.68	10.01	10.01		
Improved Fertilizer Use		1.22	1.22	1.18	1.18	1.22	1.22		
Tipping Fee						49.09	49.09		
Lost Compost Revenue						-53.03	-53.03		
Avoided Compost Cost						10.98	10.98		
Net Return (Dollars)	-70.07	-20.48	-11.45	-18.57	7.95	20.69	73.79	26.00	56.00

The studies listed above in Table 6 are based on theoretical assumptions and do not reflect actual costs of operations. These studies used various scale pyrolysis units: McCarl et al. (2009) assumes a unit with a capacity of 70,000 ton per year both for slow and fast pyrolysis (only figures for the slow pyrolysis are reported here). Roberts et al. (2010) assumes a unit with a capacity of 20,000 ton per year (or 100 ton per day) using slow pyrolysis. The WSU study on forest biomass reports on a transportable unit and a larger stationary unit that processes 20,000 ton per year. These all have higher capital costs and therefore operating costs, which amount to 3-5% of the capital costs. Thus, the per ton production cost from a 70,000 ton per year machine could be substantially higher than that for a smaller unit.

The studies also make various assumptions about the value of the energy produced by the particular pyrolysis units. In the WSU study, a certain level of bio-oil production is assumed

which may or may not be realistic. Furthermore, as is apparent from the figures given by Roberts et al. (2010), the net returns are positive for switchgrass and yard waste when a high value is ascribed to a carbon credit. To depend on such a high price for carbon in order to make production economically viable seems unrealistic. In a study mentioned earlier, Gaunt and Lehmann (2008) estimated that the value of energy foregone by producing biochar would be worth \$47 per ton of biochar produced. This gives some measure of the economic value of the carbon, though the actual carbon offset market would value this somewhat lower.

Prices for Feedstock

The price of feedstock is the principal component of the variable costs of production, as described earlier. Based on conversations with biochar technology companies, various U.S. municipalities' websites, and values reported in the literature current prices for feedstocks are:

- **Agricultural residues:** \$25-\$40 per short ton of wet matter (price at the farm gate)
- **Forestry biomass:** \$20- \$45 per short ton of wet matter (collected and delivered to unit) (WSU, 2009)
- **Switchgrass:** \$38 per short ton of wet matter at the farm gate (Roberts et al. 2010); \$68 delivered to unit w/transport (CURBI, 2010)
- **Green waste:** tipping fees are often paid by municipalities who need to dispose of this waste and are willing to pay users to take it. Prices ranging from \$20 to \$40 per ton of wet matter are reported.

The prices reported here would need to be standardized for differences in moisture content and transportation costs to make them directly comparable. Generalized values for moisture contents can be found in Demirbas (cited in Lehmann et al. 2006). If processing takes place at a lumber mill, for example, a grain facility, or someplace where the feedstock is centrally collected, costs could be lower than those stated above, which were primarily taken from interviews with market participants. As is apparent, any type of biomass requires some form of assembly, harvesting, collection and compaction, all of which involve costs (Caputo et al. 2005). As was stated earlier, these prices could change as the market for biomass grows and as other uses put pressure on prices to rise. Transport costs vary as well, depending on distances traveled and those costs are added to the procurement price stated above.

Costs of Pyrolysis Operation

The universe of biochar producers is divided among producers who intend to use fast or slow pyrolysis units, and those who intend to use some kind of gasification system, all with different feedstocks. Those using slow pyrolysis primarily intend to produce biochar, using any by-products on a local scale. Some producers who plan on using gasification systems will also concentrate on biochar, while others will produce both bio-oil and biochar. In addition, some companies that will be producing bio-oil intend to sell power generation units that can make use of the bio-oil with minimal refining.

Large plants, with a capacity of 50,000 - 70,000 short tons of feedstock or more per year, are envisioned by some producers. Such plants have establishment costs of \$20 - \$45 million, along

with the operating and maintenance costs which are calculated to be 3-5% of the initial capital cost. Obviously, these plants require a large and dependable supply of feedstock year round, and also need processing and storage capacity for biomass. It is thought that plants of this scale would be placed near wood processing plants or for use with agricultural or green waste, and would need to collect biomass from a radius of about 36 miles (60 km). These large operations require more management, more labor, and more capital than the more modest sized units, and the returns on such plants are of course, uncertain.

Smaller pyrolysis units that process up to about 50 dry tons of biomass per day are much less costly. Depending on the size and the technology, such plants can cost between \$3 and \$5 million, with more elaborate systems priced at \$10-15 million. Those smaller and less complicated gasification units, processing 1- 2 short tons per day, can cost \$150,000 to \$300,000, while others will start at \$500,000. The fixed costs, and thus the maintenance and operating costs, are lower and more manageable than with large units. These units may be mobile, and they could serve an area within a radius of 15-30 miles (25-45 km). If they are in a forest setting, the density and availability of the biomass will vary greatly. Most producers looking at units for use in forests thought they could easily find ample biomass within a 6-15 mile radius (10-25 km).

Given the variability of the costs of the pyrolysis units, of the feedstock, and for operations and maintenance, it is difficult to estimate the cost for actually producing biochar. Conversations with various companies have indicated that the cost for producing one short ton of biochar is between \$150 and \$350. Some analysts deduct the value of the electricity or syngas that is produced in the pyrolysis process, which gives a somewhat lower net cost for biochar production.

The final cost obviously depends on the system being used, the economies of scale that can be realized, and the efficiencies that can be wrung out of any system over time. Cost reductions can be generated through the recycling of energy produced within the processing plants to dry feedstock, generate power, and heat buildings, or for other uses that can offset energy use from sources such as propane, natural gas, or electricity. The bio-oil also has a potential value, which theoretically can be sold into a different market. But without actual production cost figures that include all fixed and variable costs and prices for selling electricity, bio-oil, or carbon, making these calculations is quite difficult, and at best speculative.

Table 7. Annual Potential Transformation of Biomass from Proposed Pyrolysis Plant at Cornell University

Category	Quantity of Output
Wet Tons Biomass (30% Moisture Content)	11,310
Dry Tons Biomass	8,700
Tons of Biochar	2,800

Source: CURBI, 2010

To give a sense of the transformation of biomass into biochar, Table 7 presents figures on a proposed slow pyrolysis plant that Cornell University intends to construct that will process between 15,000 and 30,000 wet tons of biomass per year. This demonstrates that such a plant could potentially produce enough biochar for 560 acres, if 5 tons of biochar is applied per acre.

Methods, Costs and Benefits of Application

There are a variety of application methods, all dependent on the farming system, available machinery, and labor. Uniform soil mixing, with disking possibly favored over plowing, might be the most important factor in catalyzing favorable soil to biochar interactions as well as minimizing potential erosive losses. Soil cover may minimize the need for thorough mixing.

Currently, very few farmers have applied biochar material into agricultural soils. Biochar soil incorporation has mostly been carried out within the context of research and testing. However, it is envisioned that farmers will make biochar applications for two main purposes. First, biochar may be applied to improve agricultural profitability or as a natural resource management tool to reduce environmental pollutants or restore degraded lands. Second, biochar applications will be made for C sequestration. To a large extent, the attractiveness of biochar application will depend on the specific cropping system and soil type. The potential benefits from the biophysical response to biochar applications, as well as the risks, have been reviewed above.

The application of biochar, as has been indicated earlier, has many potential benefits. The magnitude of these benefits, and how they are economically valued, is a complex issue. Farmers will obviously be motivated to use biochar on their fields if these benefits can be demonstrated clearly. Potential increases in soil productivity could be substantial, and could prompt a decreased use of fertilizers, which could provide additional savings. As for the use of herbicides or pesticides, it is not clear if their use would be reduced or increased. Spokas et al. (2009) found that biochar additions in a lab trial increased sorption of two common herbicides. Increased sorption would reduce leaching and runoff of herbicides, but this might lead to reduced bioavailability and require higher application rates.

Blackwell et al. (2009) also discuss incorporation of biochar into composts and manures. Such mixtures are used in some orchard systems in Australia and New Zealand. The mixtures can be spread within orchard rows without incorporation. Even though liquid manures and slurries could, in principle, be suitable for mixing with biochar, Blackwell et al. (2009) could not find any evidence that this combination is currently used. They state that there would be three major benefits to this combination: reduction of odor, retention of phosphorous in liquid manures, and reduction of dust formation.

Deep banding applications of biochar, where biochar is applied beneath the soil surface to 0.1 to 0.2 m depth, would be beneficial in a variety of farming systems. Deep banding would eliminate dustiness and create good soil-biochar and plant-biochar contact. Pneumatic systems with belt-driven feeds from supply hoppers potentially integrated with other planting operations have been used for biochar applications in Australia.

Blackwell et al. (2009) discuss top-dressed biochar applications, where dry biochar is added to the soil surface, in pasture systems, forests, or other perennial cropping systems. Protection against wind and water erosion would be critical when top-dressing biochar. Ecological delivery of biochar through animal feed is also a possibility, but the deliverable amounts would be limited.

The effectiveness of all fertilizers, including biochar, varies according to whether they are applied on the soil surface or incorporated, placed in bands or broadcast (i.e., foliar application), placed between rows or under rows, or various combinations of the above. Other factors that will affect decisions on application include: available machinery or labor, plant needs, types of fertilizers and economics. Furthermore, specific decisions on biochar applications will revolve around a few main areas: the purposes of the application or biophysical response desired, technical feasibility and safety, and economic constraints or opportunities.

An application rate of 5 tons of biochar per ha has been shown to decrease fertilizer needs by 7% because of increased nutrient availability following application (Steiner et al. 2008a). If for example, hypothetically, a ton of biochar were to cost between \$150 - \$350 per short ton, and an application rate of 5 short tons per ha is suggested, the farmer is paying at least between \$750 and \$1,750 per ha of land, excluding application costs. Depending on the soil characteristics, the application amounts, the period over which the biochar is applied, and the response to the application, it might be the case that an application rate of more than 5 short tons/ha is appropriate, making this cost substantially higher. Alternatively, less biochar might be required, or its application might be spread out over a number of years.

Soil fertility benefits are necessarily different for different soils (Kimetu et al. 2008; van Zwieten et al. 2009), and the value of biochar may need to be locally established, as for any other soil amendment. Despite the benefits that can accrue over many years, what direct financial compensation the farmer will get to offset the cost of biochar application is unclear. Furthermore, demonstrating these benefits to farmers, who must make decisions on short-term economic returns, might be difficult, at least initially.

