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Biochar: Assessing the Promise and Risks To Guide U.S. Policy

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Executive Summary

Biochar, a charcoal-like substance made from biomass and used as a soil amendment, has been credited with multiple benefits, including the ability to improve soil fertility, protect water quality, and generate carbon neutral energy. But it is biochar's potential to capture and store carbon in soils, and thus its potential role as a climate mitigation tool, which has attracted the most attention in the last three years; indeed, for a time, biochar seemed to enjoy status as a miracle cure to the global climate challenge. However, there remains a great deal of uncertainty with respect to the environmental and economic performance of different biochar production pathways, as well as key environmental risks associated with the production and use of biochar that must be addressed. As a result, estimates of the potential for biochar production and carbon sequestration remain highly uncertain and largely premature at this time.

The performance of biochar production and utilization systems depends on the feedstock used, the conversion process employed, and the manner in which the biochar is handled, transported, and applied. Though there are many possible combinations of feedstocks, conversion technologies, and application systems, much of what has been reported in the literature is hypothetical. At present, there are no commercially operating biochar production systems on which to base an assessment.

On the basis of what is known, it seems likely that waste biomass is preferable to primary biomass as a biochar feedstock, as it does not incur the energetic cost and associated land use change emissions from producing primary biomass. Within the category of waste biomass, animal manures, organic municipal solid waste and urban wood residue appear to be the most promising feedstocks, because they are most concentrated, minimizing the energy and emissions costs of collection. However, an assessment of the impacts of any biochar production and utilization system—particularly its net carbon benefits—must take into account the energy required to produce, collect, transport and process the feedstock, as well as the potential for soil carbon loss during the production, harvest and application of the biochar. In addition, the risk of fugitive black carbon emissions during biochar transport must be addressed.

Among production methods, slow pyrolysis appears to be the optimal process for maximizing biochar output.

Large production systems, uniform feedstocks, and tightly controlled application regimes are apt to be more reliable from a monitoring and verification standpoint. Though there has been a great deal of interest in small biochar production systems, stemming from long-standing efforts to introduce more efficient cookstoves in the developing world, smaller, dispersed systems will be much more difficult to characterize and monitor, and monitoring and verification challenges will be difficult to overcome. As a result, small systems should likely not be thought of as frontline tools to combat climate change.

In this report, we describe biochar production pathways, energy co-products resulting from biochar production and their potential uses, assess the key environmental risks associated with biochar production and utilization systems, discuss estimates of global technical and economic potential for biochar production and carbon sequestration, and give a brief overview of existing domestic and international policies on biochar.

We conclude with recommendations for a research agenda to support biochar policy development in the U.S. We find that a critical shortage of pilot and commercial scale biochar production and utilization systems, especially slow pyrolysis, and thus a critical shortage of biochar for field testing, are a major barrier to addressing the uncertainties and risks associated with biochar today. To acquire the data needed to develop a U.S. biochar policy, we believe that several commercial-sized demonstration projects are needed. To develop these projects and analyze results would require about eight years and cost between $100 million and $150 million.

Overview

This study aims to assist the Natural Resources Defense Council in gaining an overview of biochar production technologies, and, in particular, of the potential environmental concerns associated with biochar production and use. This is not an in-depth study of any aspect of this complex subject, but a general overview of it. We would like to call attention to two resources for those who wish to go deeper into this subject. *Biochar for Environmental Management: Science and Technology* (Earthscan, 2009) is a comprehensive treatise on all aspects of biochar production and utilization and is essential to anyone wishing to become familiar with this area. The International Biochar Initiative's website offers a number of briefing papers as well as a listing of recent biochar-related publications (http://www.biochar-international.org/).

Producing and using biochar as a climate mitigation strategy has generated considerable interest in the past three years. Although this has, in part, stemmed from the broad attention that biofuels generally have enjoyed, biochar has been especially singled out as a potential means of sequestering large amounts of carbon in soils. For example, a recent analysis published in *Nature Communications* argues that the global potential for biochar systems could yield nearly two gigatons of carbon reduction, or about 12 percent of global greenhouse gas emissions (Woolf et al., 2010). This article is based on the assumption that high percentages of "sustainably produced" biomass are devoted to biochar production (to the exclusion of other technologies) and does not consider economic, social or cultural barriers in producing its estimate. As such, it must be considered an upper bound of the *technical* potential for such systems; the *achievable* potential is apt to be significantly lower. Furthermore, single-minded focus on biochar's climate impact risks diverting attention from its other attractive agronomic attributes—the ability to protect water quality through improved nutrient management, to make use of multiple biomass waste streams, and to yield a variety of renewable energy resources.

The multiple benefits that flow from well-designed biochar systems are compelling and when considered together, make a more robust case for pushing biochar systems forward. Taking into consideration all of biochar's attributes is especially critical in view of the uncertainty that now surrounds the development of global carbon markets and the concerns that have been raised about terrestrial carbon sequestration in general. A case for further developing biochar systems that goes beyond its potential climate mitigation role, coupled with an aggressive research and demonstration strategy, is probably the best way to mitigate these uncertainties.

Environmental concerns about biochar production and utilization systems (BPUS) fall into two broad categories: (1) those associated with the sustainable supply of biomass feedstocks and the impacts of their production, harvest, transport, and transformation—concerns that cut broadly across various bioenergy technologies, and (2) concerns that are unique to BPUS. The latter include the technical uncertainty about the characteristics of various proposed BPUS, inconclusive data on the agronomic performance of biochar in soils, insufficient data on the recalcitrance of biochar-based carbon in soils, and significant challenges attending the monitoring and verification regime required for terrestrial offsets generated through application of biochar.

