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BIOCHAR LITERATURE REVIEW

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1 INTRODUCTION

Biochar is the product of pyrolysis which is the thermal decomposition of biomass in an oxygen-poor environment. It has become a research topic of increasing interest in recent years due to its potential to mitigate greenhouse gas emissions while providing numerous co-benefits. Many scientific studies have found biochar to increase plant growth, help treat contaminated sites, and offset greenhouse gas emissions. In recent years the interest in using biochar in the Yukon has been growing. While the benefits of biochar have been well assessed in other countries there was some question about its uses in a Yukon setting. The purpose of this literature review is to help both Yukon researchers and the general public determine how biochar may be used for the benefit of Yukoners.. For example, biochar can be mixed with soil to increase the soil's carbon content. This is useful here in the Yukon, as our soils are generally carbon-deficient. Biochar helps retain moisture in the soil, a real benefit with Yukon's dry climate. Biochar also promotes healthy microbial growth needed for good soil, prevents nutrients from being leached out of the soil, reduces the amount of fertilizer required, beneficially alters, and increases crop yields when used correctly. These are all things that can help make agriculture more viable in the Yukon.

Biochar can be used as a fuel for home heating. It is seen as a better fuel than the softwood used in the Yukon in fireplaces and woodstoves, as biochar produces very little smoke. Because biochar emissions are low, there may be potential to reduce wood smoke problems in the Yukon. The gas produced from biochar production can be used to fire a kiln to produce thermally modified wood, which is rot and termite resistant, and light in weight. Thermally modified wood is already a commercial product and could become more common. There can be some synergy if biochar and thermally modified wood are produced together.

The production of biochar could be used as a way to dispose of highway construction slash (wood waste from trees) without wasting the slash by burning it, and without the attendant air quality concerns and complaints.

The current concerns about ways to reduce greenhouse gas emissions helped spur more interest in biochar and increased awareness of its other benefits as well. It is hoped that the information in this literature review on the research that has already been done will provide inspiration for further research that leads to biochar being used to its full potential here in the North..

2 BIOCHAR

Not all biochar is alike. The process conditions in biochar production and the type of biomass used have significant effects on biochar's end properties. These properties can vary in pH, heavy metal content, moisture, surface structure, and size, and do so to a very wide degree. Also, the amount of syngas and bio-oils produced in biochar production varies according to process conditions.

Currently, research and interest in biochar and pyrolysis is growing. It may be possible to produce biochar, use it to sequester carbon and improve soil conditions, while at the same time producing energy from the process. This energy could be used for creating products such as thermally modified wood[1], heat, or electricity. While this may be true, there are always limits to any method, which are explored in the literature reviewed below.

For the Reader in a hurry, section 3.2 provides a short list of a few significant publications and websites particularly worth reading.

2.1 PYROLYSIS

Biochar is produced through pyrolysis, which can use many different biomass feedstocks, each feedstock producing a biochar with different properties. A feedstock produced from willow may be more porous or have a higher pH than a feedstock produced from pine. Bio-oil, syngas, heat, and biochar, or combinations of these products can be produced using pyrolysis.

Syngas is a combustible gas containing carbon dioxide (CO_2), carbon monoxide (CO), hydrogen gas (H_2), methane (CH_4), and water (H_2O), trace amounts of higher hydrocarbons, inert gases present in the gasification agent, various contaminants such as small char particles, ash, and tars (Belgiorno. 2003. p 1). Process conditions can be optimized to produce syngas alone but syngas will always be one of the by-products of pyrolysis.

Bio-oil is a by-product of pyrolysis that has the potential to produce second-generation transportation fuels such as ethanol, green gasoline and green diesel. With the rapid advance of thermochemical sciences, it is expected that within 10 years we may see rural bio-oil refineries able to produce bio-oils compatible with existing oil refineries. These oils will support the current green fuel and chemical production industries. (Methods for Producing Biochar and Advanced Biofuels in Washington State. 2011. p iv)

Some of the potential uses of biochar production are highlighted below. All the potential uses for biochar are linked together. If biochar is used to mitigate GHG emissions it can also be used to improve soil while at the same time producing energy while using waste as a feedstock. This process can be optimized for each use.

[1] See appendix 1

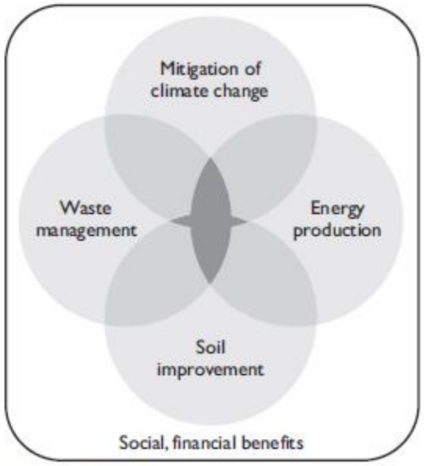

Figure 1.3 *Motivation for applying biochar technology*

Source: Johannes Lehmann

(Lehman. 2009. p 5)

2.2 SOIL AMENDMENT

To properly determine the effects biochar has on soil productivity, the properties of the biochar applied (it's porosity, composition, adsorptive properties.. etc) and the properties of the soil (pH, structure, composition.. etc) should be known. While there is little research on different biochar interactions with different soil types the methods for determining effects are well-developed. The International Biochar Initiative has written guides to this effect (See section 3.3, IBI Guides).

