UBC Social Ecological Economic Development Studies (SEEDS) Student Report

AN INVESTIGATION INTO "BIOCHAR AND ITS POTENTIAL USE AS ORGANIC SOIL AMENDMENT"

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APSC 262

April 04, 2013

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"BIOCHAR AND ITS POTENTIAL USE AS ORGANIC SOIL AMENDMENT"

Submitted to Dr. Naoko Ellis
by Royce Poon, Shivam Parmar and Seung Hyun (Peter) Kim

Source: [Untitled photograph of biochar]. Retrieved April 01, 2013, from: http://novotera.ca/wp-content/uploads/2012/07/biochar.jpg

University of British Columbia
Applied Science 262
Section T2B
April 04, 2013

ABSTRACT

"An Investigation into biochar and its potential use as organic soil amendment"

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This report investigates the use of biochar as a soil amendment for the UBC Farm. Biochar is made by the pyrolysis of biomass. As sustainable and local sources of soil amendments are decreasing in availability, biochar has come to the farm's attention for its potential to improve its soil health. Soil health directly relates to a farm's ecological and economic performance and its productivity. The UBC farm has sandy soils and is considering using biochar in hope that it might offer improved nutrient and water retention, and that it might reduce the annual cost of nutrient supplements added to the soil. The farm also demands to know if it is cost effective to use biochar. Moreover, the farm wonders if using this relatively new material has any social impact. As environmental, economic and social aspects are required for consideration, a triple bottom line assessment is conducted as part of the investigation into the use of biochar as a soil amendment.

After a close investigation of biochar's environmental aspects, it is clear that it offers several benefits to soil as well as the atmosphere. Soil benefits include improved nutrient and water retention and its persistence in soil for over hundreds to thousands of years. Atmospheric benefits include carbon sequestration and reduced greenhouse gas emissions. It holds possible unintended consequences as well. The main consequence to consider is the reduced efficiency of herbicides and pesticides on biochar-amended soils. Economic assessment suggests that the use of biochar as a soil amendment is viable; however, in the short-run, it is not promising as the short term costs of implementing biochar far outweigh the returns gained from exploiting its carbon offset value. Increase in carbon offset prices and a reduction of biochar prices is required for us to deem it economically viable for its application in the long-run. Biochar's social impact includes possible metal contaminants in its feedstock and possible presence of low concentration of Polycyclic Aromatic Hydrocarbons. The former can be avoided by a proper selection of its feedstock, and the latter can be ignored as it is not harmful to human. It also provides a beneficial use of agricultural waste which has no other use.

After a review of the triple bottom line assessment on the use of biochar discussed above, it is recommended for the UBC farm to use biochar as a soil amendment in the long-run. If the farm plans to use it for a short period of time, economic assessment suggests that it is not cost effective, but environmental and social assessments still favor it. To avoid unintended consequences, it is recommended that the farm should make sure that the supplier of biochar does a proper selection of biomass.

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GLOSSARY

Biomass:	Biological material produced from living or recently living matter.
Carcinogenic:	Capable of causing cancer.
CO_2 Sequestration:	Removal of CO_2 from the atmosphere.
Herbicides:	Chemical substances used specially to destroy unwanted plant.
Nutrient/Water Retention:	The ability to hold nutrient/water in the soil for plants to absorb.
Pesticides:	Chemical substances used to destroy unwanted plant, fungal, or animal pests.
Pyrolysis:	Decomposition brought about by high temperature without oxygen.
Soil Amendment:	A material added to soil to improve its health and plant growth.

