Union of Concerned Scientists
Citizens and Scientists for Environmental Solutions

The Scientific Basis for Biochar as a Climate Change Mitigation Strategy: Does it Measure Up?

Noel P. Gurwick[1]
Charlene Kelly[2]
Pipa Elias[3]

Noel Gurwick was a Senior Scientist at UCS from 2009 to 2012, when this work was conducted.
[2] Charlene Kelly is a former consultant with the Tropical Forest & Climate Initiative of UCS
[3] Pipa Elias is a former staff member and current consultant with the Tropical Forest & Climate Initiative of UCS

September 2012

Problem Statement

To avoid the worst consequences of climate change, we need to stop adding greenhouse gases to the atmosphere, and if possible remove CO_2 (carbon dioxide) from the atmosphere. Ideas for how to achieve this objective need to be assessed in order to make appropriate investments and policy decisions. One proposal for removing CO_2 from the atmosphere is to heat biomass in the absence of oxygen to produce charcoal (renamed biochar in the context of deliberate production for climate change mitigation).[1] The proposal rests on the fact that plant growth removes CO_2 from the atmosphere, which is then stored in the plant material, and on the premise that carbon in biochar is highly stable, i.e., that it resists decomposition and therefore does not return to the atmosphere as CO_2 for thousands of years.

This idea has attracted considerable attention. In 2010, the American Power Act -- proposed federal legislation to comprehensively address energy and climate change -- included "projects for biochar production and use" in a list of project types to be considered for a domestic carbon offsets program. The International Biochar Initiative continues to advocate for biochar as a climate change mitigation solution, and we expect to continue to see proposals for biochar as a carbon offset at both the domestic and international levels. However, a number of studies have called into question the assumption that biochar is very stable over long time frames (e.g., Nguyen et al. 2009; Wardle et al. 2008; Bird et al. 1999). Therefore, there is a strong need to assess the status of the science underlying claims of biochar stability. Our goal is to analyze the current state of the science to determine whether or not we can have confidence in biochar as a climate change mitigation strategy.

Besides climate change mitigation, biochar may alter soil fertility and water holding capacity. Furthermore, there may be production benefits ranging from co-production of renewable oils to reduction of pollution. However, we did not analyze these aspects of biochar in this study.

How Extensive is the Literature on Biochar?

Assembling a comprehensive list

To assess whether the knowledge base generally supports the assertion that biochar-carbon is stable, we conducted a thorough review of the literature. We conducted searches in Web of Science for all years, using the topic "biochar" or "bio-char" on May 16, 2011. We ran similar searches in Agricola and Google Scholar. Because these searches may have missed papers that

---

[1] In addition to charcoal and biochar, the diverse literature on charcoal also uses the terms elemental carbon and black carbon, all of which describe the same material. For simplicity, we use only biochar for the remainder of this briefing paper, regardless of the particular term used by the authors of studies to which we refer.

used the term “black carbon,” we also looked in bibliographies of recently-published papers and added all relevant literature. Finally, Dr. Jeffrey Bird and doctoral student Fernanda Santos (CUNY) – scientists who specialize in biochar stability in soil -- reviewed our list and added to it.

Finding: In total, we analyzed 329 unique references to biochar[2].

Characterizing the literature

One of our key objectives was to separate *assertions* from *evidence* about biochar stability. We characterized each reference as one of seven categories (Table 1). Papers described as original research appeared in the peer-review literature and reported original data or findings from observations, experiments or models. Methods papers evaluated or described an investigative technique and reported minimal information about the properties of biochar. Review papers summarized understanding of biochar but did not report new data on biochar stability or decomposition rates. Our search also captured news stories, book chapters, and “other” publications including extension newsletters, USDA publications, editorial notes, letters-to-the-editor, conference abstracts, and editorials in journal issues. Because we used relatively broad search criteria, some of the references we captured did not actually concern biochar in any meaningful way; some, for example, listed the products of pyrolysis, one of which was biochar. We described these papers as “biochar incidental.”

Table 1. Frequency of references captured in our literature search, according to key categories of literature.

