**Article:** **Biochar: An Emerging Market Solution for Legacy Mine Reclamation and the Environment**

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### *I. Introduction: Biochar as a Market Solution to Mine Reclamation*

In this article, the authors propose that mining companies consider investigating the economic and ecological feasibility of biochar. Biochar is essentially charcoal. Preliminary research shows linkages between biochar and improvements in vegetative cover (eg. grasses), which effectively reduces erosion, run-off, and sedimentation in rivers and streams. Furthermore, biochar can sorb heavy metals—essentially holding them in place. Specifically, early results from field research on legacy mine reclamation sites indicate that adding biochar to affected soils leads to increases in pH and soil water content[1], characteristics which are linked to increased vegetative cover. Biochar has also been promoted for its potential to retain carbon and nitrogen, which may enhance soil productivity and improve carbon sequestration.[1] Preliminary scientific results suggest more systematic investigation is required to isolate variables, such as the inputs that are used to make the char[2] to determine combinations that would demonstrate the most favorable results at mine site reclamation sites.[3]

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[1] Bruno Glaser, Johannes Lehmann, and Wolfgang Zech. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – A review 35 Biol. Fertil. Soils 219 (2002).

[2] Not all biochar is the same! Feedstock and pyrolysis condition determine biochar properties. Biochar behavior in soils is strongly dependent on the specific biochar and soil properties. Wood-derived biochar pyrolyzed at high temperature will be optimal for carbon sequestration, while grass or animal waste derived biochar have higher pH and ashes and function better to improve soil fertility in poor, acidic soils. For more information about feedstocks for char, consult Catherine M.H. Keske, Greta G. Lohman and M. Francesca Cotrufo. Biochar in Colorado. Colorado State University Extension Publication (anticipated publication date, 2012). http://www.ext.colostate.edu/.

[3] Biochar Solutions. http://www.biocharsolutions.com/technology.html. Last accessed March 27, 2012.

In addition to reducing the environmental impacts from mining, there are economic opportunities for mining companies to establish a market for biochar production. If biochar is demonstrated to be a successful soil amendment at mine reclamation sites, mining companies could potentially expand biochar production for retail production for other applications, such as gardening, where niche retail markets have emerged. Biochar also shows potential for energy production and carbon sequestration, although even less research is available for these sectors. Development of biochar co-products could provide mining companies with economies of scope that would drive supplemental income. These complementary products could counter-balance the notorious boom-bust economic cycle of mining industry.[4]

Biochar could also be used in remediation of "legacy mine sites", inactive and abandoned mine sites (defined here as land which has been mined and is now being used for another purpose, or is orphaned, abandoned or derelict and in need of remedial work).[5] In the case of many legacy mines, the liable party either cannot be traced, or is unable to pay for the damages. As a result, the government frequently takes over remediation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).[6] However, CERCLA is frequently cited for cost inefficiency, even when "joint and severally liable" parties are found.[7] The availability of biochar could prove to be an effective, market-based solution for reducing

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[4] Graham A. Davis and John E. Tilton. The Resource Curse Natural Resources Forum 233 (2005).

[5] Rhys Worrall, David Neil, David Brereton, and David Mulligan. Towards a Sustainability Criteria and Indicators and Framework for Legacy Mine Land 17 (16) Journal of Cleaner Production 1426 (2009).

[6] Also known as "Superfund" or "CERCLA," 42 U.S.C. §§ 9601-9675.

[7] John E. Tilton. Mining Waste and The Polluter Pays Principle in the United States, p. 62-65 In Mining and the Environment: International Perspectives on Public Policy, Rodderick Eggert, Ed. (1994).

remediation costs under CERCLA, and would provide biochar producers a customer with considerable demand.

In summary, an investment in biochar capacity could prove to be profitable for mining industry companies looking to diversify their revenues sources, and reduce their vulnerability to environmental lawsuits. Development of a biochar market could result in a multitude of environmental and economic benefits, including increased vegetative cover, improvements in soil and water quality, economic diversification, the development of a profitable co-product, and improvements in mine remediation.

The paper is organized as follows: Section II provides a technical description of the bio-physical properties of biochar, and biochar as a proposed soil amendment. Section III summarizes preliminary research on the application of biochar for mine reclamation and at legacy mines. Section IV presents the authors original research and discusses economic observations of emerging biochar markets. Section IV concludes that mining companies, and the environment, might profit from investing in biochar capacity.

