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ASSESSMENT OF BIOCHAR'S BENEFITS FOR THE UNITED STATES OF AMERICA

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BIOCHAR FOR RECLAMATION IN:
THE ROLE OF BIOCHAR IN THE CARBON DYNAMICS IN DRASTICALLY DISTURBED SOILS

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Shrestha & Lal (2006) defines drastically disturbed soils as those where native vegetation and annual communities have been removed with most of the topsoil lost, altered or buried, and describe three main groups (in order of commonality):

1. Construction related (urban centers, roadways and highways, fills and shoulders)
2. Resource development (mining, oil and gas, aggregate); and
3. Eroded farmland and rangeland.

Historically, drastically disturbed landscapes have been discussed in relation to the alteration of whole ecosystems with respect to nutrient and water cycling (Shrestha and Lal 2006). Soil organic matter decline is seen as a key component in drastically disturbed lands, impacting ecosystem functions such as air and water quality, wildlife habitat condition and agricultural productivity. A landscape-scale approach to managing soil carbon can improve ecological functions of soil and landscapes for the benefit of society (Reed 2007). Recent focus has also been placed on the importance of drastically disturbed lands (especially those of resource development) contributing to the atmospheric CO_2 emissions by soil disturbance and cleared biomass decomposition, and as such, provide an important opportunity to address ecosystem functions, carbon sequestration and general sustainability issues through restoration and reclamation (Shrestha *et al.* 2009). The use of biochar to address these issues in agricultural landscapes also has potential in the restoration of drastically disturbed landscapes. This paper discusses this potential in the restoration of drastically disturbed lands with respect to all three components: ecosystem function, carbon sequestration and general sustainability.

The Potential for Biochar to Improve Ecosystem Function in Drastically Disturbed Landscapes

Akala and Lal (2001) estimate that up to 70% of soil organic carbon is lost during drastic land disturbance. Soil organic matter decline in drastically disturbed land occurs through the following mechanisms (Anderson *et al.* 2008):

- Erosion of soil during stripping, storing, respreading and seeding;
- Water and wind erosion;
- Reduced inputs from vegetation in the form of above-ground and below-ground litter; and

- Dilution as surface soils with higher soil organic carbon concentrations become mixed with soils from deeper in the profile.

The loss of soil organic carbon leads to several physical and nutritional limitations that require addressing during restoration. Additionally, toxicity issues are common in mine soils. A summary of factors limiting mine soil restoration is included in *Table 1*.

Table 1. Role of Biochar in Ameliorating Drastically Disturbed Lands (modified from (Shrestha and Lal (2006)).

LIMITING FACTOR	VARIABLE	PROBLEM	SHORT-TERM TREATMENT	LONG-TERM TREATMENT	ROLE OF BIOCHAR
PHYSICAL	Soil Structure	Soil too compact	Rip or Scarify	Vegetation	Decreased soil bulk density, increased infiltration, and decreased erodibility. Increased water retention due to surface area and charge characteristics.
	Soil Erosion	High erodibility	Mulch	Re-grade, Vegetation	
	Soil Moisture	Too wet	Drain	Wetland construction	
		Too dry	Organic mulch	Tolerant species	
NUTRITIONAL	Macronutrients	Nitrogen deficiency	Fertilizer	N-fixing plants e.g. leguminous trees or shrubs	Yield increases. Slow nutrient release. Soil organic matter stabilization. Retention of released nutrients. Increased microbial activity. Habitat for mychorrhizal fungal hyphae
		Other deficiencies	Fertilizer	Fertilizer, Amendments, Tolerant species	
TOXICITY	pH	Acid soils (<4.5)	Lime	Tolerant species	Designed for alkaline surface charge.
		Alkaline soils (>7.8)	Pyritic waste, Organic matter	Weathering, Tolerant species	High CEC for Na retention.
	Heavy Metals	High concentrations	Organic matter, Tolerant cultivar	Inert covering, Tolerant cultivar	High surface area and cation exchange capacity allows for metal retention.
	Salinity	EC >4.0 dS/m, pH<8.5, SAR<13	Gypsum, irrigation	Weathering, Tolerant species	Mixed with gypsum to reduce soil structural issues. Nutritional values as described. High CEC for Na retention.
	Sodicity	EC <4.0 dS/m, pH>8.5, SAR≥13	Gypsum, irrigation	Weathering, Tolerant species	

Soil amendments are an important component of reclamation programs. These have included coal combustion by-products, biosolids, swine or poultry manure, sewage or paper mill sludge, sawdust, wood residue and limestone slurry by-products. Shrestha and Lal (2006) have summarized the role of organic and inorganic amendments in restoration including:

- Improvements of chemical and physical properties of soil;
- Improved fertility for crop establishment;
- Increased biomass productivity;
- Increased water holding capacity;
- Increased pH, electrical conductivity and cation exchange capacity;
- Increased population of phosphate solubilizing and nitrogen-fixing bacteria;
- Decreased bulk density; and
- Increased percentage of 1-2mm water stable aggregates.