Increased Yields and Reduced Nitrogen

Lehmann et al. (2003) found that the application of biochar to soil led to a reduction of N leaching by 60% and increases of crop productivity by 38 to 45%, which we assume to translate into a 20% saving in fertilizer and a 10% savings in irrigation and seeds. Others have found yield increases of up to 140% on poor soils under recommended fertilization (Lehmann et al. 2006). Other measured responses to the application of biochar are summarized in Table 8. Response rates are varied, but in many cases there is an improvement in nutrient uptake, biomass, or crop yields (Table 8).

Table 8. Crop Yield Responses as Related to Relevant Biochar Properties

Feedstock for Biochar and Rate of Application	Crops/Plants	Responses	Reasons	Reference
Unknown wood (0.5t ha ⁻¹)	Soybean	Biomass increased by 51%	Water holding capacity & black color on temp.	Iswaran et al. (1980)
Bamboo (Unknown rate)	Tea tree	Height and volume increase of 20% and 40%, respectively	Retained fertilizer, maintained pH	Hoshi (2001)
Secondary Forest wood (68tC ha ⁻¹ – 135tC ha ⁻¹)	Rice, cowpea, and oats	Rice biomass increase of 17%, cowpea biomass increase of 43%	Improved P, K, and possibly Cu nutrition	Lehmann et al. (2003b)
Bark of <i>Acacia mangium</i>	Maize, cowpeas peanut 2 sites	Biomass increase of 200%	Increase in P and N availability and reduction of exchangeable Al ³⁺	Yamato et al. (2006)
Secondary forest wood (11t ha ⁻¹)	Rice and sorghum	Little response with biochar alone. Yield increase of 880% using a combination of biochar and fertilizer.	Not stated	Steiner (2007)
Rice husk (10t ha ⁻¹)	Maize, soybean	Yield increase of 10 – 40%	Not clearly understood	Chan et al. (2007c)
Green waste (10 – 100 t ha ⁻¹)		No positive effect with biochar with application rates up to 100t per ha. Biomass increase of 266% with added fertilizer	Indirect effect of improving hard setting soil	Chan et al. (2007c)
Paper Mill Sludge (10 t ha ⁻¹)	Wheat	Increase in wheat height of 30-40% in acid soil but not in alkaline soil	Mainly liming value	Van Zweiten et al. (2007)

Source: Chan and Xu, 2009.

Value of the Carbon Offset

When evaluating carbon offsets from biochar, it is imperative to have a clearly defined protocol under which to assess these benefits. Studies of the GHG offset value based on a lifecycle analysis often do not include an accurate representation of the business-as-usual scenario and the project scenario for the project participants, limiting applicability for GHG offsets quantification.

The economic analysis done by McCarl (2009), detailed in Table 9, provides estimates of GHG accounting per ton of feedstock.

Table 9. Estimated GHG Offsets (in CO₂e t⁻¹ of feedstock) for Fast and Slow Pyrolysis

Category	Fast Pyrolysis	Slow Pyrolysis
Collect feedstock on farm	0.011	0.011
Haul feedstock and biochar	0.002	0.003
Replace lost nutrients on farm	0.007	0.007
Save fuel in tillage	-0.018	-0.018
Operate pyrolysis system	0.033	0.033
Reduce nutrients used on farms	-0.004	-0.028
Credit for displacement of coal electricity	-0.765	-0.191
Sequestration lost due to residue removal	0.033	0.033
Sequestration gain from biochar	-0.122	-0.963
Net GHG effect	-0.823	-1.113

Source: McCarl et al. (2009)

While these numbers and their supporting explanations are quite valuable in the analysis of potential GHG offsets from biochar, they do not present the carbon accounting that would be developed under a protocol. For example, these calculations include credit for the displacement of coal electricity as one of the largest components of emission reductions. In some cases, the pyrolysis plant may not be displacing fossil fuel based grid electricity because this may not be feasible given the logistics of the plant. Moreover, indirect emission reductions from reduced energy consumption may not be included as eligible GHG emission offsets in some programs, e.g., if energy emissions were a capped source under a cap-and-trade program. In addition, the assumed GHG impact for changing the treatment of feedstock from its business-as-usual scenario to the project (i.e. the sequestration lost from removing rather than retaining residues on the field), is not accounted for in the study.

The revenue generated by the registration and sale of offsets would be a direct incentive that could induce farmers to use biochar or possibly even set up their own pyrolysis system. But if farmers are purchasing the biochar, the value of the carbon offset alone will not cover the current biochar price. As the industry is in its infancy, production costs will likely decrease. Likewise, prices of both carbon and energy will change, and the overall economics of the industry will evolve. Therefore, the economic viability of developing carbon offsets from carbon sequestration in soil from biochar application will presumably improve.

4 Positive and Negative Environmental Impacts

4.1 Positive Environmental Impacts (Co-benefits)

One of the most intriguing aspects of biochar is the multiplicity of potential co-benefits from its production and application. The following section focuses on the co-benefits from biochar soil application, other than the benefits from atmospheric carbon sequestration. Biochar applications for enhanced agricultural productivity and sustainability have become a central focus of research in the past decade. In some cases, it may be difficult to clearly distinguish the co-benefits of biochar from the actual GHG related benefits, as is the case where the increased productivity from biochar treated soils reduces pressure on land and thus deforestation elsewhere.

Sohi et al. (2009) proposes three categories by which biochar may improve agricultural systems. First, biochar's compositional makeup and elements contained therein directly modify soil chemistry. Second, the chemically active surface of biochar changes soil nutrient dynamics and catalyses other important soil processes. Third, biochar enhances soil's physical structure increasing water retention, fostering root growth, and improving nutrient retention. A full exegesis of each category and the interconnections between them is beyond the present scope. However, a brief review of current findings manifests how biochar can improve soils and agricultural productivity and the rapidity with which those co-benefits are delivered.

As has been noted in previous sections, the type, nature, and origin of the feedstock, the temperatures used during pyrolysis and the duration of pyrolysis, affect the makeup of biochar. As a result, biochar qualities differ widely and it is difficult to make broad statements about adding biochar to soil only as a fertilizer (i.e. for its nutrient content). However, the availability of the nutrients contained in biochar exceeds the importance of the total content of nutrients within biochar (Chan and Xu 2009). The nutrient content of biochars differs widely, but much N is lost in the pyrolysis process particularly at higher temperatures (DeLuca et al. 2009). Other nutrients are less susceptible to loss during pyrolysis compared to N. Chan and Xu (2009) review of crop responses to the nutrient properties of biochar. The most recent studies have found positive responses to biochar additions for net primary production, grain yield, and dry matter (Major et al. 2010, Asai et al. 2009, Chan et al. 2008, and van Zwieten et al. 2009).

The cation exchange capacity (CEC) measures the total sum of exchangeable cations that a soil can hold (Brady and Weil 2008). The CEC in a soil is primarily a function of its clay content, mineralogy, organic matter (this includes biochar in addition to other organic compounds and structures), and pH. It is considered an important measure of soil fertility as well as an indicator of the environmental response of a soil. Liang et al. (2006), Cunha et al. (2009), and others have found higher CEC in biochar rich anthrosols (Terra Preta soils) when compared to contiguous soils in Brazil. The stability of biochar over time cannot be equated with stability of its positive functions (Sohi et al. 2009). However, Cheng et al. (2008a) showed that biochar from old kiln sites increased in CEC and pH over 130 years. This suggests significant functional stability.

As CEC indicates the ability of a soil to retain nutrients, the above results partially explain biochar's role in nutrient retention. Indeed, biochar increased N retention after fertilization with ammonium sulfate in work done on highly weathered soils with extremely low CEC (Steiner et al. 2008a). The researchers found increased plant uptake of fertilizer N on biochar plots, indicating reduced leaching and/or reduced gaseous losses.

Soil pH is a master variable that influences a plethora of soil chemical and biological properties (Brady and Weil 2008). Biochar affects soil pH, but it must be emphasized that biochar can be produced at a range of pHs depending upon feedstock and, more importantly, pyrolysis conditions. Lehmann (2007) produced biochar at pHs ranging from 4 to 11. The Terra Preta soils of Brazil show more favorable pH conditions (pH 5.0-6.4) than adjacent soils with an absence of biochar (pH 3.9-4.6) (Liang et al. 2006). Similar increases in soil pH have been found on active or historical charcoal making areas in Ghana, Mexico, and Pennsylvania (Oguntunde et al. 2004, Gomez-Luna et al. 2009, and Mikan and Abrams 1995). Biochar could be used by farmers to control soil pH and to reduce or replace lime applications (see Rodriguez et al. 2002). Novak et al. (2009) significantly raised soil pH and reduced exchangeable acidity on acid and infertile soils from the US southeastern coastal plain using biochar from locally available pecan shell waste. Rodriguez et al. (2009) used biochar from bagasse to increase soil pH from 4.0-4.5 to 6.0-6.5 in a maize trial in Colombia. However, yield increases were not observed on a calcareous soil bearing high pH values (van Zwieten et al. 2009). To date the evidence of biochar's effect on soil pH is mostly positive, but the pH of the biochar is strongly dependent on pyrolysis conditions.

Measurements of reduced leaching and reduced gaseous losses of N_2O and CH_4 provide evidence of enhanced nutrient retention. However, such measurements in the field can be difficult and often improved nitrogen use efficiency and reduced fertilizer use can serve as proxy indicators suggestive of reduced N_2O losses. Currently, there is a paucity of research, particularly field based, that examines biochar's effect on leaching losses (Major et al. 2009) and gaseous losses (Sohi et al. 2009). In a pot trial with rice plants, Lehmann et al. (2003) found that the addition of fresh biochar reduced ammonium N losses by 10%. Aged biochar might have been even more effective due to higher CEC. Yanai et al. (2007) did find up to 90% lower N_2O emissions with biochar additions at high water saturation levels but greater saturation overwhelmed emission suppression. Sohi et al. (2009) found an emission suppression of 15% in a pot trial. Rondon et al. (2005) cites field trials in Colombia that demonstrated an 80% reduction in N_2O emissions from soil. Sohi et al. (2009) state that the duration of the effect may be limited and that in the long term, effects from biochar are likely to be non-linear with respect to application rates. Biochar effects on soil physical structure, particularly pore space, will thus be more critical.