A recent scientific review by Verheijen et al. (2010. p 8-10) summarized the known effects of biochar which are listed below:

Potential positive effects:

- Increases soil water retention
- Stimulates microbial growth
- Retains nutrients for plants
- Acts as a liming agent: can be used to balance soil pH
- Increases earthworm activity

Potential negative effects:

- Depending on feedstock heavy metals or hazardous chemicals can be part of the biochar
- Untreated biochar can soak up nutrients required for plants.
- pH of biochar can work in reverse, acting as a liming agent where none is needed.
- Soil erosion due to the low density of biochar

2.3 GREENHOUSE GAS MITIGATION

According to a study done by Woolf et al. (2010, pg 2) maximizing biochar production around the world would decrease GHG emissions by 12% whereas using the same biomass to produce energy would decrease GHG emission by 10%.

The same study found that when soil fertility was high and coal was the fuel being used for electrical generation, only then did using biomass to offset fossil fuels outweigh using biomass to create biochar to reduce GHG emissions.

Based on one study by Matovic (2011) he theorized that sustainable biochar production could meet Canada's Kyoto Protocol obligations five times over.

2.4 ECONOMICS

Biochar is still a market in its infancy. The economics of it are still being developed. Of the approximately 150 articles survey only 2 had a minor focus on the economics of biochar. It should also be noted that there are private companies producing and selling biochar today.

2.5 PRODUCTION

The properties of biochar vary widely depending on the pyrolysis process conditions and the type of feedstock used. The three main considerations in the pyrolysis process are: heat transfer rate (slow or fast heating of biomass), mode of production (batch, semi-batch, continuous), and the heating process (auto-thermal, direct or indirect heating). (Methods for Producing Biochar and Advanced Biofuels in Washington State. 2011. p 115)

2.6 ENVIRONMENTAL CONSIDERATIONS:

If the biochar production process is done inefficiently, such as through poorly made kilns, a great deal of GHG's can be emitted. (Methods for Producing Biochar and Advanced Biofuels in Washington State. 2011. p 115) It must be remembered that ecosystems have their own processes to recycle and use biomass. If biomass is harvested to produce bioenergy, potential devastating environmental effects may follow. This is the case in many African countries where the production of charcoal from trees for a fuel source has led to widespread deforestation.[2]

On the other hand, if waste products are used and proper conservation methods are followed biochar production and use can be a significant contributor to environmental management. An example of an operating power plant that uses waste products is made by Community Power Corporation. See section 3.5.

2.7 CONCLUSIONS

The great variety in biochar production produces a great variety in biochar properties. The feedstock, the process of production and the desire for which final product (gas, biochar, bio-oil) must all be considered when choosing how to process biomass via pyrolysis. A growing body of

[2] http://news.bbc.co.uk/2/hi/africa/8272603.stm **'Africa's burning charcoal problem'**. Retrieved July 07, 2011.

scientific literature and research is becoming quickly available to those interested in using biochar for any of its purposes.

One of the greatest promises in producing biochar is the use of waste to create useful products such as syngas, biochar, and bio-oil. Yet the production must be done efficiently and well if the greatest benefits are to be achieved. The process can also be optimized for whichever product is desired. The Yukon College gasifier could be a potential source of biochar, syngas, and even bio-oil for example, if it were ever brought online with modifications.

3 BIBLIOGRAPHIC SEARCH

3.1 OVERVIEW

This bibliographic search was conducted through internet search engines, online databases and active websites. The main database used for retrieving academic papers was 'Academic Search Complete'.[3] It is also the focus of figures 1 and 2.

Figure 1 highlights the steady progression in published literature on biochar. This shows that the scientific community and their sponsors are convinced of the efficacy of its use. In figure 2 the different avenues of biochar research papers were put into general categories. Finally, figure 3 shows the steep rise in Google search words containing biochar and its continued presence in the search engine.