While organic amendments provide a source of nutrients that are readily mineralized, these do not provide a long-term source of soil carbon. Bendfeldt *et al.*(2001) found that the addition of sawdust and sewage sludge to mine soils enhanced soil quality over the short-term (1-5 years) but that there were no lasting improvements. Biochar (long residence times) represents an opportunity to enhance nutrient cycling and other ecosystem services in drastically disturbed lands (amendment, mulch, toxicity reduction).

Biochar is a promising amendment for ameliorating drastically disturbed soils due to its microchemcial (Amonette and Joseph 2009), nutrient (Chan and Xu 2009) and biological (Thies and Rillig 2009) properties as well as its stability in soil (Lehmann *et al.* 2009). Biochar is a carbon-rich product obtained when biomass is heated in a closed container with limited air with the intent of being applied to soil to improve soil productivity, carbon storage or remediation (Lehmann and Joseph 2009). The persistence of organic matter in the order of centuries in weathered tropical soils associated with the application of biochar have been reported by Glaser *et al.* (2001). The persistence is due to the highly aromatic structure of the biochar that is chemically and microbially stable. When compared to other organic amendments (sawdust, manure, Tithonia diversifolia leaves) in a highly degraded agroecosystem Kimetu *et al.* (2008) reported that the application of biochar had the greatest impact on increasing productivity and soil organic carbon concentrations, even though there was no improvement of nutrient availability. Due to the nature of production being dependent on both the feedstock and the process, biochar can be developed for site specific conditions to ameliorate a number of conditions (Table 1).

Ameliorating Physical Limiting Factors

Soil organic carbon plays an important role in soil structural stability (the resistance of soil to structural rearrangement of pores and particles when exposed to different stresses such as cultivation, compaction and irrigation). A minimum of 2% soil organic carbon has been reported to be required to maintain structural stability, with structural stability declining rapidly below 1.5% and there is generally a linear increase of aggregate stability and aggregate size with increasing levels of soil organic carbon (Krull *et al.* 2004). Different types of organic matter perform different functions in aggregate formation, however the labile carbon fraction, consisting mainly of carbohydrates, is instrumental in aggregate formation (Krull *et al.* 2004). Microbially-produced polysaccharides are of importance in the initial production of stable aggregates and that humic substances are essential for ensuring longer aggregate stability (Krull *et al.* 2004). Low rates (100kg/ha; 90lbs/ac) of humic substances with over 70% aromatic carbon improved aggregate stability and reduced disaggregation during wetting and drying cycles (Krull *et al.* 2004). Albaladejo *et al.* (2008) found that a single organic amendment to a degraded semiarid soil was effective in improving soil physical properties. Glaser *et al.* (2002) reported that much lower application rates of coal-derived humic acids (1.5 ton/ha; 50lbs/ac) when compared to undecomposed organic residues (50-200 ton/ha; 45-180 ton/ac) to obtain significantly higher aggregate stability.

The long-term residence time of biochar in soils has been attributed to mineral interactions with attachment occurring as (Hammes and Schmidt 2009):

• Free biochar particles with embedded and associated clay- and silt-size minerals;
• Small biochar particles bound to minerals; and
• Small minerals particles bound to large biochar particles.

These processes leads to improved soil aggregation (Major *et al.* 2009) which are inferred to help maintain long-term soil structural stability. These interactions occur very quickly after application to soil and gain importance over time (Lehmann *et al.* 2009).

This improved soil aggregation and associated pore space distribution with increased organic matter generally increases soil water holding capacity and conductivity (Saxton and Rawls 2006). This relationship has a greater effect in coarse texture than fine textured soils, and even decreasing in heavy soils (Krull *et al.* 2004; Glaser *et al.* 2002). Saving water by reducing runoff and evaporation is critical in enhancing biomass productivity (Izaurralde *et al.* 2001) and can have significant long-term impacts. Albaladejo *et al.* (2008) found higher saturated hydraulic conductivity in plots 16 years after a single application of urban solid refuse to a degraded semiarid soil. Application rates greater 2% soil organic carbon result in significantly higher available water content than lesser application rates, and need to be considered when determining biochar application rates.

Ameliorating Nutritional Limiting Factors

Reclaimed lands tend to have highly variable available nutrient contents (Shrestha *et al.* 2009). Soil fertility improvement is an important aspect of soil quality enhancement and C sequestration in soil and biomass. Low rates of fertilizer application are usually recommended for dry areas where rainfall is uncertain (Izaurralde *et al.* 2001). The judicious use of fertilizer, compost and nutrient management has been demonstrated in several long-term experiments (Izaurralde *et al.* 2001). Reduced leaching of applied fertilizer is thus important in the restoration of reclaimed soils. Less water percolation has been reported by Lehmann *et al.* (2003) in soil/biochar mixtures that soil alone. Additionally, biochar porosity and charge characteristics can reduce leaching of nitrogen phosphorus potassium, calcium and magnesium (Major *et al.* 2009).