As mentioned above, biochar favorably affects the physical attributes of soils. Increased porosity both from the biochar itself and from enhanced aggregation with organic matter can result in the physical retention of soil water. Thus, the complex pore structure of biochar can contribute to nutrient retention due to the trapping of nutrient-rich water within the biochar pores (Major et al. 2009). Sohi et al. (2009) and others point out the favorable effects of biochar on organic matter as a result of aggregation and protection. Increased organic matter is known to increase water retention. Glaser et al. (2002) reported 18% higher moisture retention in

Terra Preta soils compared to adjacent soils with poor to nonexistent biochar. They attributed the higher moisture levels to the combination of increased soil organic matter, protected by biochar, and the biochar itself. Gaskin et al. (2007) found that soil moisture retention increased at very high levels of biochar addition.

Biochar has lower bulk density than mineral soil with values on par with organic soils (Downie et al. 2009). Bulk density values for soils around kiln sites in Ghana were lower by 10%, compared to adjacent soils (Oguntunde 2008) and infiltration was increased in charcoal sites in Ghana (Ayodele et al. 2009). Biochar additions to a hard setting soil in Australia reduced tensile strength and improved plant growth (Chan et al. 2008). Lower bulk densities would reduce tillage costs and increase moisture infiltration. Sohi et al. (2009) comment that there has been surprisingly little work done in this area.

4.2 Negative Environmental Impacts

Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbon (PAHs) are formed anytime carbon-based materials are burned incompletely, such as during the production of biochar. PAHs are one of the most widespread pollutants resulting from natural combustion events, such as forest fires, and anthropogenic activities, such as wood processing and general industrial activities.⁹ Previous and ongoing reviews on risks from biochar production and utilization, discuss the possibility of PAH contamination of biochar and consequent toxicity toward soil fauna or consumers of plant products from biochar enriched soils. PAHs accumulate in soils and sediments, but do not dissolve easily in water. Mixed microbial populations will degrade some PAHs, with degradation decreasing with increasing molecular weight. One of the main EPA risk assessment tests is predicated on the idea that toxicity to sediment organisms is directly proportional to the amount of unbound PAH in porewater (U.S. EPA-ERASC 2008). This would imply that PAH bound to organic carbon components is partially inert on short time scales. However, recent evidence indicates that PAHs do bio-accumulate and plants can be used in phyto-remediation of PAH (Diab 2008).

The main research questions are: (1) to what degree does slow, mid-temperature pyrolysis produce PAHs, (2) which feedstocks are more likely to produce biochar with higher PAH levels, and (3) will routine biochar applications increase possibilities for bioaccumulation. Garcia-Perez (2008) and Sohi et al. (2009) cite Ledesma et al. (2002) to establish that at pyrolysis temperatures over 700°C large amounts of PAHs are created in secondary and tertiary pyrolysis reactions. Another confidential report concurs citing Maesk et al. (2008) using 750°C as the benchmark figure, above which PAH are produced to a greater extent. The latter report and

⁹ Nam et al. (2008) found background levels of PAHs from 42 to 11,200 g kg⁻¹ (mean of 640 g kg⁻¹) in soils across Norway and the UK, largely resulting from natural forest fires. Higher-than-background levels in soils are associated with urban areas (Morrillo et al. 2007), former wood processing sites from the late 19th to early 20th century (Garcia-Perez 2008), and estuaries or rivers near industrial areas (Ni et al. 2008) with levels from 1,487 g kg⁻¹ to 618,651 g kg⁻¹.

Garcia-Perez (2008) comment on the production of small amounts of PAHs in the temperature ranges of 400-600°C or 350-600°C, primarily from combustion of solid substrates rather than tertiary substrates. These are primarily low molecular weight PAHs (lower risk), but some high molecular weight PAHs, e.g. benzo[a]pyrenes (high risk) are formed. Garcia-Perez (2008) also notes the structural differences for lower temperature PAHs; these highly branched structures tend to be lower risk. The consensus seems to be that quantity of PAH production is generally low and the PAH species produced low-risk at lower temperatures, although some exceptions are noted for high PAH levels in bio oil.

An additional concern centers on feedstock type. Zhurinsk et al. (2005) found high levels of PAHs in pyrolyzed creosote treated wood, but untreated biomass had levels less than that of urban soils (Creaser et al. (1989). Conesa et al. (2009) examined a wide range of waste materials under simulated pyrolysis to assess PAHs values. Garcia-Perez (2008) and Sohi et al. (2009) conclude that to date, no evidence of leachable PAHs have been found in woody biomass biochar from either fast or slow pyrolysis. Indeed, Hockaday et al. (2007) use the soil degradation of PAH by fungal enzymes to establish an equivalency to processes causing biochar losses from soil as dissolved organic matter.

Dioxins

Garcia-Perez (2008) found no studies on dioxin content in biomass fast pyrolysis products. In order for dioxins to form, organic matter must be consumed in the presence of chlorine and metals. Biomass will not have significant chlorine, but waste products, e.g. Municipal Solid Waste (MSW), will have chlorine especially in plastics. Dioxin formation is heavily dependent on temperatures from 750°C (precursors) to over 1,000°C. Biochar pyrolysis does not reach such temperatures, therefore, dioxin formation should be of no concern. However, it is best to avoid pyrolysis of contaminated waste wood (Oehme and Muller, 1995), MSW (Blais et al. 2003), or material already contaminated with dioxins.

Heavy Metals

Heavy metals are not currently a profound concern for biochar unless the feedstocks were to come from municipal solid waste, tires or sewage sludge. Even though it is possible to produce biochar from these materials, it is generally not advised due to the heavy metal contamination risk. For this reason, this paper excludes biochar produced from municipal solid waste, tires, and sewage sludge. Rondon et al. (2007) speculate about the possibility of heavy metal (i.e., lead) content in biochar being responsible for decreased biological nitrogen fixation¹⁰ at the highest biochar rates applied to beans in a pot trial. Dairy manure biochar has been used as an absorbent for lead (and atrazine) in a Chinese study; the biochar showed two types of sorption (surface and precipitate) when compared to only surface sorption on activated charcoal (Cao et al. 2009). Hwang et al. (2007) found that pyrolysis of sewage sludge prior to landfilling might be

¹⁰ Nitrogen fixation is a biological process by which atmospheric nitrogen gas is converted into mineral nitrogen, a form of nitrogen that can be taken up by plants. Nitrogen fixation is an absolutely essential process for life because mineral nitrogen is required to biosynthesize the basic building blocks of life.

promising due to pyrolysis residue absorbing heavy metals and reducing leaching of cadmium, chromium, lead and zinc. Lievens et al. (2008 and 2009) has investigated fast pyrolysis of contaminated willow, birch and sunflower from phyto-remediation sites contaminated with heavy metals. They found that the ash/char residue concentrated heavy metals rather than releasing them as volatile fractions as in traditional incineration. They emphasize the importance of temperature in controlling the thermal products.

Other Mineral Compounds

Depending on the feedstock, biochar contains varying levels of mineral compounds including carbonates, sulphates, phosphates, and various metals such as calcium, sodium, magnesium, and potassium (Koutcheiko et al. 2007, Garcia-Perez 2008).¹¹ Even though these compounds have much lower toxicity compared to PAHs or heavy metals, very high doses of biochar in a given agricultural field may be problematic since the high concentration of alkali salts from biochar can cause osmotic or specific ion effects on crops grown in such soils, resulting in crop yield reductions.

Residual Oils in Biochar

Residual oils found in biochar may be a potential concern (Sohi et al. 2009). If bio-oils are one of the pyrolysis outputs, the subsequent question is if bio-oils have small levels of PAHs then is there any oil residue left on the biochar surface? To date the majority of relevant research has focused on bio-oils and contaminants therein; oil residue on biochar has been an ancillary topic. PyNe (<http://www.pyne.co.uk/index.php?id=18>), a project for the International Energy Agency (IEA), has compiled a material safety data sheet (MSDS) on bio-oil that sets out acceptable levels for toxic products in addition to a best practices assessment of the overall production process. The MSDS does state that PAH levels in oils from hydro-pyrolyzed wood samples were well below established risk levels. However, despite the above emphasis on bio-oil contaminants, research shows that the effects may not be deleterious. Steiner et al. (2008b) assessed the effects of pyroligneous liquid (PA), a smoke condensate from the pyrolysis process on microbial respiration. They found that microbial biomass, microbial efficiency expressed as metabolic quotient, and microbial population increased with increasing amounts of PA. They attributed this to easily degradable substances in the PA. In addition, Steiner et al. (2008b) cite the widespread use of PA, often in conjunction with biochar, in Brazil and Japan as an organic amendment and crop protection additive. Rodriguez et al. (2002) applied PA to maize crops and found that a 20% dilution level resulted in the highest maize yields. They attributed this to the PA effect on the alkaline soils by lowered pH and consequent increased micronutrient availability.

¹¹ The release of alkali metals such as Na and K during pyrolysis of woody biomass has been examined in depth due to their adverse effects on gas turbines (Kowalski et al. 2007, Olsson et al. 1997) as well as for their role in catalyzing or inhibiting pyrolysis reactions.

Dust During Biochar Transportation and Application to Soil

Dust from biochar may present problems during transportation and application. Blackwell et al. (2009) states that particles smaller than 10 µm present in biochar can be airborne by light winds during storage, transport, or application. Apart from the significant air pollution caused by dust, dustiness of chars is related to fire hazard. Finer charcoals have a higher risk of being flammable. The fire hazard is determined by the volatile compound content of biochars. Pelletizing, through dust reduction, wetting, and other appropriate safety measures in storage reduce fire hazard. Mixing biochars with manure before application can reduce the formation of dust during application. Blackwell et al. (2009) emphasize the importance of attention to quality control and safe handling during the manufacturing of rice husk biochar.

5 Review of Legislation on Soil Amendments and Ownership of Emission Reductions

5.1 Review of Rules and Regulations related to Soil Amendments

Soil amendments in general are regulated by each state. There are no federal regulations overseeing this aspect of agriculture. The International Biochar initiative (IBI) leadership has brought this issue up with USDA. The consensus is that biochar will be treated as an organic soil amendment, which should require no particular permitting.

The instance where other issues could arise is with regard to biosolids in the biochar if it is made from animal waste or sludge from solid waste plants. The presence of pathogens from using such biomass as a feedstock is thought to be solved by the pyrolysis process. The regulatory solution would be to have a carve-out within the biosolid regulation for biochar that would allow for its application without further permitting.

In the case where land is owned by a different party than the person who is cultivating it, incorporating biochar may require the explicit permission of the land owner, depending on the specific contract between the land owner and the renter of the land. In practice, it is clear that land owners should be involved in project design at an early stage.