Potential environmental concerns identified in this analysis include:

Biomass Feedstocks

- **Land use conversion related carbon emissions.** These conversions fall into two categories: direct and indirect. Direct impacts include land that is converted from forest, pasture, or conservation reserves to the production of energy crops. Indirect effects are the chain reactions that result when changing land uses in one nation affect international agricultural markets which, in turn, drive land conversions elsewhere. Indirect effects are much harder to quantify and much more controversial. Recent studies suggest that the carbon released from land conversions significantly offsets the carbon reduction claimed for the biofuel pathway.

- **Loss of biodiversity through cultivation of energy crops.** Conversion of significant acreage to production of energy crops would increase monoculture and, potentially, reduce local and regional biodiversity.

Based on these concerns, waste biomass feedstocks are likely preferable from an environmental standpoint for BPUS.

BPU Specific Concerns

- **Critical shortage of pilot and commercial-scale BPUS, especially slow pyrolysis.** Most of the claims about the performance and economics of BPUS are based on lab-scale or bench-scale demonstrations. Slow pyrolysis—the preferred technology for producing biochar—is especially poorly represented. Before BPUS can be confidently embraced as strategies for climate mitigation, we must have a significant increase in the number of actual systems in operation.
- **Critical shortage of biochar for field testing.** This grows out of the previous concern: lack of BPUS has created a serious shortage of biochars for actual field trials. Before we can accept BPUS as climate mitigation strategies, we must test a wide variety of chars on a wide range of soils. Biochar performance appears to vary a great deal, depending on feedstock composition, production conditions, and soil type. At present, we lack a classification scheme for biochars; dramatically increased field analysis is essential for developing such a scheme.
- **Inadequate characterization of production-related emissions.** Emissions associated with the operation of BPUS are not adequately understood. This is especially troublesome for small systems, for which environmental regulations are apt to be less stringent or absent. Given that some of these emissions may themselves be greenhouse gases, it is critical to gain a better understanding of BPU-related emissions and the extent to which such emissions would offset biochar's carbon sequestration benefits.
- **Fugitive loss of biochar during transport and application.** Biochar contains up to 80 percent carbon and is typically extremely friable. There is some evidence that biochar can be lost during transport and application. It is important to know more about the composition of fugitive biochar, especially the fraction that is in the submicron range. If very fine black carbon becomes airborne, it can act as a climate forcer and would need to be counted against carbon reductions attributed to biochar use. Research, development, and demonstration (RD&D) of delivery systems that reduce or eliminate fugitive loss are critically needed.
- **Carbon loss from soil disturbance during biochar application.** If tillage is used to incorporate biochar into soils, and if such soils have previously been subject to conservation tillage or no-till, carbon emissions from soil disturbance would reduce the biochar carbon sequestration benefit. RD&D are needed on incorporation methods that reduce soil carbon loss.
- **Monitoring and verification of terrestrial offsets from biochar application.** Trustworthy monitoring and verification (M&V) is a serious concern for all terrestrial offsets. Biochar could potentially be produced on a wide scale (from very small to industrial-scale systems), from a diverse variety of feedstocks, and applied to a vast range of soil types in diverse climates. Each of these variables presents M&V challenges. Large production systems, uniform feedstocks, and tightly controlled application regimes are apt to be more reliable from an M&V standpoint. Smaller, dispersed systems will be much more difficult to characterize and monitor, and it is unclear whether the statistical approaches used successfully for M&V of energy efficiency programs can be successfully adapted for widely-dispersed, small BPUS. This is because each element of the system (feedstock, production technology, soil type, and application method) will vary depending on geography and over time. When calculating benefits from energy efficiency, the utility system against which emission reductions are claimed is usually larger in scale, and reasonably predictable. Soil types can vary a great deal over small distances and biomass feedstocks could potentially change regularly; both factors would introduce additional uncertainty into M&V.

A coordinated and well-funded program is needed to develop, deploy, and study a range of commercial-scale BPUS, to produce adequate biochar for a comprehensive, nationwide field trial program, and to analyze and disseminate the results of these trials. This research program would run about eight years and would cost between $100 million and $150 million.

CHAPTER 1

Introduction to Biochar

Biochar is a recently coined term for charcoal that is used as a soil amendment. Research on ancient, anthropogenically altered soils in the Amazon—so-called *terra preta* soils—provides much of the original scientific evidence on the role that charcoal plays in soil ecology. In the Amazon, aboriginal inhabitants added charcoal to soils, improving fertility relative to adjacent soils. These findings have been supplemented by research on the agronomic impact of various charcoals on soils and crops.

Although the findings are not entirely consistent, there is evidence that charcoal can improve soil structure and favorably alter soil chemistry and ecology. Research on terra preta soils also provides the basis for claims that charcoal can create recalcitrant pools of carbon and potentially play a role in mitigating climate change. Evidence from the Amazon suggests that the terra preta soils contain elevated levels of carbon that have been stable for thousands of years. These findings have stimulated interest in producing charcoal from various biomass resources as a soil amendment. Technical efforts range from very small production systems (500 grams of biochar per day) to commercial-scale ventures (25 tons – 100 tons of biochar per day). Most proposed large-scale production systems would coproduce bio-oil and synthesis gas along with a solid char product. The prevailing biochar value proposition is based on capturing the following suite of benefits: (1) soil improvement, (2) carbon sequestration, (3) carbon-neutral energy production, (4) waste management, and (5) water quality protection through more efficient nutrient utilization. Development of biochar systems has been hampered by the persisting lack of market value for most of these attributes: only for the energy outputs can a price be reasonably ascertained, but this is usually insufficient to support a project.