As a chemical reservoir, soil organic matter is a source of nitrogen, phosphorus , sulfur and other elements (Bauer and Black 1994). Soil organic matter nutrients become plant available during decomposition, and the particulate matter fraction is considered the most important proportion of soil organic matter (Krull *et al.* 2004). Soil organic carbon concentrations <1% are considered a threshold below which effective nitrogen supply is reduced. The importance of soil organic carbon with respect to productivity was shown by Bauer and Black (1994) who estimated that 1 ton of organic matter/hectare (800 lb/acre) increased wheat dry matter productivity between 15.6 and 35.2 kg/hectare (13.8 and 31.0 lb/acre) in the northern Great Plains.

Biochar has a high variability of plant macro- and micro-nutrients due to the different feedstocks and production conditions, however, several trends have been described by Chan and Xu (2009):

• Mineral nitrogen is very low;
• Available phosphorus is highly variable;
• Available potassium is typically high.

Akala and Lal (2001) however noted that over reclamation periods of 15-20 years in Ohio, the carbon:nitrogen ratio increased suggesting the nitrogen deficiency may be a constraint in these landscapes. While biochar itself is a low nitrogen source (Chan and Xu 2009) and is not considered in calculating C:N ratios, it does not appear to immobilize nitrogen (Kimetu *et al.* 2008) and may be an important amendment for nitrogen dynamics in reclamation with the ability to improve the efficiency of mineral nitrogen fertilizer (Steiner *et al.* 2008).

Soil texture also plays a role with fine textured soils retaining greater carbon and nitrogen than coarse textured soils when the same amount of organic matter are added due to the greater protection of organic carbon by clays (Ganjegunte *et al.* 2009). This would suggest that biochar would be more effective for controlling nutrient dynamics in coarse grained soils.

Increased productivity by the application of biochar has been reported by Kimetu *et al.* (2008) on highly degraded sites. Kimetu *et al.* (2008) report a significant increase in seed germination (30%), shoot heights (24%), biomass production (13%) and crop yields (up to 200%). Glaser *et al.* (2002) also cited that crop yields can be enhanced to a greater extent when biochar is applied together with other inorganic or organic fertilizers. In addition to improving fertilizer retention for plant growth (Major *et al.* 2009), biochar may also act as a fertilizer as the cations in ash contained in the biochar are present as dissolved salts and thus readily available (Glaser *et al.* 2002). Cao and Harris (2010) developed a slow release phosphorus fertilizer by using dairy-manure as a biomass feedstock. Additionally, the physical structure of biochar provides a framework for building a slow release NPK fertilizer as proposed by Day *et al.* (2005).

Loss of soil organic matter also reduces cation exchange capacity resulting in lower nutrient retention and supply capacity, as well as water retention capacity (Kimetu *et al.* 2008). Krull *et al.*(2004) found that :

- Cation exchange capacity increases linearly with increased soil organic carbon above a threshold of 2%;
- Soil organic matter contributes to up to 70% of effective cation exchange capacity in highly weathered soils; and
- Charcoal has been shown to be a potentially important contributor to increasing cation exchange capacity.

Oxidation of biochar over time produces carboxylic groups on the edges of the aromatic core, increases cation exchange capacity and the reactivity of black carbon in soil (Glaser *et al.* 2001). As such, metal ions, dissolved organic matter and dissolved organic nutrients are retained through improved cation exchange capacity associated with biochar addition (Glaser, Lehmann *et al.* 2002). Nguyen *et al.* (2008) indicates that this process can occur in the order of months. Increases in cation exchange capacity in the range of 40-50 mmolc/kg were reported by Kimetu, *et al.* (2008) in moderately degraded sites. The oxidation rate of biochar is dependent more on mean annual temperature rather than duration within the soil (Cheng *et al.* 2008). The application of biochar for improved cation capacity in arid and semi-arid environments appears a significant tool for nutrient and moisture retention in drastically disturbed soils.

Biochar has been reported to increase microbial activity in a range of soils that may also improve nutrient availability through a various of mechanisms (DeLuca *et al.* 2009; Kolb *et al.* 2009; Thies and Rillig 2009; Warnock *et al.* 2007). Biochar inoculated with rhizobia and arbuscular mycorrhizal (Thies and Rillig 2009) has been proposed for the reclamation of degraded lands (Blackwell *et al.* 2009) and may play an important role in the availability of water and nutrients in arid environments (Allen 2007) or in drastically disturbed soils where the soil biota has been destroyed.

Increased N_2O emissions have been identified following the application of nitrogen fertilizers, incorporation of crop residue and application of liquid organic wastes and biosolids in reclaimed lands (Palumbo *et al.* 2004) Biochar can be used to offset these N_2O emissions.