Study Type	**Total**
Original Research	212
Methods Paper	12
Review Paper	42
News Story	7
Book Chapter	3

---

[2] We found 331 references, but were unable to locate abstracts for two; an additional paper was submitted but as-yet unpublished. Our subsequent analyses excluded these references, and therefore were of 329 papers. Our ISI search captured a 1933 paper on “classification of the Spiriferidae” which included numerous references to “biocharacters” but not “biochar,” and our total of 329 papers excludes this one as well.

Other	29
Biochar incidental	24
TOTAL	329[2]

Finding: We found 212 references in the peer-reviewed literature that report original research on biochar.

These 212 papers addressed a wide range of topics, revealing a diverse, non-standardized literature with many different perspectives. We classified them by topic according to ten categories described below, assigning each paper to as many topic areas as it addressed.[3]

Our ten topic areas included three directly relevant to climate change mitigation:

(1) *Stability, transport, or fate of biochar and soil carbon* – Studies that described the physical and/or chemical properties of biochar or soil organic matter mixed with char, at one or multiple points in time.

(2) *Model and/or life cycle analyses of biochar systems* – Studies that calculated the economic, energy and/or climate change mitigation potential of biochar production systems, from regional to global scales.

(3) *Influence of biochar on trace gas emissions from soil* – Studies that reported rates of methane and/or nitrous oxide emissions from soils to which biochar had been added.

The other seven topic areas were:

(4) *Soil fertility* – Studies that reported nutrient levels in soils amended with biochar.

(5) *Plant responses* – Studies that reported responses, such as yield or nutrient status, of plants grown on soils amended with biochar.

(6) *Soil biology* – Studies that reported the biomass or diversity of soil microbes, fungi, earthworms, or other soil fauna on biochar or in soil amended with biochar.

---

[3] One paper addressed biofuel production from biochar, a topic that fell outside all ten of our topic areas and is outside the common understanding of the definition of biochar.

(7) *Soil properties* – Studies that reported, for example, the pH, bulk density, water holding capacity, or cation exchange capacity of soils amended with biochar.

(8) *Nutrient loss (N, P, K)* – Studies that reported loss of nutrients, for example via leaching or gaseous emissions, from soils amended with biochar.

(9) *Product analysis and/or pyrolysis chemistry* – Studies that described biochar production processes and/or characterized the physical or chemical properties of biochar.

(10) *Influence on soil contaminants* – Studies that described the effects of biochar on the mobility of soil contaminants such as lead, arsenic, pesticides, and herbicides.

Finding: Most papers of these 212 papers (60%) addressed only 1 of the 7 topic areas we considered, and nearly 75% addressed either 1 or 2, but a small number of papers (8%) addressed 4 or 5 topic areas.

Each of these topics has application to human well-being, and further interrogation of our literature database could reveal findings and associated policy implications. Table 2 shows the number of papers that addressed each topic.

Table 2. Frequency of papers addressing each of our ten topic areas. First three topics listed concern biochar influences on climate change.

Topic Area	**Number of papers**
Stability, transport, or fate of biochar and soil organic matter (SOM)	56
Model and/or life cycle analysis of biochar	13
Influence of biochar on trace gas emissions from soil	8
Soil fertility	34
Plant responses	32
Soil biology	28
Soil physical properties	34
Nutrient loss (N, P, K)	6
Influence on soil contaminants	37
Product analysis and pyrolysis chemistry	106

As this paper concerns biochar as a strategy for climate change mitigation, we focus on the first three rows of Table 2. Modeling studies (row 2) are valuable because they take into account energy expenditure and greenhouse gas (GHG) emissions associated with the entire biochar production process (life cycle analyses), and they are necessary to estimate the consequences of field-scale studies for large regions and, ultimately, for climate. However, they rely on empirical measurements (or assumptions) about what happens to biochar after its introduction to a soil, and our main concern in this paper is what studies to date say about this latter topic. Hence, we do not address the modeling studies further here. Biochar's influence on trace gas emissions (row 3) merits a close interrogation of existing studies, although the very small number of papers (8) suggests the literature in that area is far from mature. The primary claim for biochar's contribution to reducing GHG concentrations in the atmosphere has been that biochar resists decay and persists in soil for much longer than unconverted biomass, delaying emission of carbon that otherwise would be released back into the atmosphere during plant oxidation through decay or burning. In the remainder of this paper, we focus on original research papers that address the stability, fate, or transport of biochar (row 1).