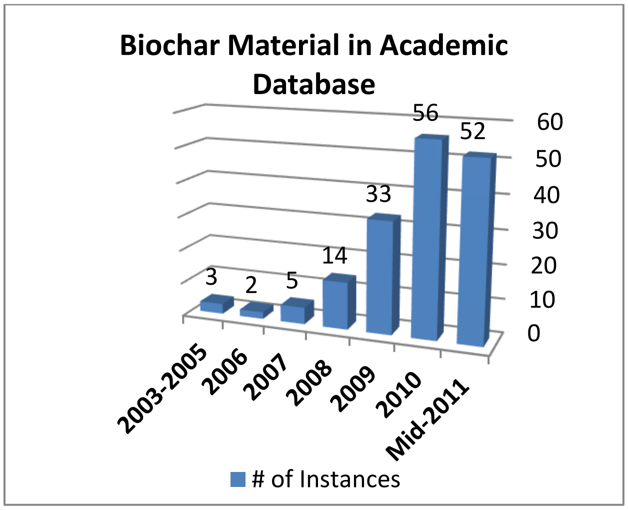

Figure 1

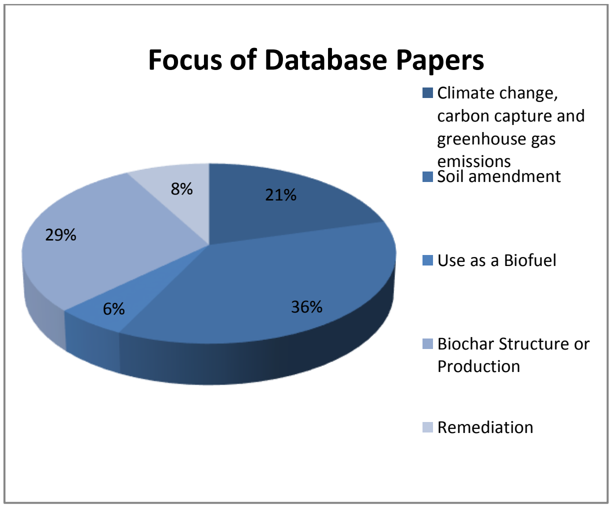

Figure 2

[3] Academic Search Complete is a multidisciplinary full-text database that includes more than 8,600 full text-periodicals and 7,500 peer-reviewed journals. (http://www.ebscohost.com/academic/academic-search-complete, Retrieved July 06, 2011).

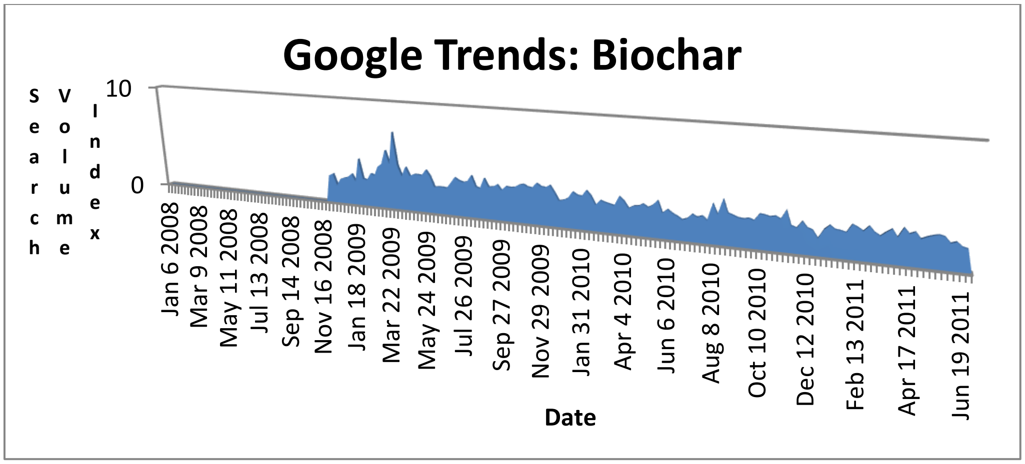

Figure 3 http://www.google.ca/trends?q=biochar Retrieved June 30, 2011.

All these figures show that biochar is an active research topic. for use in the categories shown in figure 2. These general categories do not capture the full potential for biochar use. Often the production and use of biochar has synergistic effects among its benefits. In section 3.3 scientific literature is reviewed pertaining to all the topics mentioned in figure 2. Sections 3.4-3.5 are potential useful general public sources of information and section 3.6 provides a list of some of the researchers involved with biochar in Canada.

3.2 RECOMMENDED READING

These recommended readings are designed to give the reader a broad overview of biochar while offering important specifics.

- Lehmann, J., Jospeh, S. (2009) – A book that reviews the current scientific knowledge up to 2009. This is a good introduction to the subject.
- Major, J. (2011) – A brief article that looks at the use of biochar in soils.
- Matovic, D. (2011) – A study that predicts Canadian capacity to mitigate GHGs through biochar production and use.
- Verheijen, F. (2010) – A critical scientific review by the Joint Research Council for the European Union. It provides broad to in-depth analysis of biochar.
- Woolf, D. (2010) – This document looks at biochar's potential to mitigate greenhouse gas (GHG) emissions and presents the reasoning for the potential to mitigation 12% of GHGs.

3.3 ANNOTATED BIBLIOGRAPHY

These documents were acquired through a variety of sources including *Google Scholar*, *Academic Search Complete* and general websites.

1. No Author. (2011). Methods for producing biochar and advanced biofuels in Washington State: part 1: literature review of pyrolysis reactors. *Washington State University*, *Department of Ecology*. Ecology Publication Number 11-07-017.
   - This literature review goes through known methods of reduction of cellulosic materials to gases, liquids and char, with the overall goal to support the 'development of renewable fuels'. This publication was created by Washington State University to help policy makers develop biochar production strategies. It gives a broad overview of the types of pyrolysis reactors available today. Overall this review was comprehensively researched but focused mainly on bio-oil production. The authors believe rural bio-oil production will be viable within 10 years.

2. Belgiorno, V., De Feo, G., Rocca, C.D., & Napoli, R.M.A. (2003). Energy from gasification of solid wastes. Waste Management, 23, 1-15. Retrieved from Google Scholar May 24, 2011.
   - This article summarizes the current scientific knowledge surrounding gasification technologies. The various methods of gasification, and the benefits and determents of the technology are looked at. The author concludes that gasification is a flexible technology that can be used with waste stream processes for increased energy recovery. One of the problems being gasification generally requires a heterogeneous waste stream to function optimally.