Biochar's potential as a climate mitigation tool has attracted the most attention; indeed, for a time, biochar seemed to enjoy status as a miracle cure to the global climate dilemma. Biochar has been promoted by an array of prominent scientists and activists, including James Lovelock, James Hansen, Tim Flannery, and Al Gore. Sir Richard Branson, founder of Virgin Group, is also an enthusiastic biochar supporter, both through his philanthropic efforts and through an innovation prize targeted at biochar production systems. Biochar also has its detractors. Biofuelwatch has raised concerns about "scorched earth" climate solutions, concerns that have been echoed by George Monbiot, climate columnist for the *Guardian*. Biofuelwatch submitted a petition to the United Nations Framework Convention on Climate Change (UNFCCC), signed by more than 100 NGOs from around the globe, urging that the UN body not rush to endorse biochar as a climate mitigation tool. The truth as to whether biochar is a cure-all or a scourge is apt to lie between the extremes, but we cannot say exactly where at present.

Although the potential, multifold benefits of biochar production and utilization systems are tantalizing, we are not in a position either to endorse or veto its development without additional laboratory research, field trials, and technology development and deployment.

This scoping analysis provides the following:

- Descriptions of biochar production pathways
- Descriptions of energy coproducts and potential utilization options
- Assessments of the environmental risks associated with biochar production and utilization
- A discussion of global potential estimates for biochar production and carbon sequestration
- A description of domestic and international policies aimed at promoting biochar production and utilization
- A discussion of critical information gaps and recommendations for a U.S. research agenda

Biochar Production Pathways

Biochar production and utilization systems (BPUS) entail three components: (1) feedstock acquisition and preparation, (2) feedstock conversion, and (3) biochar handling, transport, and application.

There are many possible combinations of feedstocks, conversion technologies, and application systems; much of what we find reported in the literature—especially that aimed at promoting a particular system—is hypothetical. At present, there are no commercially operating biochar production systems on which to base an assessment. There are numerous laboratory-based technologies for producing small amounts of biochar for experimental purposes. These systems are not generally useful for evaluating scaled-up production facilities because cost and environmental performance are usually inconsequential in the laboratory. These systems have been used to produce chars from many different feedstocks and have yielded important insights into how temperature, pressure, heating rate, and treatment time affect the decomposition of biomass into char, bio-oil and synthesis gas—commonly referred to as syngas. In addition, they have provided char used in small-scale pot studies and so have contributed information on the agronomic properties of certain chars. There are a few larger, pilot-sized facilities that produce greater amounts of char and that are more useful for understanding potential economic and environmental issues associated with conversion. However, these systems generally do not provide insight into feedstock acquisition and preparation or biochar handling, transport, or application—critical aspects of a system from both an economic and an environmental standpoint. Pilot-scale projects have produced most of the biochar used in actual field trials.

Biochar characteristics are variable, depending on the feedstock and the processing methods used. In addition, a biochar's agronomic impact will depend on the soil type and the crop grown. In other words, each feedstock-conversion-application combination presents a unique situation. Work has begun on a biochar classification scheme that may ultimately yield a useful predictive system, but at the present time, chemical analysis of individual chars combined with field trials are the only tools available for evaluating biochar impacts.

This assessment considers feedstocks, conversion systems, and application techniques separately. As more biochar projects yield results, the data from the separate components can be used to evaluate BPUS proposals. For the time being, however, this partitioned assessment is useful for identifying critical environmental concerns and for shaping a policy stance by providing guidance on the following questions:

- Which feedstocks are most promising from an environmental, economic, and energy generation standpoint?
- Which conversion schemes are likely to be optimal from an economic and environmental standpoint?
- How can biochar be applied to maximize soil benefits and create stable pools of soil carbon?

Biochar Feedstocks

Feedstocks can be grouped into two categories: primarily produced biomass—biomass grown for the purpose of converting it into bioenergy or biochar—and waste biomass. In the first category are perennial grasses (switchgrass, *Miscanthus*, and mixed prairie species), various tree species, and algae. The second category is much more extensive and includes forestry waste, crop residues, animal manure, food processing wastes, offal, sewage sludge, and segregated municipal solid waste. There is not universal agreement on what constitutes waste: for example, corn stover is now mainly left on fields, reducing erosion and improving soil quality. Removing it for bioenergy or biochar would have environmental costs that must be tallied in a comprehensive cost-benefit analysis.

The energetic cost and associated emissions from producing primary biomass for energy are important considerations. Significant energy is used to establish, cultivate, and harvest perennial grasses. Much of the land that is envisioned as available for growing energy crops is currently in various conservation reserve programs or pasture. This land would need to be plowed or disced to allow sowing of perennial grasses. This disturbance would result in the loss of stored soil carbon. How much is lost will depend on where the crops are established and what the prevailing land use was before conversion.

There is a crucial distinction between waste feedstocks that are geographically concentrated and those that would require a collection scheme. Gathering dispersed waste biomass is expensive and creates transport-related emissions that reduce the overall carbon benefit of the biochar project. Wastes that have already been concentrated—for example, paper mill sludge, animal manures from concentrated animal feeding operations (CAFOs), and municipal solid waste—will have an economic and energetic advantage over dispersed resources. Some concentrated wastes are already used, and widespread scaling up of biochar systems may require tapping more expensive feedstocks.

Wastes for which producers now bear a disposal cost will also have an economic advantage as potential feedstocks. If, for example, a CAFO bears significant costs for manure handling and disposal, redirecting the manure to biochar production could be advantageous to the farmer and the project developer alike. Unfortunately, in most places, disposal of biomass waste is unpriced or underpriced.