Finding: About 25% of the original research – 56 papers -- provides empirical data about the extent to which biochar remains in the soil and/or the influence of biochar on decomposition of the surrounding soil.

Evaluating the literature

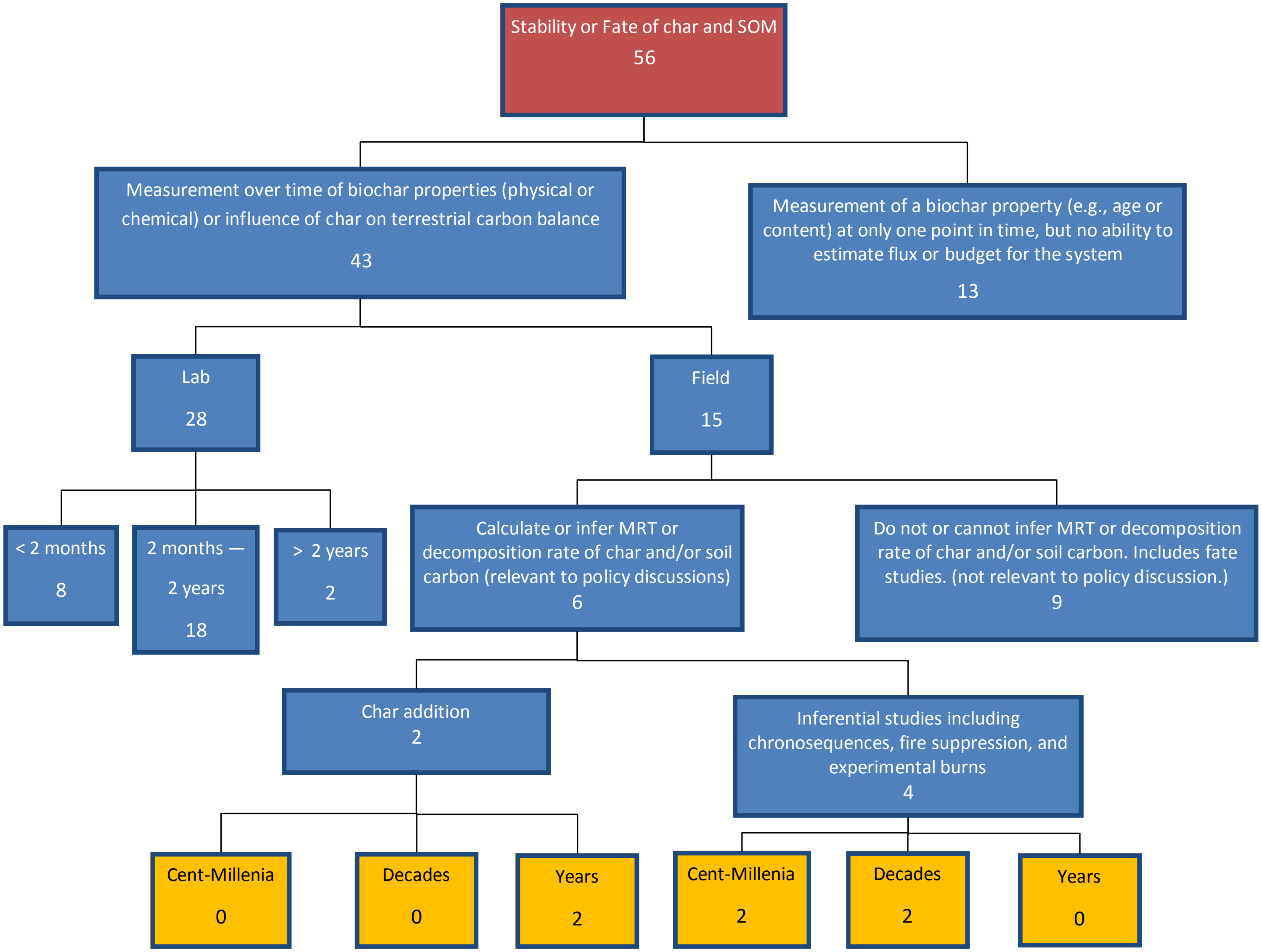
We adopted a relatively broad window for empirical studies relevant to biochar stability, including all studies that address the ultimate fate of this material and studies that consider biochar's influence on decomposition of the surrounding soil (e.g., Wardle et al. 2008). Hence, we believe our review is more likely to overestimate rather than underestimate the maturity of this field of science.