3. Bell, M. J., & Worrall, F. (2011). Charcoal addition to soils in NE England: A carbon sink with environmental co-benefits? *Science of the Total Environment, 409*(9), 1704-1714. doi:10.1016/j.scitotenv.2011.01.031
   - The research found that there was no great difference between CO_2 loss from soils without biochar and those with biochar; that there was a "significantly higher dissolved organic carbon (DOC) flux" from soils with large amounts of biochar (87,500 kg Charcoal/ha) mixed in; that biochar reduced nitrate flux in soil leachate from mineral soils by a large amount (a mean reduction of 35.1%); and that 87,500 kg or biochar/ha increased soil pH in tests, from 6.98 to 7.22. The authors state that: "[c]onsideration of both the carbon sink and environmental benefits observed here suggests that charcoal application to temperate soils typical of North East England should be considered as a method of carbon sequestration." It is expected that similar beneficial effects could be obtained here. For example, the addition of biochar could beneficially affect the carbon content of most Yukon soils.

4. Brick, S. (2010). Biochar: assessing the promise and the risks to guide U.S. policy. *NRDC Issue Paper November 2010*.
   - This paper focuses on the potential risks of biochar use and production, offers a summary of biochar knowledge and then applies this to biochar policy development. It suggests the US would need to invest approximately $130 million to assess the benefits of biochar use. Some of the risks mentioned which the author believed must be addressed include: inadequate characterization of production-related emissions, fugitive loss of biochar during transport and application, and carbon loss from soil disturbance during biochar application. Although not a scientific paper it offers perspective on possible biochar issues.

5. Fellet, G., Marchiol, L., Delle Vedove, G., & Peressotti, A. (2011). Application of biochar on mine tailings: Effects and perspectives for land reclamation. *Chemosphere, 83*(9), 1262-1267. doi: 10.1016/j.chemosphere.2011.03.053
   - This is a well-documented research paper that looks at the effect biochar has on mine tailings. For example, pH, nutrient retention, water-holding capacity increased and bioavailability of various heavy metals (cadmium, lead, thallium and zinc) decreased with biochar application. Overall the researchers believe biochar can be used on mine wastes to help establish 'green cover in a phytostabilization process.'

6. Lynch, J. & Joseph, S. Guidelines for the development and testing of pyrolysis plants to produce biochar. (2010). International Biochar Initiative.
   Major, J. A guide to conducting biochar trials. (2009). International Biochar Initiative. http://www.biochar-international.org/publications/IBI#Pyrolysis_guidelines Retrieved July 30, 2011.
   - These guides go through 'the techniques for applying biochar in different agricultural systems', assist with 'developing and testing small pyrolysis plants', and provide advice on preforming biochar 'experiments in a nursery or field plot.' These guides provide useful advice for farmers and others involved in biochar experiments.

7. Jones, D. L., Edwards-Jones, G., & Murphy, D. V. (2011). Biochar mediated alterations in herbicide breakdown and leaching in soil. *Soil Biology and Biochemistry, 43*(4), 804-813. doi: 10.1016/j.soilbio.2010.12.015
   - This paper looks at the effects biochar has on the common herbicide simazine. Biodegradation of simazine was reduced by biochar sorption of the herbicide, making it less available to microbial activity. "The rate of simazine mineralization, amount of sorption and leaching was inversely correlated with biochar particle size." Biochar was found to reduce movement of the herbicide which decreased the risk of it being transferred into plants or into water systems and into the food chain. It was noted that this 'may affect the efficiency of soil-applied herbicides'. Also, biochar aged 2 years in the field had the same effect as fresh biochar. This paper suggests that there may be an optimum biochar size for the soil being treated and that the effects of biochar are long-lasting.

8. Koide, R. T., Petprakob, K., & Peoples, M. (2011). Quantitative analysis of biochar in field soil. *Soil Biology and Biochemistry, 43*(7), 1563-1568. doi: 10.1016/j.soilbio.2011.04.006
   - This article documents the use of the "loss on ignition" method to determine the amount of biochar in soil. The researchers tested this method over the course of 15 months and found it to be accurate. This relatively inexpensive testing method may be suitable for experimental use in the Yukon.

9. Editors: Lehmann, J., Jospeh, S. (2009). Biochar for environmental management. *Earthscan*. London.
   - This is a comprehensive book of current knowledge on biochar with numerous contributors. The book points out that biochar "… is much more efficient at enhancing soil quality than any other organic soil amendment." And that biochar is also valuable for animal waste management. This is in addition to the better known benefits of biochar to sequester carbon and for energy production. This is a good starting point for those looking for an introduction to biochar.

10. Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – a review; *Mitigation and Adaptation Strategies for Global Change*; 11: 403-427.
    - According to this article converting biomass to biochar sequesters 50% of the initial carbon content of the biomass whereas burning retains 3% and biological decomposition retains <10-20% after 5-10 years. It suggests that biochar can mitigate up to 12% of worldwide GHG emissions. The authors point out that, "… slash-and burn systems cause significant degradation of soil and release of greenhouse gases and opportunities may exist to enhance this system by conversion to slash-and-char systems."