The potential presence of heavy metals and other hazardous elements in biochar may jeopardize its use as a soil amendment. Contamination with toxic substances in biochar must be solved through regulation and standardization of the biochar production industry. The chemical make-up of any particular biochar needs to be certified and approved so that the user is assured that the metals and other compounds would not detract from the efficacy of the biochar being applied to the soil. Most likely, this will require explicit chemical testing of each batch of biochar if feedstocks or production procedures are changed.

Permits for Production of Biochar

Pyrolysis is a technology that is unknown to most state Environment Agencies so there is no regulation specifically pertaining to pyrolysis facilities. Normally, when a product is being

incinerated, the emissions need to be regulated by whatever local authority (or authorities) have jurisdiction over the plant and the process in question. It is not clear whether or not the production of biochar by most pyrolysis systems would produce low enough emissions that permits would not be required. This of course needs to be confirmed with the local environmental authority. In some jurisdictions near urban areas, permitting problems have been encountered by some biochar producers as their plants are considered incinerators. In more rural areas, permitting might be less of a problem. In any case, the pertinent regulations need to be confirmed and emissions profiles verified, so that units can be constructed and put into operation. There will likely be a number of local authorities that will need to weigh in on these issues, especially those with stringent environmental regulations and oversight. Some states, such as Oregon, have begun drawing up regulations to provide the proper oversight on biochar production units.

6 Summary of Issues Related to Developing a Protocol

6.1 A Conservative Approach to Protocol Development

Carbon credits must be verifiable, transparent, and real. A carbon protocol must reflect all of these essential requirements. However, the exact volume of carbon credits generated by biochar soil incorporation projects is determined by a large number of factors related to the feedstock source, production methodology, transportation used, incorporation procedure, and characteristics of the site where the biochar will eventually be incorporated. The development of a fully comprehensive protocol that accounts for all of the different permutations of these factors is impossible at this point. There is simply not sufficient experience to fully account for all of the possible ways in which biochar soil incorporation carbon projects can be developed.

However, for a select number of circumstances, there is sufficient experience and data available to bring the carbon in biochar projects to market. Therefore, we propose to develop a biochar protocol in an iterative approach, consistent with the Reserve's protocol development process in which high priority, protocol-ready project circumstances would be developed into a protocol initially, with the possibility of eventual expansion of the protocol when more research is available and experience gained with biochar soil projects. The most challenging part of the GHG accounting for biochar soil incorporation projects are the secondary emissions and potential activity-shifting leakage effects through land-use change. Thus, for the first phase of protocol development, we propose to only allow carbon credits from biochar produced under the following conditions:

- Case 1 - Biochar from slow pyrolysis of corn stover that is left on agricultural fields under the baseline scenario
- Case 2 - Biochar from slow pyrolysis of switchgrass produced on marginal or degraded land with limited current land use with potential cogeneration of energy

- Case 3 - Biochar from slow pyrolysis of yard waste that is deposited in land-fills or composted under the baseline scenario
- Case 4 - Biochar from slow pyrolysis of forest waste that is left to decompose under the baseline scenario

This chapter will discuss all issues related to protocol development in light of these four suggested cases. Existing CAR protocols emphasize the use of a programmatic approach in which standardized baselines are used to calculate emissions under the baseline scenarios. By using a conservative approach in protocol development and limiting the allowed scenarios included in the protocol, it is easier to follow a programmatic approach based on standard coefficients or equations.

The conditions under which the biochar protocol can be applied are controlled through a clearly defined set of eligibility criteria. Third-party verifiers can check the validity of a potential project through a formal analysis of how the potential project meets the eligibility criteria. Within the remainder of this text, we will suggest a number of eligibility criteria related to each of the sections that limit the spectrum of allowable practices and conditions to which a project must adhere.

6.2 Crediting Period and GHG Assessment Boundaries

Commitment period

Similar to the forestry protocols of CAR, the commitment period for biochar carbon credits is assumed to be 100 years. However, biochar incorporation is unique in that the amount of carbon sequestered is highest at the beginning of a project, and then slowly decreases due to erosion, downward movement, and decomposition. Therefore, only the amount of carbon that is still present at the end of the commitment period (100 years after incorporation) can be brought to market. During the project crediting period, this amount can only be estimated.

GHG Assessment Boundaries: Sources, Sinks, and Reservoirs

The GHG assessment boundaries define both the physical location and the expected greenhouse gases from all sources, sinks and reservoirs (SSRs) affected by biochar soil incorporation projects. An in-depth enumeration of all sources, sinks, and reservoirs is provided in Figure 7 and Table 10. This section gives a broad overview and focuses on the relation of SSRs to protocol development and project eligibility.

The geographical boundaries of most SSRs must be explicitly defined within a project document so that credits remain completely verifiable by third-party verifiers. Some of the geographical boundaries of sources and sinks define areas that produce emissions that must be accounted for only at the initial project verification, other boundaries define areas that produce emissions from areas that must be accounted for at later project verifications.

The following sources, sinks, and reservoirs are relevant for biochar soil incorporation carbon projects:

1. On the area on which the original feedstock was produced or grown:
 - a. Sources related to fertilizer use
 - b. Sources related to farming machinery
 - c. Sources related to decomposition of the feedstock in the baseline scenario
2. The area that is affected by direct or indirect activity-shifting leakage related to primary production of feedstock.
 - a. Sources related to changes in stocks of carbon pools
 - b. Sources related to land-use change activities
3. The area where any secondary residues would have been deposited, or disposed of in absence of project activities.
 - a. Sources related to decomposition of the feedstock in the baseline scenario
4. The area in which the biochar is incorporated.
 - a. Sources related to the incorporation of biochar
 - b. Sink formed by the stable component of biochar, once incorporated in the soil
 - c. Sources related to the decomposition of the labile component of biochar, once incorporated in the soil

The geographical location of the SSRs outline above must be defined at the initial project verification. In other words, the source of the feedstock used to produce the biomass must be known at the initial project verification. However, once the project is on-going and the biochar has been incorporated, only the area in which the biochar is incorporated must be monitored.

In addition to the SSRs outline above, the following must be accounted for:

5. Sources related to the transportation of biomass between the geographical locations of the SSRs outlined above must be accounted for.

Note that for the sources and sinks that are related to changes in the soil carbon pool, the GHG assessment boundaries include the surface and horizontal extent, and the vertical depth. This is especially important for the area in which the biochar is incorporated, since there will be a vertical transport of biochar, once incorporated with a net downward flux. A set vertical depth of the system will define to what depth biochar must be monitored. Once the biochar leaves the assessment boundaries of the field in which it was incorporated through water or wind erosion, deposition, or soil removal, it must be considered as lost for the purpose of carbon credits, even if the biochar is merely displaced. Biochar that has left the assessment boundaries is not verifiable anymore.

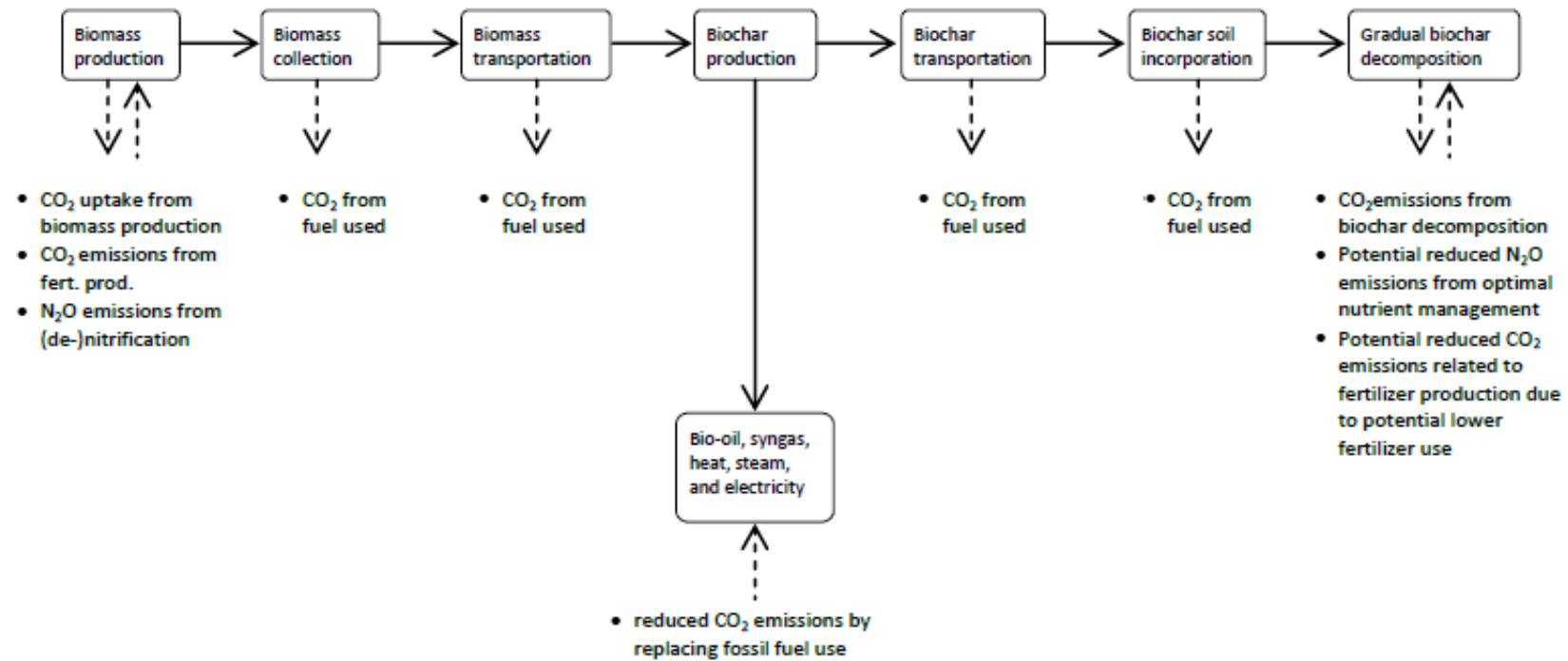


Figure 7. Simplified diagram of emissions related to the life cycle of biochar soil incorporation.