Redirection of residual biomass from land spreading or landfills to biochar production could reduce decomposition-related methane emissions. For example, food-processing waste that is land spread or improperly composted will emit methane; that could be prevented if the waste is used for biochar production. Accounting for such offsets is complex and methodologies will vary according to the circumstances.

Table 1 presents a first-order assessment of the energetic and environmental issues associated with various biomass feedstocks.

Table 1: Energetic and Environmental Issues with Biomass Feedstocks

	Land-Use Conversion Involved	Cultivation and Harvest Required	Already Concentrated	Drying Needed	Preparation Required	Other
Primary Biomass						
Perennial grasses	Y	Y	N	Y	Y	Biodiversity loss to monoculture
Tree crops	Y	Y	N	Y	Y	Biodiversity loss to monoculture
Algae	N	Y	Y	Y	N	Water use
Residual Biomass						
Logging residue	N	Y	N	Y	Y	Habitat reduction; avoided methane
Fuel treatment thinning—removals for fire prevention	N	Y	Y	Y	Y	Habitat reduction; avoided methane
Forest products processing	N	N	Y	Y	Y	
Urban wood residue	N	N	Y	Y	Y	Avoided methane
Crop residue	N	Y	N	Y	Y	Increased soil erosion; decrease tilth
Animal manure	N	N	Y	Y	N	Avoided methane; avoided nutrients
Municipal solid waste	N	N	Y	N	Y	Avoided methane
Food processing waste	N	N	Y	Y	N	Avoided methane
Sewage sludge	N	N	Y	N	Y	Avoided methane

Table 2 presents a listing of different feedstocks used to produce biochars from a review of recent literature.

Table 2: Feedstocks Used to Produce Biochar Experimentally

Feedstock	Source
Poultry DAF Skimmings	Smith, Peres, and Das (2009)
Plastics, tires, forestry residue	Paradela et al. (2009)
Wheat straw	Mahinpey et al. (2009)
Corncobs and stover	Mullen et al. (2010)
Segregated MSW	Phan et al. (2008)
Dairy manure	Cao et al. (2009)
Sewage sludge	Hossain et al. (2010)
Microalgae	Heilmann et al. (2010)
Paper mill sludge	Van Zwieten et al. (2010)
Rice husks	Heo et al. (2010)
Phragmites	Sutcu (2008)
Poultry litter	Kim, Agblevor, and Lim (2009)
Swine manure	Godbout et al. (2009)
Cryptomeria thinnings	Lin and Hwang (2009)
Cornstalk, cotton straw, rice straw	Fu et al. (2010)
Pine sawdust, peanut shell, corn	Wang et al. (2008)
Wood board waste	Girods et al. (2009)
Pine needles and cones, oak leaves, orange peels, citric acid, sugar beet chips	Titirici et al. (2007)
Pine waste and wood, peanut shell	Das et al. (2010)
Poultry litter, peanut shell, pine chips	Gaskin et al. (2008)
Wood waste	Husk and Major (2010)
Wood chips	Spokas et al. (2009)
Wood residue	Asai et al. (2009)
Glucose, yeast	Steinbeiss et al. (2009)
Pecan shell	Novak et al. (2010)

Discussion: The Case for Waste Biomass

There is a growing body of research on the greenhouse gas emissions arising from land use change (LUC). At the moment, it is unclear whether establishing bioenergy crops on new fields yields results in net greenhouse gas reductions. Furthermore, these crops require energy for establishment, cultivation, and harvesting. Although there is support for the argument that the energy required will be less than that required for conventional row-crop agriculture, the energy that is used still reduces the net carbon benefits from these systems. One recent life cycle assessment confirmed that switchgrass-based biochar systems can be greenhouse-gas positive, depending on how LUC is accounted for (Roberts et al., 2010). Energy crops are also expensive to produce. A five-year study of switchgrass cultivation found that average production costs were $66 per metric ton of dry biomass (Perrin et al., 2008). It would take about three tons of dry switchgrass to produce one ton of biochar. The feedstock cost per ton of biochar produced would therefore be $198, which is likely to be substantially higher than for waste biomass. This figure is also well in excess of both current and projected carbon prices.

The energetic and economic costs of gathering residual biomass reduce the feasibility of using these sources for energy production. Within the broad categories of residual biomass, forestry and crop residues are now mainly left *in situ*, and harvesting would require incremental energy and cost. The remaining categories of residual biomass are already concentrated to some extent and may offer the best feedstock candidates for biochar production systems.

Many residual biomass sources represent disposal costs to producers and threats to the environment. Animal manures—dairy, swine, and poultry—threaten water quality and create localized air pollution problems. Sewage sludge is produced at every wastewater treatment facility in the country, and safe disposal is often a challenge for the utility. There is some evidence that converting sewage sludge to biochar can reduce the threat of toxic leachate. Organic municipal solid waste and urban wood residue are often put in landfills or composted, yielding methane emissions. These residuals appear to offer the best candidates for biochar production, at least in the near term.

Biochar Conversion Systems

For this scoping analysis, systems have been grouped into three categories:

- Small, mobile systems for char production
- Larger-scale pyrolysis and gasification units
- Hydrothermal carbonization

Charcoal is formed by thermal decomposition of biomass in low oxygen environments. Traditional charcoal manufacture occurs in pits or kilns, where biomass is ignited and allowed to carbonize. Traditional methods are less efficient than larger, modern systems; emission levels from traditional systems can be significant. For example, total suspended particulates (TSP) from an uncontrolled batch kiln can range from 197 grams to 598 grams per kilogram, meaning that between 20 percent and 60 percent of the biomass entering the kiln leaves as TSP. Controlled, continuous kilns still have TSP emissions ranging between 9 and 30 grams per kilogram (Moskowitz, 1978). Black carbon (BC) is a powerful climate forcer, and to the extent that BC is associated with TSP from biochar production and use, it will reduce any climate benefits from biochar projects.