11. Major, J. (2011). Biochar: a new soil management tool for farmers and gardeners. *International Biochar Initiative and Appalachian Sustainable Development.*
    - This article offers an informative and comprehensive introduction to the use of biochar in soils. It was written for the general public through the International Biochar Initiative and the Appalachian Sustainable Development institution. Its purpose is to help a person decide whether to start testing the use of biochar or not. For example, the article points out that scientists believe that the charcoal in Amazonian soils has kept them fertile in "… an environment that rapidly leaches nutrients out of soil and where organic matter decomposes very rapidly."

12. Mankasingh, U., Choi, P., & Ragnarsdottir, V. (2011). Biochar application in a tropical, agricultural region: A plot scale study in Tamil Nadu, India. *Applied Geochemistry, 26*(Supplement 1), S218-S221. doi: 10.1016/j.apgeochem.2011.03.108
    - The use of biochar from rice husk, cassia stems, palm leaves and sawdust was analyzed. The researchers found that applying 6.6 metric tonnes ha^{-1} cassia biochar increased organic matter and reduced soil bulk density. Application rates of up to 10 metric tonnes ha^{-1} cassia biochar are recommended for high mineral content tropical soils. The authors refer to the use of the Anila stove for making biochar. The paper contains some analysis of biochar created from different sources with some tables on bioavailability of micro and macro nutrients and SEM (Scanning Electron Microscope) images.

13. Matovic, D. (2011). Biochar as a viable carbon sequestration option: Global and canadian perspective. *Energy, 36*(4), 2011-2016. doi: 10.1016/j.energy.2010.09.031
    - This article surveys current literature on the topic of using biochar for carbon sequestration throughout the world and Canada while making sure to exclude food stocks. Excluding food-stocks allows for the sustainable harvesting of food and bioenergy crops. The author found that biochar produced from all sources looked at could meet Canada's Kyoto protocol measures five times over, and could offset total annual Canadian CO_2 emissions.

14. McHenry, M. P. (2011). Soil organic carbon, biochar, and applicable research results for increasing farm productivity under Australian agricultural conditions. *Communications in Soil Science & Plant Analysis, 42*(10), 1187-1199. doi:10.1080/00103624.2011.566963
    - This review covers the literature concerning biochar, paying particular attention to Australia. This review assesses safe biochar application rates and examines variability of crop productivity results. The reviewers believe the limit of biochar that can be applied to soil is subject to contaminants within the biochar such as

heavy metals. Within it a summary table of current research on biochar is presented which contains studies published up to 2009.

15. McLaughlin, H. Anderson, P.S., Shields, F.E., & Reed, T.B. (2009). All biochars are not created equal and how to tell them apart. *Paper from North American Biochar Conference*, Boulder, CO – August 2009.
    - This paper offers a starting point on how to determine if a biochar produced is right for the soil it is to be used on. The authors conclude that biochars from different sources varies 'significantly in key properties' and that these properties must be known before biochar application to soils or before presenting any results from that application.

16. McLaughlin, H. (2011). How to make high and low adsorption biochars for small research studies. http://www.biochar-international.org/node/2500 Retrieved July 07, 2011
    - Here is an informal paper that outlines how to create a biochar using natural draft or fan assisted/forced air methods. The author found that fan assisted biochar had 'significantly higher adsorption capacity', an important property of biochar.

17. Vaccari, F. P., Baronti, S., Lugato, E., Genesio, L., Castaldi, S., Fornasier, F., & Miglietta, F. (2011). Biochar as a strategy to sequester carbon and increase yield in durum wheat. *European Journal of Agronomy, 34*(4), 231-238. doi: 10.1016/j.eja.2011.01.006
    - The researchers applied large amounts of biochar, 30% biochar per $tonHa^{-1}$ and 60% biochar per $tonHa^{-1}$. Both had positive effects on plant growth. This study was conducted over two years. Biochars positive effects were found into the second year even when biochar applications were not repeated. Also, a useful review of current studies with the effects biochar had on crop yield is presented in a table format.

18. Schahczanski, J. (2010). Biochar and sustainable agriculture. *ATTRA*, National Sustainable Agriculture Information Service.
    - This is a paper that covers general known points of biochar use in agriculture while giving a comprehensive reference point useful in presenting pros and cons of biochar as a soil amendment. Useful visual aids are contained in this paper. Topics such as soil pH balancing, moisture retention, fuel-vs-food debate, and potential income offsets are explored.

19. Sohi, S., Lopez-Capel, E., Krull, E., & Bol, R. (2009). Biochar, climate change and soil: A review to guide future research. *CSIRO Land and Water Science Report series, ISSN: 1834-6618.*
    - This review encompasses research on biochar from around the globe up to 2009. The paper gives a general overview of how biochar is produced and the potential benefits in agriculture. Policy contexts are presented and analyzed, and future research needs are stated. Several key questions are asked that this paper found lacking in answers from reviewed material. Examples of these questions are: "Is all biochar the same?", "How stable is it?", "Is it safe to use?", "Is it economically viable?", and several other questions. Some of these questions have been answered since. For example, the McLaughlin et al. (2009) paper above points out that not all biochar are the same.