Table 10. General Overview of All Possible GHG Sources and Sinks Related to Soil Biochar Sequestration

Category	Category	Project Scenario	Baseline Scenario
Farm	changes in soil C	increase (*)	no change (*)
	changes in CO ₂ emissions related to fertilizer manufacturing	potential decrease or increase	no change
	changes in soil N ₂ O emissions	potential decrease	no change
	changes in soil CH ₄ emissions	potential decrease	no change
On-site biochar production facility	changes in C from feedstock biomass	complete removal	depending on current use. For example: <ul style="list-style-type: none"> decomposed in the field, transferred to landfill, or used as compost/mulch complete removal when converted to energy
	CO ₂ emissions from fossil-fuel use	medium decrease when fossil fuels are displaced due to partial energy production ¹²	large decrease when fossil fuels are displaced due to partial energy production
Secondary GHG changes	N ₂ O emissions from primary production	potential increase due to fertilizer and N ₂ O production, in case of bio-energy crops	potential increase due to fertilizer and N ₂ O production, in case of bio-energy crops
	CO ₂ emissions from transport of biomass to biochar plant	increase	increase in case of biomass used for energy
	CO ₂ emissions from transport of biochar to farmer's field	increase	not applicable
	CO ₂ emissions from incorporation in farmer's field	increase	not applicable
	N ₂ O, CH ₄ emissions from landfill or compost (and CO ₂ from avoided transport to landfill)	decrease	no change

(*) All comparative language refers to changes over time.

¹² Energy production from heat exchange, syngas or bio-oil can displace fossil fuels.

Potential Eligibility Criteria Related to GHG Assessment Boundaries

The following eligibility criteria could be added to ensure that soil biochar incorporation carbon projects have set GHG assessment boundaries.

- The area on which the original feedstock was produced or grown must be known at the initial project verification.
- The fate of the feedstock under the baseline scenario must be known at the initial project verification.
- The area in which the biochar is incorporated and the incorporation depth must be known at the initial project verification.

6.3 Carbon Accounting for the Baseline Scenario and Additionality

The net GHG benefits from carbon projects are calculated by subtracting emissions under the assumed business-as-usual, or baseline, scenario from the emissions under the project scenario. Therefore, it is crucial to consider the hypothetical question of what would have happened with the feedstock in the absence of the project activities. Within a carbon protocol, baseline scenarios must be different cases based on whether the feedstock was produced exclusively for the generation of biochar, and whether energy was produced from the biomass under the baseline scenario. We identify three discrete cases:

- Biochar is produced from feedstock grown exclusively for the production of biochar and energy. For example, switchgrass can be grown as a biochar feedstock with some energy co-generation.
- Biochar is produced from feedstock that is already available and that is purely waste and would have been left to decay, be burned without energy generation, put in landfill or composted in absence of the biochar production. This case includes the use of agricultural wastes, such as corn stover, yard waste, forest slash, or mill waste that are purely waste, and that are not used for any other processes.
- Biochar is produced from feedstock that is already available but that is used for energy production. Energy is produced from the pyrolysis of corn stover, yard waste, forest slash or mill waste, and biochar is a by-product of the energy production. The conditions for energy production may be set so that the production of biochar is maximized.

Each of these three discrete cases have different baseline accounting procedures and have varying degrees of complexity regarding protocol development.

- When biochar is produced from feedstock that is exclusively grown for biochar production, the land-use and land cover before feedstock production must be considered. More specifically, if vegetation and biomass is removed to enable the production of feedstock, the associated losses in carbon should be accounted for. Likewise, potential losses in the organic carbon pool of the soil on which the feedstock is produced must be accounted for. In addition, the displacement of previous land-use

activities or the previous agricultural production system to other areas may cause emissions outside of the system boundary. The latter would be considered leakage emissions. The accounting of changes in soil organic carbon due to feedstock production and leakage is challenging. For the first phase of the protocol, the accounting can be simplified by requiring that the production of feedstock occurs only on marginal or degraded land with little or no current use. Since there is no current land use, leakage through displacement of activities will be negligible. Furthermore, it is very unlikely that soil organic carbon is greater in the baseline scenario (degraded land) than in the project scenario (switchgrass), effects of project activities on soil carbon can be ignored. A protocol would have to clearly outline how marginal land is defined. All secondary emissions related to fertilization of the land would have to be accounted for. Nitrous oxide emissions can be quantified using the IPCC standard coefficients.

- When biochar is produced from organic waste products that would otherwise have been left to decay, be burned without energy generation, put in landfill or composted, the GHG impact from the baseline scenario must be calculated for every year of the commitment period. In the case where agricultural waste products are left on an agricultural field or composted under the baseline scenario, the amount of original corn stover that would have decomposed during the commitment period would need to be quantified. Standard decomposition decay coefficients can be used to do so. In the case where the material is burned without energy generation, standard burning efficiency coefficients can be used to calculate the loss of carbon in the baseline scenario.
- When biochar is produced from feedstock that would normally be used for energy production, such as mill waste, forest slash, yard waste, or crop residues, the emissions must be accounted for from these energy generation activities. In other words, in the absence of using the biomass for biochar, what level of emissions would have been generated by firing that biomass for energy production, over the life of the project. These avoided emissions are central to this baseline calculation.

Potential Eligibility Criteria Related to Baselines and Additionality for Phase 1

- If biochar is produced from feedstock that is primarily grown for the purpose of biochar production, it must be ensured that the feedstock is grown on marginal or degraded land with little or no use prior to feedstock production.
- If biochar is produced from waste material such as agricultural residues or yard waste such as corn stover, it must be ensured that the fate of the agricultural waste prior to biochar production is known.
 - In the case where agricultural residues are left on a cropping field or composted, a two-component kinetic model must be used to quantify baseline emissions from residues. Under a programmatic approach, the exact coefficients used for the kinetic model can come from a literature study conducted during the protocol development.

- In the case where energy is produced from the residues under the baseline scenario, the fraction of the residues used for the energy production can be assumed to be completely converted to atmospheric CO₂ as baseline emissions.

6.4 Monitoring of Biochar Carbon in Soils

Given the variety of sources from which biochar can potentially be made, the variations in pyrolysis systems being developed or in (limited) use now, biochars can have a host of characteristics and can greatly vary in their decomposition characteristics. Therefore, as was concluded in sections 1.5 and 1.6, a carbon protocol must (1) require that biochar used for carbon sequestration decomposes relatively slowly, and (2) that verified carbon credits are calculated based on actual field measurements of biochar decomposition. The first point is discussed in the “eligibility criteria” part of this section. Regarding (2), at the time of biochar incorporation it cannot be guaranteed how much of the biochar will decompose during the commitment period. However, if during the commitment period the amount of biochar is monitored at regular intervals, a two-component kinetic model can be used to predict how much biochar will eventually be left at the end of the commitment period with sufficient accuracy. Following the programmatic approach of CAR, the decomposition rates of the labile and resistant pools can be fixed in a carbon protocol, while the fraction of labile-vs-resistant material in biochar is required to be quantified during field measurements. As more measurements are made over time, the accuracy of the predictions of the fraction and amount of biochar available at the end of the commitment period will improve. Therefore, a portion of the biochar carbon could be gradually “delivered” as verified carbon credits during the project’s lifetime, as more and more measurements are made and the biochar still present at the end of the commitment period is gradually better known.

The “gradual delivery” idea is illustrated in the following graph. At year 0, with only one data point available, it is statistically impossible to extrapolate the amount of remaining biochar at the end of the commitment period. However, it is known that at least some of the biochar material will remain. Therefore, only 5-10% of the biochar could be delivered as verified offsets (after the appropriate secondary and baseline emissions are taken into account). Given a second measurement, a statistical model can be fitted. Gradually, after more measurements are performed, a two-component kinetic model can be calibrated and extrapolate the remaining biochar at the end of the commitment period with increasing accuracy. As a consequence, more and more verified offsets can be issued.

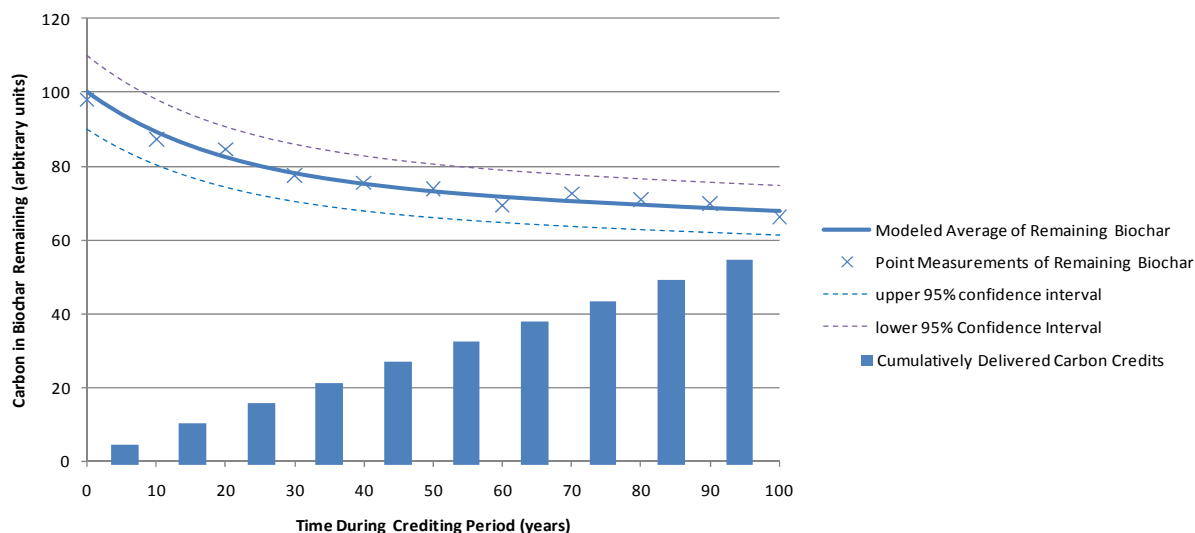


Figure 8. Illustration of how carbon credits can be gradually delivered during a commitment period, as increasingly more measurements are conducted.

An optimal sampling design should concentrate sampling near the beginning of the period (first 20 years), and allocate fewer samples near the end of the sampling period. It is known that sound measurement of the remaining biochar during the first 50 years after incorporation is sufficient to predict the remaining biochar at the end of the commitment period (Lehman and Joseph, 2009). We suggest that a carbon protocol require a minimal number of five biochar measurements; 1, 5, 10, 20 and 50 years after biochar application. Under this measurement regime, a preliminary statistical analysis indicates a discounting of maximum 20% if the lower 95% confidence interval is used to base credits on (see discounting section below).

Uncertainty and Discounting Approaches

All measurement techniques provide values that have some degree of uncertainty associated with them. However, the mere existence of uncertainty does not negate the value of a specific measurement technique. Only when the uncertainty cannot be quantified accurately or is quantified incorrectly, does a measurement approach become problematic. Once the uncertainty is correctly quantified, a discounting factor can reduce the average volume of carbon offsets to a conservatively estimated volume. As introduced before, one could issue only the volume of carbon offsets represented by the lower 95% confidence interval.¹³ This concept is illustrated in Figure 8, only the amount of offsets that represent the lower 95% confidence around the modeled mean are eventually released. The minimal level of confidence required will be arbitrary and is a matter of policy.