Temperature, pressure, and emissions can be more readily controlled in modern pyrolysis and gasification systems. The extent to which pollution control equipment will be required for these systems is an open question. For the United States, it is fair to say that larger, stationary systems are likely to require more stringent controls than smaller, portable systems.

Small Systems

Interest in smaller biochar production systems arises from two quarters.

The first is an outgrowth of the decades-long effort to develop and introduce more efficient biomass cookstoves in the developing world. Pyrolyzing stoves have been added to the complement of technologies competing in this complex and extensive niche. Soil remediation and carbon sequestration through biochar production are among the attributes claimed for pyrolyzing stoves. But, there is good reason to be cautious about these claims, especially with respect to the carbon benefits. Total biochar production from any single stove is roughly one pound per day—less than half a ton per year (Iliffe, 2009). Though a million successfully distributed and used stoves would yield a significant amount of biochar—approximately 185,000 tons per year—the complexities of aggregation and application and the variability of soils over which this biochar would be distributed would require heroic monitoring and verification (M&V) efforts. It is not clear that the statistical approaches used to estimate carbon savings from dispersed technologies like compact fluorescent lights could be reliably developed for stoves. Seeking viable alternatives to inefficient biomass combustion has clear merit—the potential human health and ecosystem benefits are well documented and considerable. However, we should probably not think of these stoves—and their associated biochar—as frontline tools to combat climate change.

The second impetus comes from the recognition that dispersed waste biomass might be better accessed by portable systems.

In the United States, for example, there is interest in using small systems to pyrolyze invasive forest species (*Tamarix*, for example) or deadfall from Pine Bark Beetle infestation. Recent proposed legislation would create incentives for such systems. (*Water Efficiency via Carbon Harvesting and Restoration (WECHAR) Act of 2009*, S 1717/HR 3748, 111th Cong., 1st sess.) BioChar Engineering of Colorado has developed and is offering for sale a portable pyrolysis unit. This unit would pyrolyze 500 pounds of dry, woody biomass per hour, yielding 125 pounds of biochar, or about half a ton per day. The system requires 220-volt grid power or a portable generator to run auxiliaries, as well as supplemental fuel for start-up. In addition, equipment for feedstock preparation and drying would be required. From a technical description and photograph on the company website, it is not clear that incremental pollution control equipment is included (Biochar Engineering, 2010). The unit is supposed to cost about $50,000. If we assume that the unit is operated by one person paid minimum wage ($16,300 per year) and that annual capital charges are 10 percent ($5,000), and, ignoring other operating costs, the production cost for biochar from this unit would be approximately $170 per ton. Although larger in scale than the village stove, biochar produced by dispersed units of this size would still require significant M&V to ensure the quality of any carbon offsets claimed.

Pro-Natura International of France has developed a larger system (with a production capacity of four to five tons of biochar per day) for use in the developing world. A principal interest is soil remediation, but Pro-Natura has begun documenting the potential carbon offsets from a system in Senegal (Pro-Natura International, 2010).

Carbon accounting methods for these smaller systems are still complicated and imprecise (although probably less so than for household cookstoves), and the carbon reductions arising from such systems are apt to be discounted in any carbon offset crediting system.

Larger Systems: Pyrolysis and Gasification

Larger pyrolysis and gasification systems are projected to process between 50 and 200 tons of dry biomass per day, or about 10,000 tons—100,000 tons per year. Depending on the process, this would yield between 3,500 tons and 35,000 tons per year of biochar.

Pyrolysis is thermal decomposition in the absence of oxygen; gasification is thermal decomposition in a limited oxygen environment. Pyrolysis is further divided into slow, moderate, and fast technologies, classified according to the residence time of vapor in the reactor. The balance between the amounts of char, bio-oil and synthesis gas produced varies, depending on the technology used. Most of the synthesis gas is used to sustain the reaction in pyrolysis units, so marketable outputs would include only bio-oil and biochar. Supplemental energy is required for biomass drying, preparation, and feeding and initiating the pyrolysis reaction. In addition to the basic pyrolysis or gasification units, projects at this scale require equipment for feedstock processing and handling, emissions control, and product handling. This balance of plant equipment represents significant capital cost, usually as large as the pyrolysis or gasification unit itself. Table 3 provides a basic breakdown of these technologies. From the data presented in Table 3, it is clear that

Table 3: Typical Pyrolysis and Gasification System Characteristics

Technology	Temperature	Residence Time	Char (%)	Liquid (%)	Gas (%)
Fast pyrolysis	~500º C	~1 sec	12	75	13
Medium pyrolysis	~500º C	~10–20 sec	20	50	30
Slow pyrolysis	~500º C	~5–30 minutes	35	30	35
Gasification	>750º C	~10–20 sec	10	5	85

(Adapted from Bridgewater, 2007)

different systems will be chosen on the basis of desired output: fast pyrolysis favors production of bio-oil, slow pyrolysis favors production of biochar, and gasification is best for producing synthesis gas.

Large-scale fast pyrolysis and gasification systems are available and have been used mainly for producing bio-oil and synthesis gas.