## *II. What Is Biochar?*

Biochar is essentially charcoal. Biochar is made from biomass that has been transformed through a process called pyrolysis. Pyrolysis is the process of heating (250-700 degrees C) a carbon substance in the absence of oxygen.[8] This process alters the biomass feedstock resulting in a charcoal-like substance, which, when used for environmental applications, is called biochar.[9] A wide variety of feedstocks can be used to make biochar, including sawmill scraps and wood chips, municipal waste and compost material, animal manure, yard waste as well as compost materials, and forest residues.

Regardless of the variable characteristics of differing types of biochar, evidence suggests that in general, biochar is very stable and persistent in soils. For example, various forms of charred substances have been used for millennia in tropical Amazon soils, referred to as Terra Petra. Recently, researchers have found biochar remnants in tropical Amazon climates that date back thousands of years[10]. These findings provide evidence to suggest that biochar, and consequently the numerous environmental benefits of biochar, are relatively long-lasting in the environment.

However, there are aspects of biochar, particularly the way in which it interacts in varying environments with respect to soil biogeochemical processes, which are not fully

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[8] George W. Huber, Sara Iborra, Avelina Corma. Synthesis of transportation fuels from biomass: chemistry, catalysts, and engineering 106 Chem. Rev. 4044 (2006).

[9] Johannes Lehmann and Stephen Joseph. Biochar for Environmental Management (2009).

[10] See generally: Wim Sombroek, Maria de Lourdes Ruivo, Philip Fearnside, Bruno Glaser, and Johannes Lehmann. Amazonian Dark Earths as Carbon Stores and Sinks In: Johannes Lehmann, Derse C. Kern, Bruno Glaser, and William I. Woods (Eds). Amazonian Dark Earths: origin, properties, management (2003).

See also Peter Winsley, Biochar and bioenergy production for climate change mitigation 64(1) New Zealand Science Review (2007).

understood. The conversion process including the feedstock selection and the time and temperature of the pyrolysis process can alter the end product and thus result in varying ecological effects when the char is applied as a soil amendment.[11] Furthermore, factors such as the climate and soil conditions as well as the biochar application rate also influence interactions.

Each type of biomass has a different carbon structure which influences the chemical composition of the end char product and consequently affects the mineralization rate of the char.[12] Additionally, the time and temperature of the pyrolysis process influence the physical dimensions of the char, in terms of particle size, surface area, and porosity, and will accordingly further influence the rate at which biochar will be mineralized within.[13] Finally, environmental conditions such as climate, soil pH, initial nutrient and mineral content and various other soil characteristics affects the way in which biochar interacts in the environment. Although each of these factors influence biochar interactions on a micro level, various studies have shown that overall soil productivity and fertility increase with the addition of biochar, regardless of feedstock, processing method, or environmental factors.[14]

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[11] Johannes Lehmann, Matthius Rillig, Janice Thies, Caroline Masiello, William Hockaday, and David Crowely. Biochar effects on soil biota – A review. 43 Soil Biology and Biochemistry 1812 (2011).

[12] Johannes Lehmann. Bio-energy in the Black 5(7) Frontiers in Ecology and the Environment. 381 (2007).

[13] Franciscus Verheijen, Simon Lee Jeffery, Aana Catarina Bastos, Marijn van der Velde, and Iason Diafas. Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. JRC Scientific and Technical Reports (2010).

[14] Johannes Lehmann and Marco Rondon, Biochar soil management on highly weathered soils in the humid tropics. In: Uphoff N (Ed). Biological approaches to sustainable soil systems. (2006).

Biochar is also recognized as a method to mitigate climate change through its ability to capture carbon, and reduce greenhouse gas (e.g. $N_2O$) emissions. Any plant naturally sequesters carbon in its biomass as a living organism. When this feedstock is pyrolyzed, 30-40% of the biomass remains in the char. Biochar is a very stable compound and when it is incorporated into soils can remain there for hundreds of years. Therefore, biochar is considered a ‘carbon sink’. As a result, biochar has recently received attention in the research community, and consequently in the media, as a way to mitigate global climate change.[15] Legal scholars have also advocated that biochar demonstrates potential for carbon sequestration policies.[16] As research continues, further potential benefits of biochar have been proposed including its value as a soil amendment that can preserve and restore soil fertility,[17] as well as to produce energy in the form of heat and electricity.[18]

For the purposes of this paper, the focus is on the benefits of biochar that affect soils, and particularly soils affected by mining operations.