Figure 1 illustrates the types of studies that fall within this topic area. Thirteen studies that address biochar fate look only at a single point in time and do not allow for conclusions about how much of the biochar stays in the soil, or how long it takes to decompose. These include, for example, an investigation of how distribution of biochar in soils of the Brazilian Amazon varies with depth, and the extent to which biochar is strongly associated with minerals that might help stabilize it (Glaser et al. 2000). Skjemstad et al. (2002) estimated the abundance of biochar in different fragment sizes in Midwest U.S. soils, and characterized the morphology of these fragments. While these point-in-time studies increase our understanding of biochar in the environment, they do not directly add to our ability to quantify how fast it decomposes, or how it influences the rate at which surrounding soil decomposes.

The other 43 studies that address biochar stability, transport, or fate contribute to understanding of how stable biochar is under different circumstances. These studies adopt a variety of approaches, including laboratory incubations, deliberate additions of biochar to field plots, and studies of field plots where fire suppression has led to different levels of biochar addition to soils over time.

We have *a priori* reasons to consider some of the approaches described above to be essential to estimates of stability that would be sufficiently robust to inform policy decisions. Most important, studies conducted *in situ*, i.e., under field conditions, are indispensable because variation in temperature, precipitation, soil moisture, soil mineralogy, the presence of live plant roots, and bioturbation by microorganisms in the soil all influence microbial activity and decomposition.

Figure 1. Original research addressing stability, transport, and/or fate of biochar and soil organic matter, showing characteristics of the literature and number of papers in each category. MRT is mean residence time; SOM is soil organic matter.



Some laboratory studies can help to establish understanding of specific controls on decomposition, particularly when conducted over long time frames. As shown in Figure 1, we identified 20 laboratory studies that lasted for more than two months, and two of these ran for more than two years. These studies should be examined and their results used to inform future field studies. However, although these studies can point us in the right direction and add confidence to conclusions drawn from field studies, by themselves we do not believe they form a sufficiently robust foundation for public policy because the field conditions under which climate change mitigation strategies would be applied are difficult to include in laboratory studies.

Of 43 studies that provide some measurement of how biochar changes over time, or of how biochar influences the carbon balance of terrestrial ecosystems, only 15 were conducted under field conditions (Figure 1) – measuring some indicator of biochar decomposition in field settings, or biochar's influence on the decomposition of soil organic matter. Of these, **six** either estimated how long biochar would persist in the soil, provided sufficient information that a reader could derive a reasonable estimate, or provided results that allow strong inferences about the role of biochar in the carbon budget of an ecosystem.

Finding: Fifteen field studies measured an indicator of biochar decomposition or influence on soil decomposition in field settings, and six of these either estimated decomposition *rate* or a related parameter (which is critical to quantify the length of time for which carbon would be sequestered).

What Do the Few Critical Studies Tell Us about Biochar Stability?

The reported values that describe biochar stability fall into several related parameters including decomposition rate, mean residence time (MRT), and turnover time. Mean residence time is the average time that a biochar carbon molecule resides in the soil; however, some molecules leave the soil much more quickly and some persist for much longer. Turnover time is the length of time required for all biochar molecules in the soil at some time to exit the system and be replaced by biochar molecules entering from elsewhere. Estimates of turnover time usually assume that inflow and outflow occur at the same rate. These estimates all provide ways to quantify biochar stability and are necessary to quantify the length of time for which carbon will be sequestered by a biochar system. Below, we briefly summarize each of these six studies.

Two studies added biochar to field soils:

Major et al (2010) produced biochar and applied it to soils in a Colombian savanna, then measured the amount of the biochar carbon respired as CO_2 from the soil and the amount percolating through the soil. Two years after the biochar addition, their measurements indicated that up to 3% of the biochar had been respired as CO_2, but they could not account for 20-50% of the biochar. Presumably it washed off the fields during intense rainfall, but Major et al. had no direct measurements of biochar in runoff. Assuming that none of the "missing" biochar carbon was respired and converted to CO_2 after leaving the site where the investigators were measuring soil CO_2 emissions, the authors calculated a mean residence time for the biochar of approximately 600 years.