Dynamotive Energy Systems of Canada uses a fast pyrolysis system to produce bio-oil from wood waste. Dynamotive operates two plants, one processing 130 tons of wood waste per day in West Lorne, Ontario and a second processing 200 tons of wood waste per day in Guelph, Ontario. Dynamotive's commercial efforts began in 2003; the company has yet to turn a profit. In the past 24 months, Dynamotive has experienced technical issues at both plants, and no bio-oil has been produced (Dynamotive Energy Systems, 2010). In 2008 and 2009, Dynamotive field tested char produced from its facilities on soybean and mixed forage crops; a report on these field trials was released in February 2010. One finding of the field trials was a reported wind loss of 30 percent of the biochar during handling and transport (Husk and Major, 2010). These windblown losses are a potential environmental concern. Biochar is mostly black carbon (65 percent in this case), a potent climate forcer. The amount of this fugitive biochar that falls into the climate relevant submicron range is unknown; this is an important area for future study.

Frye Poultry Farm of West Virginia installed a Westside Energies gasifier in 2007. The project cost $1 million and was paid for with grants from the Natural Resources Conservation Service and private philanthropy. The gasifier processes chicken litter to produce synthesis gas and biochar. The synthesis gas replaces propane, used to heat the chicken houses in winter. The unit yields about 20 percent char, which contains between 10 percent and 30 percent carbon. This is lower than in chars produced through pyrolysis processes, which contain between 60 percent and 80 percent carbon. Frye Poultry has marketed its char as a soil amendment, but systematic field trials have not been conducted. The synthesis gas could potentially be sold to other users, but it could not be sold into the broader natural gas market without considerable additional processing.

Slow pyrolysis units have not been developed at commercial scale. BEST Energies Australia has perhaps progressed furthest with its slow pyrolysis unit, but the company is still operating at pilot scale. BEST has plans to build a commercial unit that would process four tons of dry biomass per hour, and cost between $10 million and $15 million.

Hydrothermal Carbonization (HTC)

HTC is a chemical process that may be well-suited to high-moisture feedstocks, such as animal manures and algae. Recent laboratory studies indicate that chars can be produced using HTC at low temperature (~200º C) and fairly short processing times (Titirici, Thomas, and Antonetti, 2007). Energy required for feedstock drying can be significant for pyrolysis or gasification, increasing cost and emissions from those systems, so HTC would have an advantage in this respect. HTC has not progressed to pilot-scale demonstration and HTC-produced chars have not been widely tested for their agronomic effects.

Table 4: Issues Associated with Various Biochar Production Technologies

Technology	Primary Output	Biochar (%)	M&V	Other issues
Pyrolytic stoves	Heat	20	Very hard	TSP emissions
Portable pyrolyzers	Biochar	20–35	Very hard	TSP emissions Transport emissions
Fast pyrolysis	Bio-oil	12	Hard	TSP emissions
Slow pyrolysis	Biochar	35	Hard	TSP emissions
Gasification	Synthesis gas	10–20	Hard	TSP emissions
HTC	Biochar	37–60	Hard	

Discussion: The Challenges of Monitoring and Verification

From a carbon offset standpoint, very small systems present substantial monitoring and verification (M&V) challenges. Although there are many good reasons to support development of such systems, the carbon offsets that might ultimately be derived from them would likely be highly discounted and may not be a strong economic driver. Larger portable systems likewise present M&V challenges, but these may be less difficult to overcome. It remains to be seen whether the economics of such systems can bear the costs of extensive M&V. Offsets for biochar produced by larger systems will still need to pass rigorous M&V protocols, but these are likely to be comparable in complexity to protocols already developed for other offset projects.

There is a critical lack of technical demonstration of commercial-scale biochar systems, especially ones using slow pyrolysis. Comprehensive systems—including feedstock preparation and handling, pollution control, and product management—are essential for understanding full project dynamics and economics.

Given the uniqueness of individual biochars (see discussion above), it will be impossible to develop confidence in the agronomic and climate benefits without moving production beyond the laboratory scale. This is especially crucial if the carbon sequestration benefits of biochar utilization are to be demonstrated and ultimately claimed. At present, the demand for biochar for full-scale field trials greatly outstrips supply. Almost no biochar is available, slowing the implementation of field trials and the documentation of biochar's potential effects. The limited biochar available from sources such as Dynamotive or Frye Poultry is insufficient.

HTC seems to have promise as a means of dealing with high moisture feedstocks, but additional research is needed to move this technology beyond the laboratory.

CHAPTER 2

Potential Benefits and Environmental Risks

Biochar must be moved from its production site and incorporated into soils. Biochar is usually extremely friable and thus subject to loss and dispersion by wind. Because of its high carbon content (65 percent – 80 percent), fugitive biochar is a black carbon emission, a potent climate forcer. At least one study has reported significant losses of biochar during transport and application (Husk and Major, 2010). Airborne biochar also presents a health risk to humans, so exposure must be avoided during production and application. Because there is no experience with commercial biochar production and application, formal protocols for handling and transport have not evolved.

Handling, Transport, and Application

To the extent that biochar has been applied in field trials, it has been spread on topsoil and then mixed through plowing or discing. Soil disturbance can result in loss of soil carbon. If land that has been managed by conservation tillage is disced or plowed to incorporate biochar, the loss of soil carbon could be significant. These losses have been insufficiently documented, but it is clearly a matter for further study.

The agronomic effects of biochar application have been mixed. In some trials, dramatic yield improvements have been observed; in other trials, yields have not changed; in still others, biochar has exhibited phytotoxic effects. In short, we need far more in-field testing of different chars to fully understand the potential agronomic costs and benefits. John Gaunt, a prominent biochar researcher, has suggested that "low-risk disposal routes for disposal (e.g. landfill, old coal mines)" should be used until the soil science is understood better (Sohi et al., 2009). This is an extreme view, but it underscores present data gaps and the urgent need for more field trials.

There appears to be strong evidence supporting the claim that biochar can reduce soil emissions of nitrous oxides and methane, both potent greenhouse gases (Lehmann and Joseph, 2009). The mechanisms behind this impact are not entirely clear, but the research is fairly consistent.