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[15] Supra note 12. Also see Johannes Lehmann. A handful of carbon. *447* (7141), Nature 143 (2007); J. Gaunt and Johannes Lehmann. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production 42(11) Environ. Sci. Technol. 4152 (2008).

[16] Darrell A. Fruth and Joseph A. Ponzi. Adjusting Carbon Management Policies to Encourage Renewable, Net-Negative Projects Such as Biochar Sequestration 36 William Mitchell Law Review 992 (2010).

[17] Supra note 13.

[18] C.Z. Wu, H.U.A. Huang, S.P. Zheng, X.L Yin. An economical analysis of biomass gasification and power generation in China 83 Bioresource Technology 65 (2002).

**III. Biochar as a Soil Amendment for Mine Reclamation and Legacy Mines**

Biochar shows promise for soil reclamation and mining remediation due to its sorption characteristics and relatively high pH, which have been linked to quicker and more effective re-establishment of vegetative cover.[19] Preliminary results indicate that biochar sorbs heavy metals from legacy mines, thus "capturing" the metals, theoretically reducing toxic run-off, and improving water quality.

These findings show promise for addressing a far-reaching and expensive environmental problem. Legal scholars have noted that inactive and abandoned mine sites are among one of the worst contributors to soil erosion and poor environmental quality because the environmental effects are long-lasting well after the mine has closed.[20] Usually the responsible, often transient, party cannot be identified or held accountable for damage that was done long ago, or for production practices that were, at the time, considered standard.[21] When CERCLA takes over remediation of the sites, the result is typically costly, slow moving, and with questionable environmental improvements.[22] Development of a commercial product that could successfully re-establish vegetation and sorb minerals from legacy mine sites could potentially reduce

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[19] L. Beesley et al. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils 159Environmental Pollution 3269-3282 (2011).

[20] See Lynn M. Kornfeld. Reclamation of Inactive and Abandoned Hardrock Mine Sites: Remining and Liability under CERCLA and the CWA. 69 U. Colo. L. Rev. 597 (1998). See also A. Rubenstein, A. Brooke, and David Winkowski. A Mine Is a Terrible Thing to Waste: Past, Present and Future Reclamation Efforts to Correct the Environmentally Damaging Effects of Coal Mines 13 Vill. Envtl. L.J. 189 (2002).

[21] Supra note 7.

[22] Supra note 7.

taxpayer dollars associated with remediation of environmental damages, while providing revenues to the commercial industry.

Legacy mines elevate concentrations of potentially toxic elements such as silver, lead, copper, and zinc that frequently lead to increases in soil mineralization and waterway acidification.[23] For example, in the Animas River watershed in Southwestern Colorado, mining has left elevated concentrations of these minerals. In addition to effects on in-situ soil and surface water, the redistribution of these mineralized soils through water erosion processes can affect soil and waterways on a regional basis, greatly increasing the spatial scope of the resulting environmental impact. According to the U.S. Geological Survey, more than 40 percent of the watersheds within (or west of) the Rocky Mountains have headwater streams affected by historical hard-rock mining that is thought to represent a potential threat to human and ecosystem health.[24]

It has been well documented that vegetation plays a key role in reducing soil erosion and runoff [25] through intercepting rainfall[26] and surface water runoff[27], and by stabilizing soils with roots.[28]

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[23] Stanley Church, Paul von Guerard, Susan Finger. Summary and Conclusions from Investigation of the Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado. Chapter A of Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado. Professional Paper 1651, U.S. Geological Survey. http://pubs.usgs.gov/pp/1651/downloads/front.pdf. Last accessed March 29, 2012.

[24] Supra note 22.

[25] See Henry Elwell and Michael Stocking. Vegetal cover to estimate soil erosion hazard in Rhodesia 15 Geoderma 61–70 (1976); Walter H. Wischmeier and Dwight D. Smith. Predicting rainfall erosion losses. A guide to conservation planning. *USDA agricultural handbook 537*. U.S. Department of Agriculture, Washington, D.C. (1978).