20. Uchimiya, M., Klasson, K. T., Wartelle, L. H., & Lima, I. M. (2011). Influence of soil properties on heavy metal sequestration by biochar amendment: 1. copper sorption isotherms and the release of cations. *Chemosphere, 82*(10), 1431-1437. doi:10.1016/j.chemosphere.2010.11.050
    - In this research paper two distinct soils were analyzed for their copper sorption isotherms when biochar was applied. Clay-rich, alkaline soil with high heavy metal sorption capacity and eroded, acidic sandy loam soil with low heavy metal sorption capacity were amended with acidic pecan shell biochar and basic broiler litter biochar. Soils amended with selected biochar were found to increase copper sorption.

21. Uchimiya, M., Klasson, K. T., Wartelle, L. H., & Lima, I. M. (2011). Influence of soil properties on heavy metal sequestration by biochar amendment: 2. copper desorption isotherms. *Chemosphere, 82*(10), 1438-1447. doi: 10.1016/j.chemosphere.2010.11.078
    - "A positive correlation was observed between the equilibrium aluminum concentration and initial copper concentration in soils amended with acidic activated carbon but not basic biochar, suggesting the importance of cation exchange mechanism, while dissolution of aluminum oxides cannot be ruled out."

22. Verheijen, F., Jeffery, S., Bastos, A.C., van der Velde, M., & Diafas, I. (2010). Biochar application to soils: a critical scientific review of effects on soil properties, processes and functions. *Joint Research Centre, Institute for Environment and Sustainability, European Commission*.
    - This review summarizes known negative, neutral and positive impacts of biochar on soils. It summarizes current research on the physicochemical properties of biochar, its effects on soil, its potential to threaten soil, wider issues and then a summary of findings. This is a large review conducted very thoroughly by the European Joint Research Centre. Their main conclusion is that biochar research is at a relatively early stage and that more needs to be carried out.

23. Warnock, D.D., Lehmann, J., Kurper, T.W., & Rillig, M.C. (2007). Mycorrhizal responses to biochar in soil – concepts and mechanisms. *Marschner Review – Plant Soil*, 300, 9-20.
    - This article reviews current literature on effects of biochar and activated charcoal on mycorrhizal growth. It presents ideas on how biochar enables increased growth and provides 'roadmaps' for research on biochar topics such as: provision of refugia from fungal grazers, detoxification of allelochemicals on biochar, indirect effcts on mychorrhizae through effects on other soil microbes, and alteration of soil physico-chemical properties.

24. Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., & Jospeh, S. (2010). *Sustainable biochar to mitigate global climate change*. Nature Communications. D0I: 10.1038/ncomms1053. http://www.nature.com/ncomms/journal/v1/n5/pdf/ncomms1053.pdf Retrieved May 16, 2011.
    - An article that looks at the potential of biochar to reduce greenhouse gases at a global level. It offers several different scenarios on how this can be achieved and suggestions on how to make sure this a 'sustainable' way of GHG reduction. The author believes that: "Biochar has a larger climate-change mitigation potential than

combustion of the same sustainably procured biomass for bioenergy, except when fertile soils are amended while coal is the fuel being offset."

25. Xu, R., Ferrante, L., Hall, K., Briens, C., & Berruti, F. (2011). Thermal self-sustainability of biochar production by pyrolysis. *Journal of Analytical and Applied Pyrolysis, 91*(1), 55-66. doi: 10.1016/j.jaap.2011.01.001

- The paper looked at the effect of pyrolysis temperature and vapour residence time on biochar yields of several different feedstock (grape residues, sugarcane residues, dried distiller's grain, palm oil residues, apple pomace and forestry residue). This paper also looked at how to make the pyrolysis process self-sustaining (in a pilot bubbling fluidized bed pyrolyzer) to reduce fossil fuel usage. Some of the authors main conclusions are: "The pyrolysis temperature greatly affects biochar production. Incomplete pyrolysis at lower temperatures favours char production.", "In fluidized bed systems that retain the solid particles, the vapour residence time does not affect the biochar yield.", and "Higher biochar yields were obtained for agricultural residues than for forestry residues." This paper has extensive documentation, graphs and discussion of results.

26. Zimmerman, A. R., Gao, B., & Ahn, M. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry, 43*(6), 1169-1179. doi: 10.1016/j.soilbio.2011.02.005

- An extensively documented and researched paper that documents the effects that five different types of biochar have on five different types of soil. The overall goal was to look at the effect biochar has on soil CO_2 evolution (priming). It was shown that biochar has the potential to decrease soil degradation and increase the potential of soil to store carbon by "organic matter sorption to biochar and physical protection". The authors estimate that biochar could sequester more than 12% of GHG's based on the data they found.

3.4 WEBSITES

These websites offer a starting point for general to specific information on the production and use of biochar.

International Biochar Initiative Publications. http://www.biochar-international.org/publications/IBI (accessed June 23, 2011).

- This website is a general knowledge source for biochar. It offers continuing updates and a community for those interested in biochar to communicate through.

Cornell University. Department of Crop and Soil Sciences. http://www.css.cornell.edu/faculty/lehmann/research/biochar/biocharproject.html (accessed June 23, 2011).

- University of Cornell's Department of Soils and Crops is involved in exploring the interactions between soil and biochar. Johannes Lehmann, one of the prominent figures in the biochar world is employed here.