Ameliorating Toxicity Limiting Factors

Soil pH in disturbed lands is a function of the quantity, quality and activity of carbonaceous or pyritic overburden material (Akala and Lal 2001) or the nature of site specific management practices where land application occurs (Ganjegunte *et al.* 2008). Generally, disturbed lands lead to a lowering of pH values. Acidic conditions limit root growth and the establishment of plants (Shrestha and Lal 2007).

Soil buffering capacity allows for the reasonable stability in soil pH and determines the amount of other chemicals required to change soil pH. The availability of different functional groups (e.g. carboxylic, phenolic, acidic alcoholic, amine, amide) allows soil organic matter to buffer over a wide range of soil pH values (Krull *et al.* 2004). Soil organic matter maintains fairly stable pH values, despite acidifying factors and more acidic soils are better buffered than less acidic soils. Given the increase in carboxylic groups with time during biochar weathering, the buffering capacity of biochar is expected to be important in acidic soils associated with mine lands.

Smernik (2009) has suggested that biochar amended soils can be used to control the toxicity and movement of organic chemicals. Organic matter can also be used to stabilize toxic metals in soils (Palumbo *et al.* 2004). Soil organic matter has the greatest capacity and strength of bonding with most metals of any soil component (Krull *et al.* 2004) and those metals that bond strongly in organic matter (e.g. lead, copper) are most rapidly adsorbed and most slowly desorbed (McBride 1989). Absorption of metals occurs within amorphous soil organic matter (humic/fulvic substances, lignin), while more condensed components, including charcoal, contribute to the adsorption of metals (Krull *et al.* 2004). Tejada *et al.* (2007) showed that the addition of organic wastes with high humic acid concentrations is the most beneficial for remediation of lead impacted soils. Municipal biosolids combined with limestone or other high calcium carbonate equivalent residuals are being used to restore metal contaminated sites (Brown *et al.* 2009).

High lead sorption (93-100%) observed by Cao and Harris (2010) on a low specific surface area biochar from dairy-manure was attributed to precipitation with phosphate rather than direct adsorption. Modeling by Cao *et al.* (2009) confirmed this by showing that approximately 85% of the lead retention was due to phosphate precipitation while the remaining 15% was due to sorption. This work shows the importance of determining the biochar characteristics to address a specific issue.

Arid and semi-arid regions with low rainfall and high evapotranspiration rates are particularly prone to salinization (Uliana 2005). The development of oil and gas as well as coal-bed natural gas (also called coal-bed methane) produces large volumes of groundwater (referred to as produced water) required to recover either the oil or natural gas (Whittemore 1995; Zhao *et al.* 2009). Major concerns associated with these waters include salinity, sodicity and high carbonate/bicarbonate, and where applied to soils, result in significant increases in soluble salt accumulations over time (Ganjegunte *et al.* 2008) resulting in adverse soil physical and chemical conditions that restrict soil water movement (Vance *et al.* 2008).

Enhancing soil organic carbon is an important component in the reclamation of salt-affected soils. Organic amendments including manure, compost and farm byproducts have been added in conjunction with gypsum to increase biomass yield (Ansari 2008; Ghosh *et al.* 2009; Izaurralde, *et al.* 2001). To date biochar has not been investigated with this application. However, the properties of biochar described above would suggest that this is a promising application where produced water is used in land application programs, especially when combined with intensive fertilized irrigation programs where the biochar can be used to reduce fertilizer requirements and potentially offset other greenhouse gases.

The Role of Biochar in Sustainability during Disturbed Land Restoration

Sohi *et al.* (2009) has developed a spatial context for the use of biochar in an agricultural landscape that has similar implications for the resource industry. The resource sectors have adopted both industry-wide and company-specific sustainability practices, for which biochar may provide opportunities. While additional costs may be incurred with the use of biochar as a more intensive reclamation strategy, these may be offset with other sustainability targets, including carbon sequestration.

Factors to be considered include feedstock sources, manufacturing facility location, land use and application considerations.

Feedstock Sources

Mining land is commonly associated with either agricultural and forestry activities that can produce wastes that can act as a feedstock for a sustainable biochar production system (Lehmann *et al.* 2006). For example, Cao *et al.* (2009) have proposed that high-phosphorus animal waste has the potential as a feedstock for a phosphorus-rich fertilizer as well as for the mitigation of lead contaminated soil. Other biochar feedstocks that can be incorporated into the mining cycle include:

• Biomass cleared for operation and infrastructure at the mine site;
• Woody biomass weeds;
• Fuel mitigation in forests;
• Biomass production from the land application of produced or mine water; and
• Waste products from the mining operations e.g. wood pallets.

Facility Locations

The proximity of a pyrolysis facility to the feedstock is important in determining logistical and cost impacts (Sohi *et al.* 2009). The optimal position is to have a 'closed loop' scenario, i.e. the application of biochar in the same location that produces the feedstock. However, where mining operations are located in remote areas, transport costs may be prohibitive. Where possible to meet sustainability guidelines, the development of the closed loop approach is optimal. These may also provide opportunities for income generation within the local community, meeting social sustainability guidelines. Economic analyses are required to determine the most cost effective location for the facility when considering the transportation of feedstock and the finished product, especially if carbon sequestration standards are to be met.