A number of studies have extrapolated this relationship between vegetation and soil erosion and runoff to anthropogenically-disturbed lands such as mine reclamation sites.  In studying vegetation succession and establishment in reclaimed mining areas, results show that plant establishment is inversely related to soil erosion[29] and that there is a direct relationship between plant performance and soil erosion rates.[30]

The potential for soil erosion is perpetuated through the lack of vegetative cover in these areas as a result of the acidic and inhospitable soil conditions that prevent the establishment of vegetation.   Plant establishment can be additionally inhibited, and thus erosion can be further compounded by environmental factors.  For example, Leadville, Colorado has a renowned, colorful mining history dating back to the early 1860s.  Leadville is also established at an alpine elevation of 10,000 feet above sea level, where the climatic conditions are harsh and variable, the growing season is shortened, and further adverse physical conditions lead to challenges in

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[26] See John M. Tromble.  Water interception by two arid land shrubs 15 *Journal of Arid Environments* 65–70 (1987); Jose Cabezas, P. Vaquero and Jose Escudero.  Valoración de las lluvias interceptadas por especies de matorral dotadas de distintas estrategias estructurales 5 *Ecología* 163–171 (1991).

[27] Gerardo Sánchez and Juan Puigdefábregas.  Interactions between plant growth and sediment movement in semi-arid slopes. 9 *Geomorphology*  243–260 (1994);  Ester Bochet, and Patricio García-Fayos. Factors Controlling Vegetation Establishment and Water Erosion on Motorway Slopes in Valencia, Spain 12 Restoration Ecology166–174 (2004).

[28] Supra note 27.

[29] Mariano Moreno-de las Heras, Jose Nicolau and Tiscar Espigares. Vegetation succession in reclaimed coal-mining slopes in a Mediterranean-dry environment 32 Ecological Engineering 168-178 (2008).

[30] Tiscar Espigares, Mariano Moreno-de las Heras, and Jose Nicolau, Jose. Performance of Vegetation in Reclaimed Slopes Affected by Soil Erosion 19 Restoration Ecology 35–44 (2011).

establishing vegetation.[31] However, even in complex high elevation environments, the sorption characteristics of biochar have been shown to decrease the leachate and heavy metal concentrations which in turn may improve water quality and consequently increase plant establishment in these rugged areas.[32]

Clearly, the ecological issues that result from mining operations are complex. Environmental consequences such as soil mineralization, erosion, compaction, and factors that render soils inhospitable to plant growth, are often compounded by physical location. However, if soil health (and particularly acidification in hard rock mining situations) could be ameliorated, the consequential ecological problems could be pared down, and the negative environmental feedback loop between acidic soils, erosion, and plant establishment could be reduced. Thus, researchers have turned to biochar to study its impacts on mine reclamation sites that present low pH, nutrient devoid soils with a high propensity for erosion.

In summary, when it is incorporated into soils, biochar can increase the soil organic carbon levels, and improve the fertility and structural stability of the soil, thus reducing soil erosion, water sedimentation, and run-off. [33] Due to the absorption capacity, high surface area, and the porous nature of biochar, nutrient and water retention is increased. There is an additional

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[31] Greta G. Lohman, Catherine M.H. Keske, and Eugene F. Kelly. Environmental Impacts from Recreation on Colorado Fourteeners 10 (2011).

[32] Chris Peltz, Koren Nydick, Gretchen Fitzgerald, and Cathleen Zillich. Biochar for soil remediation on abandoned mine lands. Poster Presented at the Geological Society of America Meeting. (2010).

[33] Daniel D. Warnock, Johannes Lehmann, ThomasW. Kuyper, Matthuis.C. Rillig. Mycorrhizal responses to biochar in soil – concepts and mechanisms 300 Plant Soil 9 (2007).

increase in sorption of organic contaminants.[34] Although the properties of biochar have potential benefits for many soils and locations, much of the current research has been focused on hard rock mining sites in which soil mineralization and soil water acidification is the dominant environmental issue.[35] As follows is a summary of two case studies of the use of biochar on legacy mine sites.