Worldstove Corporation. http://worldstove.com/products/ (accessed June 23, 2011).
- This site offers a variety of stoves to produce biochar from biomass to provide heat or cooking fires.

Biochar | Info. http://www.biochar.info/biochar.biochar-overview.cfml (accessed June 23, 2011).
- A website that gives a general summary of biochar production (DIY and buyable) methods and sources of information on biochar. This website is more of a gateway to other information.

Biochar Links. http://www.biocharlinks.net/ (accessed June 23, 2011).
- A website that provides a general list of links to other sites offering biochar information or services.

3.5 PRIVATE COMPANIES AND ORGANIZATIONS

The companies and organizations listed here are concerned with the production and use of biochar.

Canadian Biochar Initiative. http://www.biochar.ca/ (accessed June 23, 2011).
- The 'Canadian Biochar Initiative'. It has no recent web updates and does not seem active.

Biochar Ontario: Google Group. http://groups.google.com/group/biochar-ontario (accessed June 23, 2011).
- A Google group called 'Biochar Ontario'. There is active posting but not much on Biochar.

US Biochar Initiative. http://www.biochar-us.org/index.html (accessed June 23, 2011).
- The 'US Biochar Initiative' is active with many references to other biochar information sources.

GEK Gasifier Experimenters kit: Pushing Wood Beyond the Imbert. http://www.gekgasifier.com/ (accessed June 23, 2011).
- A group that looks at producing electricity from biomass. They are active, informative, provide guidance and open source engineering. There are some methods given for producing biochar, but mainly the website focuses on converting biomass to gas and then electricity.

Alterna biocarbon. http://www.alternabiocarbon.com/ (accessed June 23, 2011).
- A private company based in Prince George, BC that works in converting biomass into biochar to use as a coal-like substitute. The company is trying to build a biocarbon plant at Ness Lake, BC.

Community Power Corporation: The Modular Bioenergy Company. http://www.gocpc.com/evolution/bm50.html (accessed June 23, 2011).
- This is one of the few companies in the states that have seemed to have succeeded in commercial biomass to energy production.

Biochar Solutions. http://www.biocharsolutions.com/index.html (accessed June 23, 2011).

- This company produces and sells biochar and biochar making equipment, and is based in Colorado.

3.6 CANADIAN RESEARCHERS

The researchers listed here are those found through Canadian University websites.

Hugh McLaughlin, Ph.D., P.E.
Director of Biocarbon Research
Alterna Biocarbon Inc., div of Alterna Energy
Email: hmclaughlin@alternabiocarbon.com

- A researcher highly involved in the biochar initiatives and publications throughout North America.

Chessi Milter, M.Sc. Student
McGill University
Email: Benjamin.miltner@mail.mcgill.ca

- Is researching 'biochar production and use in swidden cultivation systems: slash-and-burn as a sustainable alternative to slash-and-burn in the Peruvian Amazon'

Dr Donald L. Smith
James McGill Professor
Department of Plant Science
Phone: 514-398-7866
Fax: 514-398-7897
Email: donald.smith@mcgill.ca

- Professor Don Smith of the Plant Science Department has received an NSERC strategic grant to conduct research on biochar

Rutherford, P Michael, Assc. Prof.
UNBC, Enviro. Sci.
960-5885
Email: rutherfm@unbc.ca

- In 2010 conference in Saskachewan presented 'Positive Influences on root symbioses by biochar enhances seedling growth in sub-boreal forest soils'. His research work seems geared towards soil sciences.

Mark Johnson
Assistant Professor
Water and Sustainability, Ecohydrology, Watershed Biogeochemistry
Phone: 778-999-2102
Email: mark.johnson@ubc.ca

- Dr. Mark Johnson is the leading biochar expert in BC and is currently investigating its use as a means for reducing GHG emissions and nutrient leaching in BC forestry operations.

Nathan Basiliko, Assc. Prof.
University of Toronto
Phone: 1-905-569-4515
Fax: 1-905-828-5273
Email : nathan.basiliko@utoronto.ca

- His research explores biochar as a potential link to sustainable and carbon negative forest biomass.

APPENDIX 2

Terminology

This is a list of terms often encountered in biochar research.

Activated Charcoal – This is a processed form of carbon whose surface area usually exceeds 500m^2 per 1 gram of carbon. The high surface area gives it excellent adsorption, filtration or chemical reaction potential. It is used in many industrial processes. ('Activated Carbon': wikipedia.org, retrieved August 3 2011)

Biochar – The product from the pyrolysis of biomass.

Bio-oil – Bio-oil "is extracted from biomass and converted to a liquid through destructive distillation in a reactor at temperatures of about 500°C. Pyrolytic oil (or bio-oil) is similar to tar and normally contains too high levels of oxygen to be a hydrocarbon. As such it is distinctly different from similar petroleum products." ('Pyrolytic oil':wikipedia.com, retrieved July 06, 2011).

Charcoal – The product of heating woody biomass in an oxygen poor environment. "Note that the current trade nomenclature for charcoal is "lump charcoal" and that products sold as "charcoal briquettes" are made from a mix of materials, such as low-grade coal, sawdust, wax, and starch binders, and often do not contain any true charcoal." ('Charcoal': wikipedia.com, retrieved July 06 2011).