Biochar appears to improve a soil's ability to retain and use artificial fertilizers, reducing the amount lost to leaching. If fully documented, this capability could be tied to water quality improvement as less phosphorous and nitrate are lost from agricultural lands into waters.

Finally, the recalcitrance of biochar-based carbon in soils is not fully understood. Evidence from the Amazon suggests that very long lifetimes are possible, but it is difficult to generalize broadly from these findings. Field trials have been limited, and more research is needed to validate long-term carbon sequestration claims.

Energy Co-Products For Multiple Uses

Biochar systems produce bio-oil, synthesis gas, and charcoal, each of which has value as an energy source.

Historically, creating an energy source has been the main purpose for producing charcoal; most charcoal produced today is still used for energy. Biochar is designated—by definition—for nonfuel uses; yet biochar will continue to have high Btu value and be usable as a fuel. This is especially important in the context of biochar production in fuel-scarce regions of the developing world.

The quality of bio-oils produced through pyrolysis varies widely, depending on the feedstock and pyrolysis conditions. Generally, bio-oils can be used directly as generator fuel in diesel gensets.[1] Bio-oils can also be used to produce a variety of chemical feedstocks. But, they cannot be used for transportation purposes without upgrading. At the present time, a great deal of research, most of it publicly funded, is focused on using bio-oils to replace petroleum for transportation

HOW SIGNIFICANT A ROLE CAN BIOCHAR SYSTEMS PLAY IN ADDRESSING THE GLOBAL CLIMATE CHALLENGE?

The answer depends on how several key questions are answered:

- **What portion of the sustainably produced biomass resource is assumed to be devoted to biochar systems?**

  There are many promising biomass conversion technologies, each of which will compete for the same biomass resource. Studies of the potential contribution of these technologies often assume absence of competition for the primary feedstocks. For example, analyses of the potential for producing transportation fuel from cellulose often assume that all crop residues and dedicated energy crops will be converted to ethanol. Analyses of the potential for producing electricity and natural gas through anaerobic digestion assume that all manures and food processing wastes will be captured. Biomass-to-electricity schemes assume that all dedicated energy crops and forestry wastes will be burned for power. In reality, none of these technologies is likely to corner the market for any given feedstock.

- **What are the comparative economics of the competing products that can be produced from biomass (i.e., transportation fuels, bio-based chemicals, electricity)?**

  Assumptions about the price of various outputs from biomass conversion systems will drive assessments of economic potential. If low-carbon substitutes for petroleum are highly valued, cellulosic ethanol and biodiesel will be favored. If low-carbon electricity is in demand, biomass to electricity technologies will be favored.

- **What is the market price for carbon?**

  Currently, most biomass conversion technologies cannot compete economically against prevailing fossil alternatives. One principal reason for this is the absence of a carbon price signal. The various biomass conversion technologies will require different levels of carbon price to be cost-competitive.

- **How stable is the market for carbon?**

  Carbon price stability is as critical to the economic viability of biomass conversion technologies as the existence of a carbon price. If carbon prices vacillate dramatically, as has been the case in the European Union Emission Trading System, it will be difficult to convince investors to support a project whose revenues depend, in part, on the sale of carbon credits.

- **How high are the hurdles for claiming carbon credits?**

  All emission trading schemes depend upon systems to ensure that any offset credits issued represent emissions reductions that are real, additional, verifiable and permanent. In the discussion above, we highlight concerns with very small biochar production systems. Monitoring and verification (M&V) requirements will reduce the technical potential of offset credits generated based on biochar projects by excluding those projects for which the costs of meeting M&V protocol requirements exceed the potential revenues from carbon offset credits.

[1] A diesel- or gas-powered electric generator.

fuel. The U.S. Department of Defense, in particular, is interested in the use of bio-oils as substitutes for petroleum-based fuels. The National Renewable Energy Laboratory, in conjunction with private contractors, is working on upgrading bio-oils to create "green" diesel or gasoline.

Synthesis gas (syngas) is a low Btu combination of constituents, mainly consisting of carbon dioxide (CO_2), carbon monoxide (CO) and hydrogen (H_2). This gas can be burned directly to produce heat or burned in a gas turbine to generate electricity. The electricity could be used to provide on-site power or be sold into the grid, depending on local economics. Generally, some gas cleanup is required if syngas is to be burned in a turbine.

Summary of Environmental Risks

The following is a summary of key environmental concerns by production segment.

Feedstock production
- Land use conversion emissions for primary biomass
- Habitat and biodiversity loss
- Collection and transport emissions
- Diversion of crop residues from soils

Conversion
- Particulate emissions (especially for small units)
  - Climate relevant black carbon component
  - Human health
- Supplemental energy use

Application
- Fugitive loss of biochar during transport and application
  - Climate forcing effect
  - Human health effect
- Soil carbon loss due to biochar incorporation
- Phytotoxicity
- Recalcitrance of biochar-based soil carbon

DOMESTIC AND INTERNATIONAL SUPPORT FOR BIOCHAR

The "WECHAR" legislation, described above, is the only U.S. legislation that provides specific incentives for biochar production. This legislation provides loan guarantees for small and fixed systems and creates the possibility that the federal government will pay a biochar producer to pyrolyze waste biomass from western forests. This legislation was introduced in both the Senate and the House in the fall of 2009 and referred to committee. No action has been taken. *The Clean Energy Partnerships Act of 2009*, S 2729 was introduced in November 2009 and referred to committee. Biochar is one of many technologies named in this legislation. No action has been taken.

The U.S. Department of Agriculture (USDA) is conducting research on the agronomic effects of biochar. Some of the research has been completed, but much of it is hampered by inadequate supplies of biochar for field testing.