Haefele et al. (2011) produced biochar from rice husks and applied it to rice cropping systems in the Philippines and Thailand. At one site they measured CO_2 emissions from the soil immediately after application and again two years later. At all sites they measured biochar carbon in the soil after application and two years later. Where Haefele et al. measured soil respiration they found no change between the two time points, and, more significantly given the limited sampling of CO_2 emissions, found no change in the amount of biochar in the soil. The authors conclude that "realistic residence times might be in the range of thousands of years…."

Three studies used field sites where fire produced biochar, and where fire had been suppressed for some time (sometimes more than 100 years). Provided the investigator has a sound estimate of the amount of biochar in the soil prior to fire suppression, situations like this afford the possibility of estimating long-term stability without waiting decades for an experiment to run its course.

Hammes et al. (2008) studied changes in biochar contents of soils on the Russian steppe over 100 years. In that landscape, fire periodically added biochar to the soil, but fire -- and hence biochar inputs -- essentially ceased following the establishment of a reserve one hundred years ago. The authors also had access to a large soil monolith collected and preserved at the time of reserve establishment; hence, they could measure the quantity of biochar in the soil 100 years ago, and in monoliths collected at virtually the same location 100 years later. They found that biochar content of the soil declined about 25% over a century. With this information, and using several reasonable assumptions, Hammes et al. calculated a turnover time for biochar in these soils of 293 years (with a range of 182-541 years). The range estimates derived from sensitivity analyses in which Hammes et al. varied, for example, the assumption that all biochar decays at the same rate, and the possibility that some biochar additions to soil continued after the reserve was established (perhaps via transport by wind from other locations). The authors wrote: "We emphasize that the best-estimate turnover time presented here is a conservative value and that turnover, or at least a significant fraction of soil BC [biochar], could be even faster than predicted."

Nguyen et al. (2009) measured the amount of biochar in topsoil of 18 Kenyan fields. In each case, people had burned the forest, creating a field and producing biochar in the process. Clearing had occurred at different times in the past, between 2 and 100 years ago. By assuming that the amount of biochar in each field at the time of clearing roughly equaled the amount of biochar in a recently burned site, the authors estimated the rate of biochar loss over 100 years (a space-for-time substitution). Over the first 30 years, approximately 70% of the biochar exited the system, with losses occurring most rapidly soon after clearing. Nguyen et al. calculated a mean residence time of 8.3 years for the biochar in these topsoils.

The authors could not quantify the relative importance of different loss pathways (respiration, surface runoff, leaching), although they suggest that losses due to erosion were likely small owing to the flat landscape and the observation that the amount of biochar in the soil did not decrease appreciably after the first 20 years following clearing. Nguyen et al. also characterized the biochar using a variety of chemical analyses and found that particles in fields cleared long ago were smaller and had a different (likely more stable) chemistry than biochar particles in more recently cleared fields.

Bird et al (1999) described biochar content in the topsoil of a Zimbabwean savanna that had been protected from fire for 50 years, and in plots that had continued to burn every 1-5 years. They found biochar degradation in the soils protected from fire and calculated that biochar at this site had a half-life of "considerably less than 50 years" under natural conditions. They also noted that conditions at this site might contribute to the short half-life of biochar, and that biochar might remain longer in temperate soils.

In the final study under consideration, *Cheng et al. (2008)* collected biochar produced approximately 130 years ago at 11 historical charcoal blast furnace sites located between Quebec, Canada and Georgia, USA. They also produced biochar using kilns rebuilt to resemble those thought to have produced the older biochar. The authors characterized the carbon, hydrogen, and oxygen content of the biochar to assess the extent of decomposition. They found that biochar particles had been highly oxidized after 130 years under field conditions. The average carbon concentration was 91% in newly-produced biochar and 71% in the 130-year-old material. Similarly, oxygen concentration increased from 7% in the historical samples to 25% in newly-produced biochar. Although the authors stopped short of estimating mean residence time or turnover time, these figures suggest that at least 23% of biochar carbon escapes to the atmosphere over 130 years.

Summary of the Six Key Studies

In Table 3, we summarize key information from these six studies, including mean residence time or turnover time, study location, experimental approach, and biochar source. Estimates of MRT and/or turnover times vary widely among the few studies that have made the necessary

Table 3. Characteristics of field studies that reported measurements over multiple times and allowed for empirically-based estimates of biochar stability.