While the focus of this paper has been on the application of biochar to soil, the other side of the pyrolysis process is the formation of an energy source. In remote locations, provided a sufficient and on-going feedstock is present, this is may also provide an opportunity to provide energy and/or heat to buildings at the mine site.

Application Considerations

Rates of biochar application over the landscape scale generally involved in disturbed land reclamation may be prohibitive. Glaser *et al.* (2001) estimated 250 ton/ha (100 ton/acre) to a depth of 1 meter (3.1 feet) where characteristic in the 'Terra Preta' soils. However, lower rates of 1-3 ton/ha (0.9-2.7 ton/ac) are predicted by Glaser *et al.* (2002) to be sufficient for significantly increasing production.

While the application of biochar over large areas can be cost-prohibitive (Blackwell *et al.* 2009), reclamation generally involves the re-application of topsoil and opportunities exist to incorporate biochar during the application phase or for the mixing of biochar with topsoil during the stripping and storing stage. If suitable biomass is removed during the mine clearing stage, this provides another opportunity for the generation of biochar and incorporation during topsoil removal. As heavy equipment is already utilized in various phases of the mine establishment and reclamation phases the incorporation of biochar into these processes would add value and not burden.

Shrestha and Lal (2007) found that the most of the soil organic carbon in reclaimed soils in Ohio was found in the upper 5 cm, however land use (hay, pasture, forest, agriculture) had a significant influence on deeper soil organic carbon concentrations. While current restoration techniques involve either surface spreading or the shallow incorporation of carbon amendments, deeper incorporation (up to 60 cm) will provide access to a much larger soil volume for rooting and provide a moisture reservoir in arid and semi-arid climates (Palumbo *et al.* 2004).

Additionally, the burial of biochar has also been considered as an option (Sohi *et al.* 2009). Where carbon sequestration is a priority, this option may be effective prior to mine pit backfilling and reclamation.

Grazing is a common post-reclamation land-use (Anderson *et al.* 2008; Bengson 1999). A potential integration of biochar is using the cattle to incorporate biochar into the soil simply as they graze. Additionally, the incorporated biochar may be used as an offset to the nitrates produced by the cattle. Bengson (1999) estimates that cattle excrete 30-65 lbs of green manure each day producing approximately 190 lbs of nitrogen and 60 lbs of phosphorus per acre. Urine patches in grazed pastures can be a dominant source of N_2O. Biochar has been proposed as a means to reduce the soil inorganic-N pool available for N_2O-producing mechanisms (Clough *et al.* 2010; Rondon *et al.* 2005; Van Zwieten *et al.* 2009) as well as methane sources (Van Zwieten *et al.* 2009). The influence of biochar on these non-CO_2 greenhouse gases is uncertain at this time. While Rondon *et al.* (2005) and Van Zwieten *et* *al.* (2009) reported a reduction in emissions, no significant reduction of the inorganic –N pool was been reported by Clough *et al.* (2010). Van Zwieten *et al.* (2009) attributes the specific characteristics of the biochar as influencing the activity of the microorganisms responsible for N transformations.

Carbon Sequestration

Carbon sequestration is essentially the process of transforming atmospheric CO_2 into biomass through photosynthesis and incorporation of biomass into soil as humus. Globally, soils have the capacity to draw substantial amounts of CO_2 from the atmosphere by photosynthesis in cropland, managed forest and grassland soils (Izaurralde *et al.* 2001). At a local and regional scale, increased adoption of land use management that incorporates multiple ecosystem services could deliver significant benefits.

The potential for soil to sequester carbon has been well documented (Izaurralde *et al.* 2001) and the storage of carbon in soils is hypothesized to depend on four main factors (Knops and Bradley 2009):

1. Organic matter inputs;
2. Organic matter decomposability;
3. The level of physical protection of organic matter in aggregates; and
4. The depth at which the organic matter is deposited.

The carbon content of spoil material is typically very low compared to undisturbed surface soils, therefore the potential for carbon sequestration is significant (Shrestha and Lal 2006), predominately through the development of soil horizons over long (decades) time periods. The low soil organic carbon in drastically disturbed soils can be enhanced by:

- Proper reclamation;
- Adoption of Best Management Practices;
- Improvement in soil fertility using integrated soil management technologies;
- Nutrient cycling by returning biomass to the soil; and
- Growing leguminous annuals or tree plants with potential for biological N2-fixation.

Soil organic carbon sequestration is focused on enhancing natural capacity of ecosystems to increase rates of organic matter input into soil in a form with long residence time (Post *et al.* 2004). Drastically disturbed soils are the ones with the high potential to sequester soil organic carbon at rates of 0.5 to 1.0 ton C/ha/yr and as high as 4 ton C/ha/yr (Shrestha and Lal 2006). Additionally, the most degraded sites have been shown to have the greatest response to any form of organic matter, including biochar (Kimetu *et al.* 2008).