Discounting carbon offsets based on the difference between measurements and the actual values may seem a circular approach as the actual values remain unknown and can only be

¹³ Statistically, this means that the issued credits will be lower than the actual volume of carbon offsets generated in at least 95% of the cases, if the measurement protocol would be repeated a large number of times.

approximated through measurements. Thus the question arises: should one base the discounting on the closeness of individual measurements or by comparing different measurement techniques? Within this context, it is important to distinguish two different and often confused concepts: accuracy and precision. While accuracy refers to how close a measured or modeled quantity is to its actual value, precision expresses how reproducible a measurement is. Ideally, a measurement technique is both accurate and precise. However, one can imagine a measurement technique that yields very different values every time a measurement is taken, but that provides accurate measurements when a large number of individual measurements are averaged. Such a technique would be accurate but not precise.

In contrast, a technique that continuously reproduces values within a narrow range, but far from the actual value will be precise but not accurate. The measured values will be characterized by a systematic bias. In classic sampling theory, the accuracy and precision of a measurement system are established by creating a reference standard with known properties (i.e., the quantity of biochar), and repeatedly measuring against the reference standard. The precision is usually defined as the reciprocal of variance, while the accuracy is quantified by the difference between the measured mean and the reference level.¹⁴ Given the expectation that measurement technique will change drastically within the project duration, project proponents could be required to make a reference standard themselves by keeping a homogenous and mixture of biochar and soil, in which the proportion of biochar is known.

Potential Eligibility Criteria Related to the Biochar Quality and Monitoring

- A carbon protocol must have some sort of constraint on the decomposition rate of biochar. Once a generally accepted test is available, this constraint could be in the form of a minimal fraction of resistant material in the biochar. For example, it could be required that the resistant fraction of biochar used in a carbon project is minimally 50%. However, since currently no generally accepted test is available, a carbon protocol should limit the feedstock sources and pyrolysis conditions used in the production of the biochar. For example, biochar from woody material pyrolyzed at 500 C is known to have a relatively long decomposition rate and must be eligible for a carbon project. In contrast, poultry litter pyrolyzed at 300 C has a relatively fast decomposition rate and should be excluded from a carbon protocol. Future refinements of a biochar protocol could include a wider variety of feedstocks and pyrolysis conditions once it is better understood which biochars have relatively slow decomposition rates.
- Biochar must be measured at regular time intervals after soil application. A minimal number of five measurements are required, 1,5,10, 20 and 50 years after biochar application.
- No generally accepted measurement technique is available yet for auditing of biochar soil incorporation purposes. Therefore, instead of prescribing a technique, a carbon

¹⁴ Ideally, accuracy and precision are not quantified by a single value but rather by continuous probability distributions.

protocol could state the minimum precision and accuracy of a measurement technique. The measurement technique used must be able to measure changes in biochar with a precision of at least x% and an accuracy of at least y%.

- A reliable estimate of the non-biochar black carbon content of soils before biochar application must be carried out. Many analytical methods have a low selectivity for biochar. Therefore, this “background” black carbon content can be used to normalize biochar measurements after soil application.

6.5 Ex-ante Carbon Accounting under the Project Scenario

The main variable affecting decomposition is the fraction of labile-vs-resistant matter in biochar material. As of yet, no generally accepted methodology is available to quickly, accurately and robustly measure this proportion, as explained in Section 2.3. However, assuming that a protocol would be in place, and biochar incorporation projects become commonplace, it is expected that such a technique will become available.

The influence of microclimate and soil type on biochar decomposition is secondary to the biochar quality. A set of generalized coefficients could be used to incorporate the effect of microclimate and soil type on ex-ante biochar decomposition. However, more research is necessary to develop such coefficients. Biogeochemical process models can be used to develop such generalized coefficients. Such models are designed to simulate the processes behind greenhouse gas emissions and uptake by the landscape. Rather than relying on field measurements for quantifying ecosystem greenhouse gas exchanges, models can predict greenhouse gas exchanges based on readily available data such as soil types, quality of the organic matter, soil management, and climate. Models for describing soil organic carbon dynamics have been available for almost three decades and have matured to a point where, once calibrated, they could be employed for carbon offset calculations¹⁵. However, more research is necessary to use these models for biochar decomposition. To our knowledge, no one has calibrated any of these models to predict the decomposition of biochar. More work is needed in this area to quantitatively describe biochar decomposition. However, it is not expected to be an extensive process.

In the future, a more systemic approach could be envisioned that utilizes multi-level dispersed field measurement with feedback loops to national or regional databases in combination with biochar decomposition models based on models such as Century or Roth C. The Carbon Management and Evaluation Tool, COMET-VR, described by Paustian et al. (2009), is an attempt at this approach for total organic C. COMET-VR compiles direct measurements of changes in SOC, as a result of soil/crop management practices and/or environmental fluctuations, through

¹⁵ Examples of biogeochemical process models are CENTURY/Daycent, EPIC, DNDC, CASA, and Roth C. Note that nitrous oxide and methane emissions are more challenging to predict due to their very high temporal variability and their sensitivity to small differences in microclimate. However, modeling approaches require specialized experience and only work reliably when calibrated for the ecosystem where they are used. Therefore, they are usually combined with ground measurements to increase their accuracy and verify the model results.

a multi-level participant network with an integrated database linked to the Century SOC model. Paustian et al. (2009) believe that such a modeling measurement framework along with a coordinated nationwide soil carbon monitoring network represents the future for monitoring field and regional levels of SOC and emissions of greenhouse gases. The development of such a tool would be catalyzed if a carbon protocol requires all measurement data to become public. In this way, a useful calibration and validation dataset would become available to train and test systemic biochar decomposition models.

6.6 Potential Reversals and Mitigation of Potential Negative Impacts

Reversals are the release of sequestered carbon through intentional or unintentional changes in the condition of the agricultural field in which the biochar is incorporated. Reversals, therefore, are unlikely but possible events that reduce the amount of biochar in a soil after the biochar is incorporated. Project design must reduce the risks of reversals through proper project design and third-party verification. A carbon protocol must outline all of the potential reversals and require that projects meet specific eligibility criteria that minimize the risk of reversal and lead to an optimal project design. Note that loss of carbon in biochar through decomposition or vertical soil movement is expected and is therefore not considered a reversal. Reversals are divided into intentional and not intentional reversals. Unintentional reversals are caused by circumstances beyond the control of the project participants, such as extreme weather events, while intentional reversals are caused by conditions over which the project participants do have power, such as a change in land use or management. See section 2.5 for a more in-depth coverage of the potential reversals.

Unintentional Reversals

- **Loss due to water erosion.** Severe rainfall events can lead to sheet or gully erosion and a significant amount of loss of top soil. Loss of land through erosion can be avoided by requiring that the project is developed on non-sloping land.
- **Landslides.** Even though landslides are rare events, their occurrence is possible on sloping terrain during the long duration of biochar soil incorporation projects. Similarly as for erosion, the risk of loss of incorporated biochar through landslides can be avoided by requiring that biochar is only incorporated on non-sloping terrain

Intentional Reversals

- **Soil removal.** If top-soil is removed from the land, the biochar that is incorporated into the top-soil is lost from a carbon accounting standpoint since it is impossible to trace where the soil will end up.
- **Land Development.** When agricultural land is developed, it is altered in such a way that the biochar incorporated could be nearly completely removed.
- **Increases in tillage intensity** form a very small reversal risk. Even though cultivation typically increases decomposition of SOM, this effect seems minor or even non-existent for biochar compared to other organic matter.

Potential Negative Impacts (From Section 4.2)

- Presence of PAHs and dioxins in biochar is dependent on the original feedstock and pyrolysis conditions. More specifically, the pyrolysis temperature should be limited to be below 750°C. For verification reasons, it could be requested to perform a PAH and dioxin measurement by an independent and accredited laboratory.
- The original feedstock should not contain any material that is high in heavy metals, such as sewage sludge or organic material from phyto-remediation sites.
- The potential negative effects of mineral elements in biochar can be eliminated by limiting the maximal mass of biochar that can be incorporated in a soil.
- The effect of dust during transportation and soil incorporation can be minimized if it is required that biochar is moistened right before transportation and incorporation.

Potential Eligibility Criteria to limit Risks of Reversal and Mitigate Negative Impacts

- The land on which the biochar is incorporated should be non-sloping.
- The land on which the biochar is incorporated will remain in agricultural use for the duration of the crediting period.
- No soil may be removed from the land on which the biochar is incorporated.
- The temperature of pyrolysis to produce the biochar must be lower than 750°C.
- The original feedstock used to produce the biochar may not be contaminated with heavy metals.
- The amount of biochar that can be present in a soil is capped. This cap must take into account previous biochar that was previously incorporated into a soil.
- Dust must be avoided by pre-wetting biochar before transportation or incorporation.

6.7 Verification of Offsets

As with any carbon offset project type, the carbon accounting of biochar carbon offsets must be fully verifiable. This is straightforward for the actual incorporation of biochar. The presence of biochar can be easily verified by the naked eye. The amount of biochar added can be quantified through a sound sampling approach and analytical techniques discussed in Section 2.3 and Appendix B. However, compared to verifying the actual presence or quantities of biochar present, verifying the stated origin, baseline scenario and secondary GHG emissions is less straightforward. The source of the original feedstock cannot be cross-checked once the feedstock is transformed into biochar without any ancillary documentation. Therefore, in most cases, it will be challenging for a third-party verifier to verify any statements made by project proponents on the exact feedstock of biochar, and the level of emissions associated with production and transportation of biochar. Within a project document, project proponents may be required to include official logs of transportation companies and biochar production companies, testifying to the origin and history of a certain batch of biochar. Such a system resembles a supply-chain approach in which the full history of the biochar, from plant production to field incorporation, is documented.

6.8 Ownership of Carbon Offsets

The project proponent(s) must be identified in a project document. The project document should contain a certificate of origin of the biochar and the feedstock used for the biochar, as well as an agreement from the owner of the agricultural land to incorporate the biochar.

The issue of offset ownership will have to be worked out by contract, between the project proponents (i.e. feedstock supplier, biochar producer, and farmer) and the buyer. There are no specific laws or regulations that are pertinent here so it will be left to the contracting parties and any guidelines provided within the protocol to clarify the ownership.