Pyrolysis – The process of creating biochar or charcoal, which is the thermal decomposition of biomass in an oxygen-poor environment. ('Pyrolysis':wikipedia.com, retrieved July 06 2011).

Thermally Modified Wood – Sometimes known as heat treated wood; this is the process of 'baking' wood in a kiln at temperatures upwards of 500°F. The baking changes the structure of wood sugars making them less accessible to microbes. The end product is also more easily transported than other typical treated woods.

Syngas – Syngas literally meaning 'Synthetic Gas', a 'mixture of carbon monoxide, carbon dioxide and hydrogen. (I)s produced due to the gasification of a carbon containing fuel to a gaseous product that has some heating value.' ('What is Syngas':biofuel.org.uk/what-is-syngas.html, retrieved July 06, 2011).

APPENDIX 1

A list of surveyed articles

Accompaniment to Biochar Literature Review (2011) by the Energy Solutions Centre

The list of articles on biochar below came from the 'Academic Search Complete' database. This database is a multidisciplinary full-text database that includes more than 8,600 full text-periodicals and 7,500 peer-reviewed journals. The articles were categorized based on the article abstracts. The categories used were: climate related, soil, use as a biofuel, biochar structure or production, and remediation. The percent each heading contained of all articles in each category is presented in the Biochar Literature Review as the graph 'Focus of Database Papers'

Some articles appear in more than one category as their subject matter touches on several points. For example, a review of biochar knowledge may contain information relevant to a few subjects. Also, there were a number of scientific experiments that contained new results on differing subjects.

*Note articles contained in the section 3.3 were also added to this appendix.

CLIMATE CHANGE, CARBON CAPTURE, AND GREENHOUSE GAS EMISSIONS

One of the major drivers into biochar research is its potential to mitigate greenhouse gas emissions. Any articles that contained information on the potential biochar has for mitigation is contained within this section. Some papers main focus is this subject while others touch on it while delivering a broader argument.

Topics covered include:

- Biochar's effect on mineralization
- Biochar's effect on soil respiration
- Biochar's geo-engineering potential

Abend, L. (2008). The biochar solution. Time International (Atlantic Edition), 172(24), 56-56. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,cookie,uid&db=a9h&AN=35622037&site=ehost-live

Allen-Stevens, T. (2009). Soil solution for carbon capture. Crops, , 14-14. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,cookie,uid&db=a9h&AN=47591591&site=ehost-live

Binh, T. N., Lehmann, J., Kinyangi, J., Smernik, R., Riha, S. J., & Engelhard, M. H. (2008). Long-term black carbon dynamics in cultivated soil. *Biogeochemistry, 89*(3), 295-308. doi:10.1007/s10533-008-9220-9

Brick, S. (2010). Biochar: assessing the promise and the risks to guide U.S. policy. *NRDC Issue Paper November 2010*.

Bruun, S., & Luxhøi, J. (2008). Is biochar production really carbon-negative? Environmental Science & Technology, 42(5), 1388-1388. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,url,cookie,uid&db=a9h&AN=31272855&site=ehost-live

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Clough, T. J., Bertram, J. E., Ray, J. L., Condron, L. M., O'Callaghan, M., Sherlock, R. R., et al. (2010). Unweathered wood biochar impact on nitrous oxide emissions from a bovine-urine-amended pasture soil. *Soil Science Society of America Journal, 74*(3), 852-860. doi:10.2136/sssaj2009.0185

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SOIL AMENDMENT

One of the first things noticed about biochar was its potential to increase soils plant productivity. As such, research into biochar as a soil amendment is one of its largest and its oldest fields of research. Many papers in this section only touch on biochar's use as a soil amendment but there are many that contain new facts recently brought to light through scientific research.

Topics include:

- Biochar's ability to increase ethylene production
- Biochar's potential to decrease nutrient run-off
- Biochar's effect on mycorrhizal fungi
- Biochar's effect on earthworms

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BIOFUELS AND CO-PRODUCTS

The processes used to create biochar creates great possibility for a carbon neutral heating and electrical source. System efficiency is a topic raised in all walks of life now as we continue to see that our way of living is inherently unsustainable. To increase biochar production efficiency the by-products of its creation must be used for useful ends. This is a topic that is touched upon, directly or indirectly, by the papers within this section.

Topics include:

- Gasification technologies
- Bio-oil production in tandem with biochar production
- Biochar use in biodiesel production

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BIOCHAR PROPERTIES OR PRODUCTION

This section deals with how biochar is produced and/or the properties of produced biochar. In some papers these topics are tied together while in others they are separate. In order to best determine the end uses of different types of biochar the end properties must be known. There are many different variables that are being explored in scientific experiments like those documented below.

Topics include:

- The activation of biochar (see activated charcoal, appendix 1)
- Algal biochar production and properties
- Characteristics of different types of biochar
- High temperature pyrolysis of blended animal manures

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SOIL REMEDIATION

Biochar is very similar to 'Activated Charcoal' in its potential for environmental remediation purposes. This section presents some of the current literature available on the use of biochar in these remediation settings.

Topics include:

- The efficiency of biochar in reducing lead and copper mobility and uptake to ryegrasses
- Removal of lead from water using biochar
- The use of biochar to reclaim mine tailings

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