*Biochar Case Studies*

The Mountain Studies Institute, located in Southwestern Colorado in the San Juan Mountains, has spent several years testing biochar and soil interactions at abandoned mine sites.[36] The purpose of their 2010 study was to determine if biochar additions would result in: 1) increased vegetative cover and above ground biomass; 2) increased soil water holding capacity; 3) reduced soil leachate concentrations, specifically for arsenic, cadmium, copper, molybdenum, nickel, lead and zinc.

Field sites were located near Silverton, Colorado, at elevations of 2,800 to 3,700 meters, with soils ranging from pure rock waste to partially reclaimed soils, as well as acidic low pH soils and non-acid alkaline soils. A comparative study of the effects on water holding capacity, vegetation establishment and growth, as well as soil leachate chemistry was conducted for both biochar and straw compost in the summer of 2010. Biochar was purchased from Biochar

[34] Supra note 18.
[35] Supra note 29.
[36] Supra note 30.

Solutions from Golden, Colorado, made of Colorado lodge pole pine feedstock that had been infested with mountain pine beetle.[37]

Findings showed that, with the addition of 30% biochar by volume, water holding capacity increased by 90-180% in all soils. When compared to seeding alone, vegetative cover increased by 240% when biochar was added to acidic soils with an additional 192% increase in overall measureable biomass. However, in the alkaline soils (the control condition), no difference in vegetative cover was observed. This indicates that the mechanism driving the increase in vegetative cover can be linked to the increase in pH in the acidic soils, driven by the biochar addition. Additionally, seed emergence increased in number, at a faster rate, and with longer sprouts in biochar amended soils. Soil leachate results were mixed, with some heavy metal concentrations increasing (copper) while others decreased (aluminum and iron), while the remaining concentrations showed no change overall.

Although many questions remain unanswered by this study, it serves to provide evidence that biochar does have desirable characteristics which may be useful for remediating acidic soils affected by mining operations. As shown by the Peltz et al. study, specifically, the increase in pH as a result of biochar additions may be highly linked to increases in vegetative cover for acidic soils, which could in-turn decrease soil erosion. Additionally, decreases in leachate concentration, although documented as minimal in this study, encourage further investigation into the potential for biochar to actually trap and contain these minerals, decreasing the overall presence within the soil profile.

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[37] Biochar Solutions Website: http://www.biocharsolutions.com/team.html. Last accessed March 29, 2012.

A similar study was undertaken in Northeastern Italy in 2009.[38] The Raibl Mine, which produced primarily lead and zinc, had been mined for centuries with minimal environmental protection policies, until operations ceased in 1991. The 2009 study was focused on determining whether biochar amendments to the soil could influence substrate characteristics and aid in plant establishment and growth. Various biochar application rates of 0%, 1%, 5%, and 10% were established to test whether differences in biochar amounts would lead to observed differences in soil characteristics. Findings showed that leachabililty was reduced for some of the pollutants, and a decrease in bioavailability was shown for copper, lead, and zinc. Furthermore, water retention and pH increased for all application rates. Once again, this study serves to provide evidence of the potential benefits of biochar in mine reclamation. However, the researchers caution that variables exist with regards to feedstock selection, site selection and project scale – each of which can impact the outcome of the biochar interactions.

Although the case studies suggest that biochar has a clear potential for reducing soil contaminants, more work is needed to understand how biochar may interact with other soil amendments. There is more work to be done across various landscapes and soil types in order to fully understand the environmental interactions with biochar. Furthermore, there is a lack of long-term field data to support extrapolations of current research. For example, the Hope Mine outside of Aspen, Colorado has received wide media attention as several stakeholders have worked to establish biochar field trials over the last several years. Preliminary observational data

[38] Guido Fellet, L. Marchiol, Gemini Delle Vedove, Alessandro Peressotti. Application of biochar on mine tailings: Effects and perspectives for land reclamation 83 Chemosphere 1262 (2011).

suggests that vegetation establishment is increasing.[39] However, the relatively short time span of this project and similar projects does not yet provide sufficient evidence to make arguments for the long-term implications of biochar amendments. One proposal for the Appalachian region outlines a long-term approach which applies "ecological principles to the healing of the landscape and the formations of an economy based on natural resources and renewable energy."[40] This proposal would in-part utilize biochar to reestablish ecosystem health but as yet is in the early stages of development.