Biochar advocates have tried to persuade the UNFCCC to include biochar production and utilization systems as a mitigation option in various negotiating texts; in September 2009, specific references to biochar were dropped from the negotiating texts, although the general language would probably not exclude biochar. The United Nations Convention to Combat Desertification (UNCCD) has been a strong supporter of including biochar as a mitigation option at the UNFCCC.

Potential for Biochar Production and Carbon Sequestration

One recent study estimates the maximum sustainable technical global potential for carbon mitigation from biochar systems at 1.8 billion tons per year, or 12 percent of global emissions (Woolfe, et al., 2010). This analysis assumes that high percentages of sustainably produced biomass are used in biochar conversion systems (100 percent of available dedicated energy crops, 25 percent of global cattle manure, 90 percent of pig and poultry manure, and conversion of 170 million hectares from tropical grass pasture to silvopasture[2]). The study also does not take into account any "economic, social, or cultural barriers that might further limit the adoption of biochar technology" (Woolfe, et al., 2010). It is also noteworthy that the study concludes that competing bioenergy systems would yield a 10 percent reduction in global emissions

[2] The practice of combining forestry and grazing of domesticated animals in a mutually beneficial way.

compared to the 12 percent estimated for biochar systems (Woolfe, et al., 2010). This suggests that biochar has only a slim carbon edge over its competition, and that even slightly altered assumptions would yield different results. Finally, the authors restrict their analysis to "systems in which modern, high-yield, low-emission pyrolysis technology can feasibly be used to produce high-quality biochar" (Woolfe, et al., 2010). This may be an acknowledgement of potential problems with very small, dispersed systems, although the authors do not make clear exactly what is meant by their statement.

It is axiomatic that economically achievable potential will be less than technical potential. For example, we have been conducting analyses of the potential for energy efficiency in building systems for many years. Technical potential studies often conclude that 50-80 percent of current energy use could be saved; economic potential studies are usually in the 10-20 percent range. This difference is attributable to a host of non-market barriers—economic, social, and cultural.

It is likely that the global economic potential for carbon reduction from biochar systems will be less than the 12 percent estimate in the above referenced study. If the difference between technical and economic potential in other energy studies is an indication, the economic potential will likely fall in the 2-6 percent range.

The critical question is whether the technical or economic potential should be a guide to support further development and deployment of promising technologies. We believe that an exclusive focus on very large impact technologies is misdirected. First, it encourages all competing technologies—and there are many—to produce analyses that demonstrate very large results, regardless of the validity of the assumptions used to generate such results. Second, it encourages society to think about solution sets to a very complex problem in a simplistic fashion. Regardless of the size of biochar's ultimate contribution, biochar production systems clearly merit further investigation and support as one of many promising technologies in the global energy-climate mix.

CHAPTER 3

Recommended Research Agenda to Support U.S. Biochar Policy Development

The development of meaningful U.S. policy on biochar awaits further research. Before a policy can be developed, we need increased confidence in the performance parameters of various biochar production systems, a better sense of the types of biochars that potential feedstocks will yield, better strategies for transporting and incorporating biochars into soils, and expanded knowledge of how various biochars perform from an agronomic and carbon sequestration perspective. A combination of federal support for the construction and operation of five to 10 biochar production systems along with a coordinated national field trial program will provide the data needed to develop sound policy.

Step 1 – Technical Demonstrations

Five to 10 commercial-sized projects are needed to gather baseline data on various production systems and to provide an ongoing source of biochar for a coordinated national field trial program. The total capital costs for the 5 to 10 demonstrations contemplated would be in the range of $100 million to $150 million. Federal loan guarantees would be easiest to obtain from a political perspective, but may not be sufficient to move projects forward. A federal cost share would be a stronger incentive; given recent market conditions, such subsidies would have a better chance of leveraging private investment than loan guarantees alone. A third option would be for the federal government to take an ownership stake in various technologies, with the potential for payback if the technologies proved successful.

Demonstrations would be needed on a range of technologies, although slow pyrolysis (as the leading candidate for maximizing biochar production) is critically important. Some support of bench-scale work may be justified as well. Hydrothermal carbonization, in particular, appears to be a promising means of converting very wet feedstocks to biochar and should be investigated further.

Projects should be located strategically around the country to ensure access to as wide a range of potential feedstocks as possible and to make biochar available to a representative spectrum of soil types and cultivation systems.

Waste biomass feedstocks should be priorities for production and field testing; feedstocks that represent additional environmental and economic costs (such as animal manures) should receive highest priority.

Step 2 – Coordinated National Field Trial Program

The USDA should receive funding to conduct a five-year coordinated program of field trials to test the agronomic and carbon sequestration performance of a wide variety of biochars on U.S. crops and soils. Under such a program, biochar production system developers receiving federal support should be required to coordinate production strategies and schedules to support the national field trial program. The field trial program should be coordinated with existing national and international efforts to develop a meaningful classification scheme for biochar. We recommend that five regional institutions representing the broad agricultural regions of the country (Southeast, Midwest, Great Plains, Northwest, and California) manage this work, and be funded at $14 million per center for the seven-year program.

Schedule

Year 1
Solicitation and award for first-round (3–5) technical demonstration projects
Solicitation and award for regional field trial managers

Year 2
Solicitation and award for second-round (2–5) technical demonstrations
Construction of first-round projects
Development of national field trial strategy by managers

Year 3
Construction of second-round projects
Beginning of field trials with round one biochars

Years 4–8
Field trials

Total Cost Estimate
Technical Demonstrations (50 percent cost share) – $37.5 million to $75 million
National Field Program – $70 million

Total – $107.5 million to $145 million

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