Study	**Location**	**Char source**	**Approach**	**Biochar loss rate (years)**[4]
Major et al. 2010	Colombian savanna	Investigator-produced from mango wood; added by disking	Biochar addition; intensive measurement of soil respiration and leaching for 2 years	MRT 3,624
Haefele et al. 2011	Phillipines and Thailand	Investigator-produced from rice husks	Biochar addition; periodic measurements of biochar C for 3 yrs	MRT >1,000
Hammes et al. 2008	Russian steppe	Naturally-occurring fire	100-year suppression of fire	Turnover time 293
Nguyen et al. 2009	Kenya	Slash-and-burn conversion from forest to cropland	100-year chronosequence	MRT 8.3
Bird et al. 1999	Zimbabwean savanna	Naturally-occurring fire in savanna vegetation	50-year fire suppression of fire	MRT <100
Cheng et al. 2008	Eastern North America	Historic blast furnaces operating 130 years ago	Produce char in reconstructed kilns as proxy for char before decay	23% biochar C loss in 130[5]

---

[4] MRT – Mean Residence Time, defined in text.

[5] If this rate were to continue, all the biochar would have decayed in 565 years, also implying a turnover time of this duration. Generally, decomposition proceeds more quickly immediately after deposition and more slowly later on, meaning that turnover could be longer than this figure. However, the rapid phase of decomposition likely lasted less than 130 years.

measurements; MRTs range from eight to more than 3,000 years. As long as this variation remains unexplained, we cannot assume that all field-applied biochar would remain stable for long periods of time.

Table 3 also makes it easy to see that field studies that measure rates of biochar decomposition have appeared very recently. With one exception (Bird et al. 1999), these studies appeared in the peer-reviewed literature in 2008 or more recently, underscoring the very young character of this field of inquiry and the absence of time to conduct many experiments and, as important, allow alternative perspectives to emerge, be debated and reconciled with a combination of data, theory, and modeling.

Although we focused in this paper on studies of biochar stability, roughly half of the original research papers we found focused on the properties of biochar or the process of biochar production (pyrolysis) (Table 1). Those papers revealed a wide range of biochar source materials and a variety of pyrolysis conditions (e.g., different temperatures) that result in products that vary widely in physical and chemical properties. How the decomposition rates presented here might vary with these different types of char, as well as with different environmental conditions (dry, wet, hot, cold etc.), remains poorly characterized given the wide variation in properties of biochar. One of the review papers that appeared in our search identified the molar ratio between oxygen and carbon – a difference dependent on pyrolysis temperature, plant material, and post-production handling – as a key characteristic influencing biochar stability (Spokas 2010). Spokas hypothesizes that biochar materials with O:C ratios below 0.2 have longer half-lives (of over 1000 years) because there is less oxygen to disrupt the lattice structure of the carbon and increase reactivity. [Natural biochar materials geologically created under extreme temperature and pressure, like graphite and bituminous coal, have O:C ratios below 0.2.] With O:C ratios over 0.6, which is fairly common, biochar will likely have a half-life of less than 100 years. Many more field studies will be needed to test relevant hypotheses.

What about Other Studies?

Of the remaining 9 field studies that measured biochar properties at more than one point in time (Figure 1), at least two addressed the influence of biochar on surrounding organic matter and yielded contradictory results. Wardle et al. (2008) used buried bags filled with soil, biochar, or a mixture of the two, and showed biochar can accelerate the rate of decomposition of surrounding soil organic matter (SOM). Kimetu and Lehmann (2010) conducted a 2-year biochar addition experiment in which they added biochar derived from Eucalyptus wood to soil in Kenya. In a carbon-poor soil, they measured much lower rates of CO2 emissions from a plot amended with biochar than from a plot amended with a green manure. These results underscore the need to consider the influence of biochar on the whole system carbon balance and the challenge of achieving that objective, which further emphasizes the gap between the relatively immature science of biochar stability and proposals to rely on biochar as a climate change mitigation strategy.