*Laboratory Results*

The previously presented studies were done in-situ at historic mine sites. However, much of the research conducted on biochar is done in the lab. For example, Uchimaya et al.[41] tested biochar derived from cottonseed hulls that was pyrolized at four temperatures--350, 500, 650 and 800 degrees Celsius. These chars were later applied to a Norfolk (fine-loamy, well drained) soil contaminated with high concentrations of soluble lead, cadmium, copper and nickel, which are commonly found at mine sites. Reductions in soluble heavy metal concentrations were observed overall for each char variation, with the lowest temperature char producing the greatest reduction in concentration, ranging from a decrease of approximately 30-300 micrometers across

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[39] April Reese. Pilot biochar project puts wood waste to work cleaning up mines. Land Letter, The Natural Resources Weekly Report (April 2011).

[40] J Todd, S. Doshi, A. McInnis. 2010. Beyond Coal: A Resilient New Economic for Appalachia 1(4) Solutions 45-52 http://www.thewsolutionsjournal.com/node/706. Last accessed April 3, 2012.

[41] Minori Uchimiya, Lynda Wartelle, K. Klasson, K. Thomas, Chanel Fortier, and Isabel Lima. Influence of Pyrolysis Temperature on Biochar Property and Function as a Heavy Metal Sorbent in Soil 59(6) *J. Agric. Food Chem.* 2501 (2011).

treatments. Additionally, an increase in pH was observed for all chars with the exception of the highest temperature derived char. The pH was shifted from an acidic 5.6 to neutral and alkaline ranges. This study addresses the need to better understand the interactions between biochar production processes and the resulting effect within the environment. Overall, the results align with previous studies, suggesting that biochar may be a successful tool in soil remediation processes.

Preliminary findings from lab experiments at Colorado State University, however, show that the carbon sink capacity of biochar (defined as the time it remains in soil before being respired by microbes and returned back to the atmosphere as $CO_2$), may also depend on the content of soil organic matter. After 606 days of incubation under optimum conditions, only 0.6% of the biochar had been respired from a carbon-rich agricultural soil (1.5% carbon) while 4.5% of the carbon in biochar was mineralized in a steppe soil (0.7% carbon).[42]

These findings and similar studies provide evidence to support the proposed benefits of biochar as a long-term carbon sink, a beneficial soil amendment, as well as a soil remediation tool.

***IV. The Emerging Market for Biochar in Legacy Mining***

Although there remains a need to assess the interaction and stability of biochar in different types of soils, ecological environments, and climates, there are considerable financial incentives for mining companies to invest in developing biochar capacity. That is, any company

[42] Maria Francesca Cotrufo. Interactive effects of biochar addition rates and soil type on black C losses as $CO_2$ and sequestration in different soil organic matter fractions. ASA-CSSA-SSSA annual meeting (2011).

that masters its ability to use biochar for reclamation on its own properties will find a ready market to do the same at other mine sites. This could lead to a rapid expansion of the biochar industry, as environmental agencies would likely have an interest in purchasing the product for legacy mine reclamation, and other private mining companies would also likely see the environmental benefits and purchase the product for their own sites.

A commercial biochar market has begun to develop in the U.S., despite the fact that scientific results are only emerging and primarily confined to laboratories and experimental field sites. Preliminary evidence suggests that biochar in the continental U.S. is primarily being sold for mine reclamation purposes. Once the effectiveness of biochar in mine remediation is better established, there could be considerable market demand for this product in the U.S., as well as internationally. The Bureau of Land Management estimates that as of February 23, 2011, there were approximately 31,000 abandoned mine sites on public lands alone. Approximately 25% sites do not currently have a remediation plan in place, and the remaining 75% require further remediation. [43]

In a series of 33 qualitative research interviews in 2011 with biochar purchasers, the majority of char was sold for mine reclamation applications and experimental forest research

[43] Bureau of Land Management. Abandoned Mine Lands. http://www.blm.gov/wo/st/en/prog/more/Abandoned_Mine_Lands.html. Last Accessed March 29, 2012.

conducted by government agencies and entrepreneurs. Pine wood chips comprised the typical feedstock, and the average order was approximately 6,400 lbs.[44]