Credit ownership becomes more complex when there is no direct relationship between the feedstock producer and the farmer. This can also be an issue if the land managed by the farmer is not owned by the farmer. Issues that arise will likely have to do with land sales, rentals, destruction of carbon, or development of land. Again, these need to be covered in either the contracts between sellers and buyers of carbon offsets, and later, the sellers and buyers of land from which a carbon offset has been created due to the application of biochar. Such contracts also need to reflect the permanence issue and the monitoring and verifying of the presence of carbon so that the terms of the carbon purchase agreement can be met.

6.9 Conclusion

Soil biochar incorporation carbon projects lead to net GHG benefits, if designed and implemented well. In addition, soil biochar incorporation may lead to higher yields through more optimal nutrient management and better water infiltration in biochar-amended soils, potentially reducing erosion. The accounting of such projects is complex due to the large number of variables involved in producing biochar, most notably the origin of the feedstock, and the pyrolysis conditions. However, for a number of situations the GHG accounting and verification is relatively straightforward and the generation of verifiable carbon credits is feasible. Therefore, it is suggested to develop a protocol with a conservative approach, in which only a discrete number of project scenarios are initially allowed. The protocol can be gradually expanded when experience is gained.

Further research could help with streamlining some aspects of bringing carbon credits from biochar projects to market. More specifically, we identified the following research needs:

- Rapid, accurate and robust techniques must be developed to test the fraction of resistant matter in biochar that do not take years or months but weeks or days so that some kind of certification can be provided and producers and consumers of biochar alike can know what they are using.
- A set of generalized coefficients to predict the effect of microclimate and soil type on biochar decomposition for ex-ante use must be developed.
- A maximally allowed amount of biochar that can be incorporated, expressed as tons per acre, must be established.

7 Glossary

Basic Definitions Related to Carbon Accounting

- **Project and Baseline Scenarios.** Carbon offsets are issued when a specific activity occurs that was not occurring before and that sequesters carbon from the atmosphere or reduces emissions to the atmosphere. Only the GHG benefits that are directly caused by this new activity may be claimed as carbon offsets. In practice, carbon offsets are calculated as the difference between the GHG emissions under the project scenario and the GHG emissions under a hypothetical scenario in which the project activities did not take place, the baseline scenario. In the case of biochar, one has to consider what would have happened to the biomass in the scenario where it was not converted into biochar. The question becomes, for example, what would have happened with the sawdust and other slash left behind after forest management and harvesting interventions in a forest when not used as a feedstock for biochar?
- **Additionality.** This is the consideration of whether a project activity is “additional” to what would have happened anyway, in the absence of the Climate Action Reserve and carbon offset markets generally. In other words, it must be demonstrated that the project activity and the offset reductions are a response to the incentives created by the market.
- **Permanence and Risks of Reversal.** Within a land-based carbon offset framework, permanence refers to the evaluation of the longevity and fate of the carbon stored in a pool. Carbon that is stored in a pool such as trees and soil carries risk that it could be released in the future. In the case of carbon stored in the woody biomass of trees a portion of it is converted into atmospheric CO₂ when a forest fire occurs. In cases where the biochar is destroyed through unanticipated factors such as land distribution for development, the risk of non-permanence must be addressed
- **Secondary Emissions.** Before biochar effectively ends up within a farmer’s field, many steps must be taken, with each possibly releasing GHGs. For example, during biomass production, the transport of biomass to a biochar production unit, the transport of biochar to a farmer’s field, and the incorporation of the biochar into the soil will all require the use of fossil fuels.
- **Uncertainty and Discounting.** The production and lifecycle of biochar is incredibly diverse and it is difficult to quantify all of the benefits versus the disadvantages and secondary effects in an exact fashion. There will always be some uncertainty related to the calculation of the net GHG benefits. However, the existence of such uncertainties is not an insurmountable barrier to the use of biochar as a creditable form of offset, as long as the uncertainties can be properly and conservatively bounded. However, a practice-based assessment can be made, and accurate GHG discounting mechanisms can be developed for certain biochar systems.

- **Ex-ante vs. Ex-post.** Offsets are only issued after the GHG benefits have been realized and verified. However, for project design budgeting and initial project verification purposes, it is necessary to estimate the volume of carbon offsets that can be realized beforehand. Offsets that have been realized are named ex-post, while (an estimate of) the offsets before they are realized, are referred to as ex-ante. Generally, the baseline for a project is set up-front and only the project and secondary emissions are estimated ex-post.
- **Geographic GHG Accounting Boundaries and Leakage.** Any land-based carbon project must set geographic boundaries for GHG accounting so that the location of new projects can be verified against a database of existing projects to avoid double accounting. For biochar soil incorporation projects, there can be two geographic GHG accounting boundaries: the area for production of feedstock and the farmer's field boundaries. Only increases in carbon pools (compared to baseline increases in carbon pools) within the geographic boundaries or on-site, is the basis for calculating gross carbon offsets. From the gross GHG benefits, secondary emissions and emissions from leakage must be subtracted to get net GHG benefits. Leakage emissions are emissions from the displacement of activities through activity shifting or market effects outside of the geographic boundaries. Note that carbon standards generally do not allow accounting for positive leakage.
- **Commitment Period.** The period of time over which a project is required to store carbon in order to receive full credit for offsetting CO₂ emissions.

Basic Definitions Related to Biochar Production

- **Feedstock.** The biomass used to produce biochar. In this paper, use of "feedstock" and "biomass" are used interchangeably and refer specifically to inputs for the production of biochar.
- **Mineralization.** The process of converting an organic compound into its mineral constituents. Within the context of biochars, mineralization refers to the conversion of biochar carbon into carbon dioxide and is therefore a synonym of decomposition.
- **Pyrolysis.** The process of controlled chemical decomposition of feedstock biomass by heating under limited or no oxygen supply. The process becomes exothermic above a threshold temperature, which is dependent on the feedstock type. Pyrolysis converts feedstock biomass into energy rich gas and liquid products (syn-gas and bio-oil) and leaves a solid residue rich in carbon content, about 75-90% carbon on an ash-free basis, which is called biochar.
- **Recalcitrance.** The resistance of a chemical compound to decomposition. Recalcitrant compounds are inert and inherently stable against biotic and abiotic processes that lead to the breakdown of the compound.

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9 Appendix A – Equipment Available and Biochar Producers

Domestic Companies	Website	Location	Commercial Product	Process	Capacity (dry ton/day)	Cost of Unit	Feedstock	Stage of Commercialization	Notes
ABRI-Tech / Forespect		Canada	Tech	Fast	1, 10-15, 50	\$1.5 mil (10-15 t), \$4 mil (50 t)	Ag waste, wood chips, forest slash	Installing first customer unit	Partner with ABRI (Advanced Biorefinery)
Advanced Biorefinery Inc.	www.advbiorefineryinc.ca	Canada	Tech: mobile pyro unit	Fast	1, 10-15, 50	\$1.5 mil (10-15 t), \$4 mil (50 t)	Ag waste, wood chips, forest slash	Installing first customer unit	Partner with ABRI Tech / Forespec
Alterna Energy	www.alternaenergy.ca	Canada	Char	Slow?			Wood, waste, tires		
Applied Ecological Services	www.appliedeco.com	WI	Customer						Wants to use biochar, not produce it.
Biochar Engineering Corporation	www.biocharengineering.com	CO	Tech	Slow gasification	10, 25, 50	\$100K, \$250K	Woody biomass, ag waste, manures	Pilot units, first customer or 2	BEC sells tech; Biochar Systems sells char
Biochar Products	www.biocharproducts.com	OR	Char/Oil	Fast	10, 15, 20	\$750K, \$1 mil; \$1.5 mil	Forest slash		Using ABRI tech
Biochar Systems	www.biocharsystems.com	CA?	Char	Slow gasification			Woody biomass, ag waste, manures		JV btw BEC and EcoTechnologies Group
Carbon Diversion Inc.	www.carbondiversion.com	HI	Tech	Flash	400 lbs - 3.5 tons; batch process		Anything: ag waste, green waste, woods, plastics, tires, MSW, wastewater sludge	Forming new company	Mantria partnership soured after a couple of months
Chip Energy	www.chipenergy.com	IL	Tech	Microgasification	1/3 ton/year (household scale)		Rice husks, cherry pits, coconut shells	Prototype, seeking funding.	Small stoves - residential heating
Eprida	www.eprida.com	GA	Tech?	Fast	100kg/hr		Biomass, raw sewage, "whatever's local"	Pilot projects, fundraising	"Pretty much non-existent"; works with licensee eGenesis in CA
Eterna Green / Mantria	www.eternagreen.com	PA	Char/Oil	Flash/pressurized	40; batch process		Anything	First plant operational; opening 2nd plant	Owns Biochar Brokers
GreenPyro	no web site	CA	Char (enriched)	Slow	20-25		Woody biomass: urban tree waste, forestry waste	Goal: 2 plants in 2010	
Prairie BioGas Ltd.	www.prairiebiogas.com	Canada	Char, electricity	Slow (vacuum)	15-100		Forestry waste, ag waste, MSW	Projects ready, seeking funding	
R&A Energy Solutions	randaenergysolutions.com	OH	Own/operate units; electricity, oil, char	Slow	3; planning for 50	\$250K, \$2 mil + gen set	Anything: Dairy waste, manure, crop waste, MSW	Initial contracts signed; raising more funding	
re:char	www.re-char.com	NY	Tech	Fast	4		Primarily wood waste	Not yet commercial,	Mobile units

Evaluation of the opportunities for generating carbon offsets from soil sequestration of biochar

							still testing
Renewable Oil International	www.renewableoil.com	AL	Tech	Fast			
Stine Seeds	www.stinseed.com	IA	Ag customer	Fast	50	Ag waste	Putting ABRI plant on farm
	www.toleroenergy.com/abou						Using ABRI tech. on own farm
Tolero Energy	ut/	CA	Oil/Char	Fast	goal: >50	Forestry waste, ag waste, MSW	First commercial unit in early 2010