Traditional reviews of the potential for terrestrial carbon sequestration have focused on agricultural, forestry and grassland. Negative externalities of such an approach include the competition for agricultural lands, decreased food and fiber production, increased consumer prices and the increased use of pesticides and herbicides in reduced tillage agriculture (Izaurralde *et al.* 2001). Palumbo *et al.* (2004) estimates that disturbed lands in the United States (1.4×10^8 ha) can account for a modest, yet significant carbon sequestration potential (11 PgC over 50 years). An evaluation by Sperow (2006) of carbon sequestration potential in East-Central mine lands of the United States indicated that current carbon sequestration potential represented between 0.3 -1% of the CO_2 emissions of the same region. Biochar may be able to increase the amount of offset emissions via the following mechanisms (Gaunt and Cowie 2009):

- Avoided emissions from conventional use of feedstock biomass;
- Stabilization of biomass carbon;
- Avoided emissions of N_2O and CH_4 from soil;
- Displaced fertilizer and agricultural inputs;
- Enhancement of agronomic efficiency and yield; and
- Fossil fuel displacement.

While the actual numbers for increased carbon sequestration from the use of biochar in the restoration of drastically disturbed lands are unknown at this time, it is anticipated that it will increase the numbers quoted above. While there is still no formal approach (approved methodology) for sequestering carbon through biochar, these techniques can be implemented immediately and provide a transition towards larger efforts moving forward.

Conclusions

Izaurralde *et al.* (2001) have noted that soil carbon sequestration is able to play a strategic role in GHG emission control. Compared with other proposals for the immediate removal of atmospheric CO_2, terrestrial sequestration techniques are well established, immediately deployable and known to have beneficial effects on the environment. The strategic use of biochar in disturbed lands is an important piece of this strategy. As has been shown above, biochar has the potential to increase productivity and mitigate several detrimental properties associated with disturbed land reclamation, it is not an unreasonable assumption that the addition of soil organic carbon in the form of biochar can be done without net cost to reclamation projects. Techniques for the reclamation of disturbed land are well established, and the incorporation of biochar in soils as another amendment can be easily adopted.

The evidence from both the study fog biochar application itself and the body of reclamation and restoration work would suggest that the application of biochar would be most effective in the reclamation of highly degraded sandy to clayey sandy soil types. Additionally 2% organic carbon appears to be the threshold at which significant changes to physical properties (e.g. soil structure, available water content) occur. Application rates if biochar with this criterion may have the most promising opportunities for the restoration of drastically disturbed landscapes.

However, no general application rate can be determined from the data available and requires testing for specific soil and plant conditions (Glaser *et al.* 2002). Palumbo et al (2004) recommended a program of systematic research to understand how interacting processes are expressed in various mineralogical, geochemical and hydrologic settings for the optimal application of biochar in disturbed land reclamation. This is especially true for the arid and semi-arid regions where mining is common and, to date, little biochar research has been undertaken (Blackwell *et al.* 2009). Additionally, appropriate carbon trading protocols are required for generating another income stream (or at minimum a process for entities to calculate a carbon impact number in order) for mining companies and land owners (Shrestha *et al.* 2009).

References

Akala VA, Lal R (2001) Soil Organic Carbon Pools and Sequestration Rates in Reclaimed Minesoils in Ohio. *Journal of Environmental Quality* 30, 2098-2104.

Albaladejo J, Lopez J, Boix-Fayos C, Barbera GG, Martinez-Mena M (2008) Long-term Effect of a Single Application of Organic Refuse on Carbon Sequestration and Soil Physical Properties *Journal of Environmental Quality* 37, 2093-2099.

Allen MF (2007) Mycorrhizal Fungi: Highways for Water and Nutrients in Arid Soils. *Vadose Zone Journal* 6, 291-297.

Amonette JE, Joseph S (2009) Characteristics of Biochar: Microchemical Properties. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 33-52. (Earthscan: London)

Anderson J, Ingram L, Stahl P (2008) Influence of reclamation management practices on microbial biomass carbon and soil organic carbon accumulation in semiarid lands of Wyoming. *Applied Soil Ecology* 40, 387-397.

Ansari AA (2008) Soil profile studies during bioremediation of sodic soils through the application of organic amendments (vermiwash, tillage, green manure, mulch earthworms and vermicompost). *World Journal of Agricultural Sciences* 4, 550-553.

Bauer A, Black AL (1994) Quantification of the Effect of Soil Organic Matter Content on Soil Productivity. *Soil Science Society America Journal* 58, 185-193.

Bendfeldt ES, Burger JA, Daniels WL (2001) Quality of Amended Mine Soils after Sixteen years. Soil Science Society America Journal 65, 1736-1744.