Despite the fact that outcomes and correlations between various biochar parameters are only beginning to emerge, there appears to be considerable enthusiasm and "buzz" about potential environmental biochar benefits and commercial production,[45] As is not uncommon in a fledgling, emerging market,[46] there is an apparent race between the physical scientists to document and quantify the bio-physical impacts of biochar on soil chemistry and the entrepreneurs to promote a product that yields uncertain bio-physical outcomes. At this writing, the authors have identified 13 commercial biochar manufactures in the U.S. The majority of the manufacturers are located either in mountainous regions like Colorado or West Virginia, or in tropical regions.[47]

In Hawaii and Florida biochar has been used with anecdotal success for gardening, where the low pH levels of the tropical, weathered soils require soil amendment. Biochar retail prices

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[44] Catherine M.H. Keske, and Greta G. Lohman. Biochar: An Economic Assessment of the Viability in the State of Colorado. Poster Presentation at Colorado State University Clean Energy Supercluster Annual Meeting. April 20, 2011. Research results based upon telephone interviews gathered through research funded by the Colorado State University Clean Energy Supercluster, 2010-2011.

[45] Marc Gunther. Biochar: Too Good to Be True? June 26, 2011. http://www.marcgunther.com/2011/06/26/biochar-too-good-to-be-true/. Last Accessed March 28, 2011.

[46] Catherine M. Keske, Dana L. Hoag, and Christopher T. Bastian. Economic efficiency in emerging markets: the case of conservation easements 8(1) Western Economics Forum, 7 (2009).

[47] Supra note 44.

at \$22.99-\$24.99/$ft^3$ in Hawaii[48] and approximately \$28/$ft^3$ -\$32/$ft^3$ biochar in Florida [49] are based upon relatively small packages and appear to be distributed for gardening and household use. Prices are similar in western states like Colorado where biochar[50] is typically sold in larger bulk sizes at \$250/$yard^3$, and in Idaho at \$350/$yard^3$.[51] As previously stated, distribution in the western U.S. appears to be limited to mine reclamation sites and governmental agencies, rather than nurseries.

A survey by the authors of 33 nurseries along the Front Range including Fort Collins, Denver, Boulder and Golden confirmed that biochar is not currently available on the commercial market in the state and is not yet a widely recognized product in the agricultural, horticultural and gardening sectors in Colorado.[52] However, as demonstrated by the Hawaii market, there could be considerable interest in the gardening sector if biochar is shown to be an effective soil amendment. Thus, with emerging research showing effectiveness in mine reclamation, there could be considerable economic rewards to develop biochar as a co-product for mine reclamation, as well as for a soil amendment for gardening.

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[48] Supra note 44.

[49] Waste to Energy Solutions, Inc. http://wesionline.com/index_files/Page512.htm. Last accessed March 27, 2012.

[50] There are nine feet within a cubic yard, thus \$28/$ft.^3$ *9= \$252, which is the approximate price for which biochar is being sold in Colorado. At this writing Biochar Solutions appears to be on of two manufacturing sources that are also distributing biochar commercially in Colorado. http://www.biocharsolutions.com/the-network.html

[51] Personal communication with Dr. Dan McCollum, U.S.D.A. Forest Service Research Economist, USDA Forest Service Rocky Mountain Research Station. January 20, 2012.

[52] Supra note 44.

Producers who are the first to develop and market a product—commonly known as the "first mover" advantage—can achieve high profits from overcoming the learning curve quickly compared to others who enter the market. If producers keep the information proprietary to keep ahead of the competition, they can develop a low cost production advantage that yields higher profit margins. [53] Mining companies, particularly those located in forested regions, could develop the first mover advantage from establishing and developing biochar as a soil amendment for mining, as well as gardening and other agricultural uses. For example, in the case of Colorado, biochar feedstock from pine beetle invested trees could be particularly cost effective, if the biochar production takes place near the mine remediation site. The proximity of a pyrolysis facility to the feedstock is important in determining logistical impacts and reducing costs.[54] In the western United States where wildfire prevention and mitigation is a top environmental and safety priority of the U.S.D.A Forest Service, removal of thousands acres of dead trees killed by pine beetle infestation could serve multiple environmental goals.[55] Finding a commercial use for the dead trees (that must nonetheless be removed) presents an inherently sustainable system, economically, as well as environmentally; as the trees would otherwise like

[53] David B. Lieberman and David B. Montgomery. First Mover Advantage. Stanford Business Research Paper 969. (1987). https://gsbapps.stanford.edu/researchpapers/library/RP969.pdf. Last Accessed March 29, 2012.