Other Companies	Website	Location	Commercial Product	Process	Feedstock	Notes
Agri-THERM Ltd.	www.agri-therm.com	Canada	Tech: mobile pyro unit	Fast	Ag waste	Spin-off company of WORLDDiscoveries
All Power Labs	www.allpowerlabs.org	CA				
Biz-Solutions	pyrogreen.com	UT?	Char			
Carbon Char Group	www.carbonchar.com	NJ	Char			
Dynamotive	www.dynamotive.com	Canada	Tech/Oil/Char	Fast		
Ensyn	www.ensyn.com	Canada & DE (US)	Oil	Fast?		
Full Circle						
Golden Sheep Power Inc.	www.goldensheeppowerinc.com	Canada				
NTS Group / Burchell Consulting		CO				
VenEarth	venearth.com	CA				
Landmark	www.landmark.coop/index.html	WI	Ag			
Academic Researchers	Website	Location	Commercial Product	Process	Feedstock	Notes
Iowa State	-					Academic
NWNL	-					
Outside North America	Website	Location	Commercial Product	Process	Feedstock	Notes
3R Environmental Technologies	www.3ragrocarbon.com	Hungary				In stealth
AnthroTerra	-	Australia				
BEST Energies	www.bestenergies.com	Australia				
Carbon Gold	-	UK				Investor
Carbonscape	carbonscape.com	NZ	Char		Biomass	Ag co-op - sells fertilizer, etc.
Mongolia Biochar Initiative		HI	Tech: biochar cookstoves	Slow		
PYREG	www.pyreg.de	Germany				
World Stove	worldstove.com/products	MA & Italy	Tech: biochar cookstoves	Slow	Cattle dung, ag waste (shells, etc)	

10 Appendix B – Overview of Carbon Measurement Techniques

- **Walkley Black (or wet oxidation or chemical oxidation):** This technique is done with an acid dichromate solution with (Mebius modification) or without heat.
Advantages: The analytical investments required for Walkley Black are low.
Disadvantages: A correction factor, experimentally determined, is required, because the oxidation of organic carbon is not complete (only 75-85%) (Bisutti et al. 2004 and Schroth 2003). Schroth et al. (2003) suggest that Walkley Black can only be used for treatment comparison with the same soil and not across different soil types. They also note, as do Bisutti et al. (2004), that the procedure largely excludes elemental carbon, e.g. black carbon, and that application of the procedure ought to reflect that fact. Skjemstad et al. (1999) also show that Walkley Black does not capture biochar well; therefore, it cannot be used for biochar verification in soil. Furthermore, labor requirements are high.
- **Dry Oxidation (or dry combustion):** This technique is based on thermal oxidation of the OC and thermal decomposition of the IC minerals in a furnace. It directly measures released CO₂ by gas chromatography.
Advantages: The technique is the most accurate. All carbon forms in the soil are measured including biochar carbon. Nitrogen and other elements (optional S, H, O) can be measured as well. It can also be used as a reference for other methods. The technique is fast and has minimal variability.
Disadvantages: The technique requires the use of automated elemental Carbon Nitrogen analyzers. The machines are very expensive and individual samples cost \$10-\$20. The sample must be heterogeneous or great care must be taken to homogenize soil samples, because sample weight is very small. Calcareous soils must be treated with acid to remove carbonates (this may change soil weight). VOC contamination may be a problem.
- **Loss on Ignition (LOI or ashing):** The technique heats samples at 550°C or lower and uses conversion factors or regression equations (Bisutti et al. 2004).
Advantages: It is the least expensive of all methods.
Disadvantages: The temperature used can give erroneous (high) results for soils that have clay associated water (lower temperatures, 300-400°C are now used at Cornell University Soils Analytical Lab). One must know the soil type well to develop conversion factors, since LOI does not quantify carbon directly but only weight loss by oxidation of total organic matter. Thermal stability of both OC and carbonates can be problematic. It may not capture biochar.
- **TOC determination by elemental analysis:** Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC) are separated at different combustion temperatures. The lab technique uses a dynamic heating system (Bisutti et al. 2004).

Advantages: There is a high degree of accuracy and analysis is relatively fast. No VOC loss occurs and there is no use of toxic reagents. The analysis is easily automated.

Disadvantages: Easily decomposable carbonates may cause problems.

- **Near Infrared (NIR), Mid-infrared (MIR) or Diffuse Reflectance Mid-infrared Fourier Transform Spectroscopy (DRIFTS), and hyperspectral reflectance spectroscopy:** MIR and NIR are used for measuring SOC (handheld or in a lab) together with calibration to direct determination, mostly dry combustion analysis. MIR is more robust and accurate than NIR for organic carbon measurements because it captures regions in the IR spectrum that are more sensitive to organic carbon.

Advantages: Techniques do not require chemical treatment, are fast (after calibration has been established), and are less costly than many lab measurements. It has an excellent predictive accuracy for TOC and biochar (Janik et al. 2007).

Disadvantages: Statistical correlation needs updating. Handheld equipment, especially in the MIR range, is still relatively expensive.

- **Inelastic Neutron Scattering (INS).** Not yet commercially viable (Havemann 2009).
- **Laser-induced Breakdown Spectroscopy (LIBS).** LIBS uses short laser pulses to determine the elemental composition of sample.

Advantages: cheap, fast, direct measurement, accurate, essentially nondestructive.

Disadvantages: correction factor needed.

Changes in Black Carbon Content

- **UV-NMR:** The soil sample is oxidized in oxygenated water using UV light; residual C is then determined with elemental analysis. ¹³C-NMR (nuclear magnetic resonance) is used to correct for any lignin products that may have survived the oxidative treatment.

Advantages: Developed for assessing black carbon that includes charcoal in soils and therefore useful for biochar quantification. The method detects BC across most of the continuum of products.

Disadvantages: May overestimate biochar because 1) other aromatic C may interfere if no NMR is used for correction; and 2) BC might be produced during UV treatment.

Expensive, time consuming, involves specialized equipment and hazardous chemicals (Janik et al. 2007).

Summary: At this point in the development of the UV-NMR method, it is not applicable for routine biochar quantification.

- **NMR:** ¹³C-NMR is used quantitatively (verified by so-called spin counting) on total soil. Often, a treatment with hydrogen fluoride is needed before NMR analysis, especially if iron oxides are present in soil. NMR spectra then need to be compared with known spectra of model substances using a molecular mixing model (see Nelson and Baldock 2005).

Advantages: Determines biochar relatively accurately.

Disadvantages: Expensive, time consuming, and requires specialized equipment.

Summary: This method is not applicable for routine measurements of biochar in soil, but can be used as a calibration method for NIR and MIR.

- **Chemical-Thermal Oxidation (CTO-375):** The soil sample is oxidized at a high temperature of 375°C followed by elemental analysis.
Advantages: Identified most condensed forms of BC. The method is inexpensive and rapid.
Disadvantages: Does not detect low temperature biochar and may destroy low temperature biochars. In some cases, it may overestimate soil biochar contents by charring labile organic matter.
Summary: This method is not applicable as a measurement for biochar.
- **Thermal Analysis (TG/DSC):** After heating in controlled atmosphere, C components are assessed by gas analysis, weight loss, or scanning calorimetry.
Advantages: This method is able to capture black carbon in soil. It may also be combined with isotopic analyses of the biochar fraction. This affords the possibility to identify sources of biochar and unequivocally relate the recovered biochar to a certain application of biochar.
Disadvantages: In some cases, biochar cannot always be distinguished from other black carbon. The equipment is expensive.
Summary: Not for routine measurement, but has potential as a high-end verification tool.
- **Thermal/optical transmittance and reflectance (TOT/R):** Particulate samples are heated and the evolved CO₂ is measured, as is transmittance and reflectance. Designed for analysis of airborne particulates.
Advantages: May be useful to determine the impact of biochar applications on air quality.
Disadvantages: Did not distinguish between BC and non-BC organic components. Dark soils did not transmit optically.
Summary: Not applicable to biochar.
- **Biomarker Analysis:** BC is oxidized causing aromatic C to convert to benzene polycarboxylic acids and then measured (Glaser et al. 1998; Brodowski et al. 2005).
Advantages: Identifies aromatic carbon in solution. Provides information about the nature of the aromatic carbon, i.e. source and formation.
Disadvantages: Distinguishes all aromatic C, so does not identify biochar specifically. The method is time consuming and expensive, and requires expensive equipment (gas chromatography).
Summary: This method is not applicable for routine measurements of biochar in soil, but can be used as a calibration method for NIR and MIR.
- **Chemical Oxidation** (dichromate or sodium hypochlorite): OM is oxidized, BC remains, and C content is determined with elemental analysis.
Advantages: Least expensive and no specialized equipment is necessary.

Disadvantages: May overestimate biochar contents if other aromatic C sources are present. NaClO may destroy biochar and thus may underestimate biochar.

Summary: Not applicable to biochar.

- **Hydrogen Pyrolysis (HyPy):** A new technique in which pyrolysis with high pressure hydrogen separates labile and refractory carbonaceous components (Ascough et al. 2009).

Advantages: Potential high accuracy and specificity.

Disadvantages: Not yet tested on scale.

Summary: The method has potential but must be tested further.

Analysis of Black Carbon Based on Near or Mid-infrared Reflectance Spectroscopy

- **NIR and MIR (with PLS analysis):** MIR is used with partial least squares analysis (PLS). PLS correlation obtained from soil samples analyzed physically and chemically.

Advantages: Simple, rapid, low cost. Sensitive to specific organic and mineral soil components. Predictive accuracy for biochar is good (Janik et al. 2007, Bornemann et al. 2008)

Disadvantages: NIR is probably not sensitive for BC. Requires extensive calibration to a direct quantification technique (such as NMR, UV-NMR, HyPy, biomarkers).

Summary: Currently has the greatest potential for wide-spread application, but relies on calibration that needs to be performed for all different soil and ecosystem types.

11 Appendix C – Review of Carbon Gold Methodology Submitted to the Voluntary Carbon Standard

A methodology for developing carbon credits under was submitted under the VCS standard. The methodology contains a relatively sound GHG accounting framework, but falls short with respect to reducing risks or reversal and negative impacts. More specifically:

- The methodology limits the feedstocks used in the biochar production to those that are left to decay on an agricultural field or that will be burnt without any energy production. In practice, a substantial amount of feedstock will be used for biochar production with co-generation of energy. The assumption that the biomass is abandoned under the baseline scenario is flawed and probably overly simplistic. Many pyrolysis systems will co-generate energy in some form. By changing the pyrolysis conditions, the fraction of feedstock biomass used for energy vs. biochar can be altered. Any carbon protocol must incorporate the trade-off between biochar production and energy use.
- The project duration is surprisingly short (10 yrs). Given the decomposition dynamics of biochar, a project duration of at least 50 years is required.
- The eligibility criteria are insufficient to limit the risk of reversal and negative impacts of biochar incorporation.
- The methodology assumes that the volatile-carbon/fixed-carbon ratio is sufficient to determine the fraction of resistant matter in biochar. While the methodology of measuring the volatile-carbon/fixed-carbon has proven its merit for coal measurements, it has yet to be demonstrated and generally accepted