Bengson SA (1999) The use of livestock as a tool for reclamation of copper tailings in Southern Arizona. In 'Mining and Reclamation for the Next Millennium: Proceeding of the 16th Annual National Meeting of the American Society for Surface Mining and Reclamation.' pp. 704-706

Blackwell P, Reithmuller G, Collins M (2009) Biochar application to soil. In 'Biochar for Environmental Management'. (Eds J Lehmann and S Joseph) pp. 207-226. (Earthscan: London)

Brown S, Svendsen A, Henry C (2009) Restoration of High Zinc and Lead Tailings with Municipal Biosolids and Lime: A Field Study. *Journal of Environmental Quality* 38, 2189-2197.

Cao X, Harris W (2010) properties of dairy-manure-derived biochar pertinent to its potential use in remediation. *Bioresource Technology* 101, 5222-5228.

Cao X, Ma L, Gao B, Harris W (2009) Dairy-Manure derived biochar effectively sorbs lead and atrazine. *Environmental Science and Technology* 43, 3285-3291.

Chan K, Xu Z (2009) Biochar: Nutrient Properties and Their Enhancement. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 53-66. (Earthscan: London, UK)

Cheng C, Lehmann J, Engelhard MH (2008) Natural Oxidation of Black Carbon in Soils: Changes in Molecular Form and Surface Charge along a Climosequence. *Geochemica et Cosmochimica Acta* 72, 1598-1610.

Clough TJ, Bertram JE, Ray JL, Condron LM, O'Callaghan M, Sherlock RR, Wells NS (2010) Unweathered Wood Biochar Impact on Nitrous Oxide Emissions from a Bovine-Urine-Amended Pasture Soil. *Soil Science Society America Journal* 74, 852-860.

Day D, Evans RJ, Lee JW, Reicosky D (2005) Economical CO_2, SO_x, and NO_x Capture from Fossil-Fuel Utilization with Combined Renewable Hydrogen Production and Large-scale Carbon Sequestration. *Energy* 30, 2558-2579.

DeLuca TH, MacKenzie MD, Gundale MJ (2009) Biochar effects on soil nutrient transformations. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 251-270. (Earthscan: London)

Ganjegunte GK, King LA, Vance GF (2008) Cumulative Soil Chemistry Changes from Land Application of Saline-Sodic Waters. *Journal of Environmental Quality* 37, S-128-138.

Ganjegunte GK, Wick AF, Stahl P, Vance GF (2009) Accumulation and Composition of Total Organic Carbon in Reclaimed Coal Mine Lands. *Land Degradation and Development* 20, 156-175.

Gaunt J, Cowie A (2009) Biochar, Greenhouse Gas Accounting and Emissions Trading. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 317-340. (Earthscan: London)

Ghosh S, Lockwood P, Hulugalle N, Daniel H, Kristiansen P, Dodd K (2009) Changes in Properties of Sodic Australian Vertisols with Application of Organic Waste Products *Soil Science Society America Journal* 74, 153-160.

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

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility of Soils* 35, 219-230.

Hammes K, Schmidt M (2009) Changes of Biochar in Soil. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 169-182. (Earthscan: London, UK)

Izaurralde RC, Rosenberg NJ, Lal R (2001) Mitigation of Climatic Change by Soil Carbon Sequestration: Issues of Science, Monitoring, and Degraded Lands. *Advances in Agronomy* 70, 1-75.

Kimetu JM, Lehmann J, Ngoze SO, Mugendi DN, Kinyangi J, Riha SJ, Verchot L, Recha JW, Pell AN (2008) Reversibility of Soil Productivity Decline with Organic Matter of Differing Quality Along a Degradation Gradient. Ecosystems 11, 726-739.

Knops JMH, Bradley KL (2009) Soil Carbon and Nitrogen Accumulation and Vertical Distribution across a 74-Year Chronosequence. *Soil Science Society America Journal* 73, 2096-2104.

Kolb SE, Fermanich KJ, Dornbush ME (2009) Effect of Charcoal Quantity on Microbial Biomass and Activity in Temperate Soils. *Soil Science Society America Journal* 73, 1173-1181.

Krull ES, Skjemstad JO, Baldock JA (2004) 'Functions of Soil Organic Matter and the Effect on Soil Properties.' (Grains Research & Development Corporation)

Lehmann J, Czimczik C, Laird D, Sohi S (2009) Stability of biochar in soil. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 183-205. (Earthscan: London)

Lehmann J, da Silva JP, Steiner C, Nehls T, Zech W, Glaser B (2003) Nutrient availability and leaching in an archeological Anthrosol and a Ferrasol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil* 249, 343-357.

Lehmann J, Gaunt J, Rondon MA (2006) Bio-Char sequestration in terrestrial ecosystems - A Review. *Mitigation and Adaptation Strategies for Global Change* 11, 403-427.

Lehmann J, Joseph S (2009) Biochar for Environmental Management: An Introduction. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and J S.) pp. 1-12. (Earthscan: London, UK)

Major J, Steiner C, Downie A, Lehmann J (2009) Biochar Effects on Nutrient Leaching. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 271-287. (Eartscan: London)

McBride MB (1989) Reactions controlling heavy metal solubility in soils. *Advances in Soil Science* 10, 1-56.