[54] Saran Sohi, Elisa Lopez-Capel, EvelynS. Krull, and Roland Bol. Biochar, climate change and soil: A review to guide future research. CSIRO Land and Water Science Report May 2009.

[55] U.S.D.A U.S. Forest Service. Western Bark Beetle Strategy: Human Safety, Recovery and Resiliency U.S. Forest Service. July 11, 2011 Report. http://www.fs.fed.us/publications/bark-beetle/bark-beetle-strategy-appendices.pdf. Last Accessed March 29, 2012.

be disposed through controlled burning and large amounts of carbon dioxide would subsequently be released into the atmosphere.[56]

Development of a biochar industry in mining regions might also diversify economic revenues from energy and mineral extraction industries, which are known for economic volatility.[57] For example, extraction economies, including Colorado's, were hit relatively hard by the economic recession.[58] The economic boom-bust cycles associated with extraction are driven by fluctuations in prices and spending leakages that result from high rates of commodity exportation. When an economic structure is heavily export-based, other sectors within the economy may be under-developed, creating an over-reliance on one industry, commonly known as the "Dutch Disease".[59] The exportation of energy and minerals, combined with the often temporary workforce, frequently does not generate sustainable regional spending multipliers. The combination of commodity price volatility and an undiversified, extraction-based economy can result in a deep economic retraction. Economic diversification is a key component of achieving economic stability in these resource-based economies.[60] Development of a biochar co-

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[56] U.S.-Focused Biochar Report. Assessment of Biochar's Benefits for the United States of America.
http://www.biocharsolutions.com/uploads/3/1/6/8/3168871/biochar_in_reclamation.pdf

[57] Supra note 4.

[58] John B. Loomis, J.B. and Catherine M.H. Keske. Did the great recession reduce visitor spending and willingness to pay for nature-based recreation? Evidence from 2006 and 2009, 30(2) Contemporary Economic Policy 2012.

[59] Graham A. Davis. Learning to Love the Dutch Disease: Evidence from the Mineral Economies. 23(10) World Development 1765 (1995).

[60] Supra notes 4 and 59.

product could diversify these resource based economies, particularly if the product proves beneficial as a soil amendment for gardening and agriculture, or if damages from greenhouse gas emissions are monetized, as is predicted.[61] Some research has shown that biochar production shows promise for energy production, which could potentially add another dimension of sustainability in rural economies, and have the potential to reduce energy costs.[62]

As shown in Figure 1, in order to establish a predictable, stable, and profitable commercial biochar market, several supply chain variables must be controlled. These variables include controlling transportation costs, establishing distribution and application procedures, and securing available consistent feedstock sources. To grow the demand side of the market, there must be a scientific understanding of the interactions between the end biochar product and soil conditions, which are summarized in Figure 1.

In summary, a financial investment by the mining industry into biochar research could prove financially lucrative by establishing first mover advantage. Biochar could also be produced and supplied for legacy mine reclamation, resulting in a multitude of environmental

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[61] Catherine M.H. Keske, Samuel Evans, and Terrence Iverson Total Cost Electricity Pricing: A Market Solution for Increasingly Rigorous Environmental Standards 25(2) The Electricity Journal 7 (2012).

[62] The biochar production process can result in, depending on adjustable variables in the pyrolysis process, two co-products – heat and bio-oil. Supra note 17. The amount generated of these co-products varies with adjustments in temperature of the pyrolysis process, and either production of char or co-products can be optimized depending on the desired outcome. However, if generated, these products can be captured and utilized either at the production site to power and heat the facilities there, or the products can be sold back to the utility company to be used on the grid. At this point, utilizing these products is not wide-spread among biochar producing operations, but as production increases and expands the feasibility and implementation of these options is expected to increase. See also A. Faaij. Modern Biomass Conversion Technologies 11 Mitigation and Adaptation Strategies for Global Change 343 (2005).

benefits. There is an emerging level of enthusiasm surrounding biochar, and there is the potential for biochar to bolster regional economic development, in particular in rural areas, by creating a valuable product that can be made from forest waste products. In summary, biochar presents a market solution for mine reclamation and the environment.

**Figure 1.**