Certainly there are insights to be gained from some of the other 41 original research papers that focused on biochar stability. For example, two of the laboratory studies lasted for over two years, and 18 more lasted for over two months. Studies of this length could certainly add to our understanding of *potential* biochar decomposition rates, the controls on those rates (e.g., soil mineral composition, nutrient availability, moisture) and of the extent to which biochar may influence stability of surroundings soil. However, without testing those hypotheses generated with lab studies through long-term field measurements, there will be great uncertainty about the extent to which factors not present in the lab could yield different results under the field conditions in which biochar would actually be applied.

Conclusions

We asked how effectively biochar application on land sequesters carbon and for how long. We found that the data required to answer this question do not yet exist. Only a handful of studies have collected the data necessary to estimate biochar stability, i.e., MRT or turnover time. The true variable of interest – the influence of biochar on whole system carbon balance – is even less well-quantified. And those studies that have estimated biochar stability are as likely to yield short MRT values as long ones. Hence, it is too early to rely on biochar as a climate mitigation tool, and to devote public resources to biochar deployment for that purpose.

To evaluate where it will or will not work requires many more field studies that:

- include both chronosequences and manipulative experiments conducted over appropriate time scales;
- cover the range of biochar types and soil, agricultural and climate conditions;
- include trials on working agricultural lands; and
- address both biochar stability per se and the influence of biochar on decomposition of surrounding soil organic matter.

Results of field studies on biochar stability also need to be compared with alternative mechanisms of soil C sequestration including forest management.

Where might biochar be useful?

In some cases, biochar production may be a wise practice. For example, Haefele et al. (2011) wrote: “Rice residues are a by-product of food production. Therefore, bioenergy based on rice residues does not impair food security.” They continue: “Residue removal from rice fields for energy production directly reduces emissions of greenhouse gases and air pollution caused by residue incorporation or field burning.” If indeed these rice husks both need to be removed from the rice paddies for agronomic reasons and increase methane production if they remain in the paddies (by providing methanogens with a carbon source under anaerobic conditions), then removing the husks and deriving a benefit from them is likely a wise approach. Whether producing biochar or simply burning them to generate heat is the best approach is beyond the scope of this paper. We wish only to make clear that we do not question all policies for producing biochar, only policies that treat biochar production as an alternative to reducing carbon emissions, justified by the claim that biochar resides in soil for thousands of years without appreciable decay.

Literature Cited

Bird, M.I., C. Moyo, E.M. Veenendaal, J. Lloyd, and P. Frost. 1999. Stability of elemental carbon in a savanna soil. *Global Biogeochemical Cycles* 13(4): 923-932.

Cheng, C.H., J Lehmann, and M.H. Engelhard. 2008. Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta* 72: 1598–1610.

Glaser, B., E. Balashov, L. Haumaier, G. Guggenberger, and W. Zech. 2000. Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region. *Organic Geochemistry* 31 (2000) 669-678.

Haefele, S.M., Y. Konboon, W.Wongboon, S. Amarante, A.A. Maarifat, E.M. Pfeiffer, and C. Knoblauch. 2011. Effects and fate of biochar from rice residues in rice-based systems. *Field Crops Research* 121: 430–440.

Hammes, K., M.S. Torn, A.G. Lapenas, and M.W. I. Schmidt. 2008. Centennial black carbon turnover observed in a Russian steppe soil. *Biogeosciences* 5, 1339-1350.

Kimetu, *J.M. and J.* Lehmann. 2010 Stability and stabilization of biochar and green manure in soil with different organic carbon contents. *Australian Journal of Soil Research* 48: 577–585.

Major, J., J. Lehmann, M. Rondon, and C. Goodale. 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. *Global Change Biology* 16(4): 1366-1379.

Nguyen, B.T., J. Lehmann, J. Kinyangi, R. Smernik, S.J. Riha, and M. Engelhard. 2009. Long-term black carbon dynamics in cultivated soil. *Biogeochemistry* (2008) 89:295–308

Skjemstad, J.O., D.C. Reicosky, A.R. Wilts, and J.A. McGowan. 2002. Charcoal Carbon in U.S. Agricultural Soils. *Soil Science Society of America Journal*. 66: 1249-1255.

Spokas, K. 2010. Review of the stability of biochar in soils: predictability of O:C molar ratios. *Carbon Management.* 1(2):289-303.

Wardle, D.A., M-C Nilsson and O. Zackrisson. 2008. Fire-Derived Charcoal Causes Loss of Forest Humus. *Science*. 320(5876):629.