Nguyen BT, Lehmann J, Kinyangi J, Smernik R, Riha SJ, Engelhard MH (2008) Long-term Black Carbon Dynamics in Cultivated Soil. *Biogeochemistry* 89, 295-308.

Palumbo AV, J.F. M, Amonette JE, Fisher LS, Wullshleger SD, Daniels WL (2004) Prospects for enhancing carbon sequestration and reclamation of degraded lands with fossil-fuel combustion by-products. *Advances in Environmental Research* 8, 425-438.

Post WM, Izaurralde RC, Jastrow JD, McCarl BA, Amonette JE, Bailey VL, Jardine PM, West TO, Zhou J (2004) Enhancement of Carbon Sequestration in US Soils. *BioScience* 54, 895-908.

Reed D (2007) Economic and societal benefits of soil carbon management: policy implications and recommendations. In 'Soil Carbon Management: Economic, Environmental and Societal Benefits.' (Eds JM Kimble, C Rice, D Reed, S Mooney, RF Follett and R Lal) pp. 13-43. (CRC Press: Boca Raton, FL)

Rondon MA, Ramirez JA, Lehmann J (2005) Greenhouse Gas Emissions Decrease with Charcoal Additions to Tropical Soils. In 'Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration'. Baltimore, MD p. 208

Saxton KE, Rawls WJ (2006) Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. *Soil Science Society America Journal* 70, 1569-1578.

Shrestha R, Lal R (2006) Ecosystem carbon budgeting and soil carbon sequestration in reclaimed mine soil. doi:10.1016/j.envint.2006.05.001. *Environment International* 32, 781-796.

Shrestha R, Ussiri DAN, Lal R (2009) Terrestrial Carbon Sequestration Potential in Reclaimed Mine Land Ecosystems to Mitigate the Greenhouse Effect. In 'Soil Carbon Sequestration and the Greenhouse Effect'. (Eds R Lal and RF Follett) pp. 321-346. (Soil Science Society of America: Madison, WI)

Shrestha RK, Lal R (2007) Soil Carbon and Nitrogen in 28-Year-Old Land Uses in Reclaimed Coal Mine Soils of Ohio. *Journal of Environmental Quality* 36, 1775-1783.

Smernik RJ (2009) Biochar and sorption of organic compounds. In 'Biochar and Environmental Management: Science and Technology.' (Eds J Lehmann and S Joseph) pp. 289-300. (Earthscan: London)

Sohi S, Lopez-Capel E, Krull ES, Bol R (2009) 'Biochar, climate change and soil: A review to guide future research.' CSIRO Land and Water Science Report 05/09.

Sperow M (2006) Carbon Sequestration Potential in Reclaimed Mine Sites in Seven East-Central States. *Journal of Environmental Quality* 35, 1428-1438.

Steiner C, Glaser B, Teixeira W, Lehmann J, Blum W, Zech W (2008) Nitrogen retention and plant uptake on a highly weathered central Amazonian Ferralsol amended with compost and charcoal. *Journal Plant Nutrition and Soil Science* 171, 893-899.

Tejada M, Hernandez MT, Garcia C (2007) Application of Two Organic Wastes in a Soil Polluted by Lead: Effects on the Soil Enzymatic Activities. *Journal of Environmental Quality* 36, 216-225.

Thies J, Rillig M (2009) Characteristics of Biochar: Biological Properties. In 'Biochar for Environmental Management: Science and Technology'. (Eds J Lehmann and S Joseph) pp. 85-106. (Earthscan: London, UK)

Uliana MW (2005) Identifying the source of saline groundwater contamination using geochemical data and modeling. *Environmental and Engineering Geoscience* 11, 107-123.

Van Zwieten L, Singh B, Joseph S, Cowie A, Chan K (2009) Biochar and emissions of non-CO_2 greenhouse gases from soil. In 'Biochar for Environmental Management. Science and Technology.' (Eds J Lehmann and S Joseph) pp. 227-249. (Earthscan: London)

Vance GF, King LA, Ganjegunte GK (2008) Soil and Plant Responses from Land Application of Saline-Sodic Waters: Implications of Management. *Journal of Environmental Quality* 37, S-139-148.

Warnock DD, Lehmann J, Kuyper TW, Rillig MC (2007) Mycorrhizal responses to biochar in soil - concepts and mechanisms. *Plant and Soil* 300, 9-20.

Whittemore DO (1995) Geochemical differentiation of oil and gas brine from saltwater sources contaminating water resources: case studies from Kansas and Oklahoma. *Environmental Geoscience* 2, 15-31.

Zhao H, Vance GF, Urynowicz MA, Gregory RW (2009) Integrated treatment process using a natural Wyoming clinoptilolite for remediating produced waters from coalbed natural gas operations. *Applied Clay Science* 42, 379-385.

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