LIST OF ABBREVIATIONS

CCX- Chicago Climate Exchan**ge**

CH_4 – Methane

CO_2 - Carbon Dioxide

ECX- European Climate Exchange

GHG - Greenhouse Gas

MT – Metric Ton

NPP - Net Primary Production

N_2O - Nitrous Oxide

PAH - Polycyclic Aromatic Hydrocarbon

1.0 INTRODUCTION

The purpose of this report is to conduct an in-depth analysis on biochar and its potential use as organic soil amendment. Biochar is a type of charcoal specially produced to be used as a soil amendment and is produced by the pyrolysis of biomass. The UBC Farm is considering supplementing its current soil amendments with biochar in hopes that biochar would improve the water retention of the soil and increase the soil's ability to absorb nutrients. A triple bottom line assessment is utilized to analyze the environmental, economic, and social impacts of the application of biochar at the UBC farm. For the environmental aspect, we will look at particular soil benefits, if any, that biochar provides and that are lacking in the soil amendments currently used. For the economic aspect, we will estimate the revenue generated by GHG offsets and increase in productivity due to the application of biochar and compare it against its cost price. For the social aspect, we will look at possible health hazards involved in the handling of biochar and also if it is a sustainable type of soil amendment. Ultimately, with the results from the triple bottom line assessment, we will then be able to provide a recommendation as to whether the UBC farm should implement biochar as a soil amendment.

2.0 ENVIRONMENTAL ASSESSMENT

One of the three factors of triple bottom line assessment is the environmental assessment, which measures the impact on the environment. It is important that we take this into consideration when investigating a project because we need sustainable technology to maintain our planet's well-being. According to the conversation, which can be found in Appendix A, with Jessica Dennis (5 February 2013), the lead researcher on the UBC Farm biochar project, the UBC Farm is considering using biochar as a soil amendment in hopes that it may improve the retention and uptake of nutrients for the sandy soils that the farm has. To provide further knowledge of biochar, this part of the report focuses on its ecological impacts. There are a number of environmental benefits of using biochar. It offers soil benefits particularly for the UBC Farm and atmospheric benefits particularly for our environment.

2.1 INCREASED NUTRIENT AND WATER RETENTION

By using biochar as a soil amendment, the UBC Farm can benefit from enhanced nutrient and water retention. As it has sandy soils, these benefits are highly desirable. By adding biochar to soils, more nutrients and water are retained in soil and remain available for plants to absorb (Lehmann, 2007). Therefore, plants are healthier and less fertilizer runs off into surface water. Moreover, a case study has been done to prove that the application of biochar to sandy soils increases water-holding capacity (Basso, Miguez, Laird, Horton, & Westgate, 2013). The researchers mixed biochar, that was made from hardwood and by fast pyrolysis, with oven dried soils. There were three percentages of biochar application, 0%, 3%, and 6%. By looking at Figure 1 below, it is clear that biochar improves water retention.

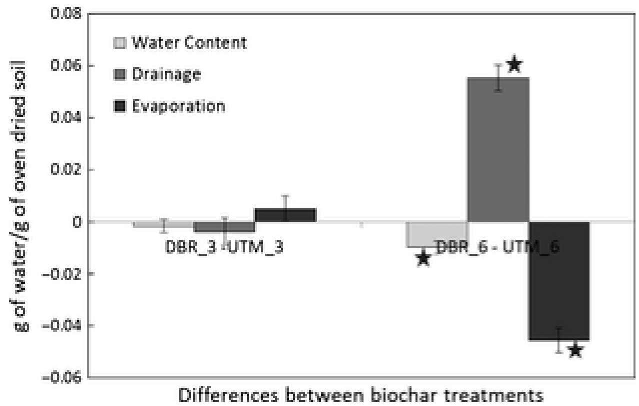

Figure 3- Differences in water content between biochar treatments after 91 days of incubation (Basso et al., 2013)

The soil with 6% biochar significantly had less water evaporated, more water held, and less water loss to drainage. This case study suggests that biochar amended soils have increased water retention (Basso et al., 2013).

2.2 PERSISTENCE

Biochar persists in soil far longer than any other organic soil amendments. It lasts hundreds to thousandss of years according to Cheng, Lehmann, and Engelhard (2008). Many argue that soils have limited ability to store carbon dioxide (CO_2), saturate after 15-35 years (Maraseni, 2010). On the other hand, biochar can capture carbon and can be retained in soil for many years. During the conversation with Dennis (5 February 2013), she mentioned that the UBC farm is also hoping that using biochar may reduce the amount of annual nutrient inputs added to the soil. As biochar persists for a very long time with the benefits of nutrient and water retention, the farm can benefit from this.

2.3 CO_2 SEQUESTRATION AND REDUCED GHG EMISSIONS

One of the many benefits of using biochar is that it is carbon-negative. It captures more carbon in the air than it produces during its production period. This suggests that the excessive carbon in the atmosphere can be reduced by using biochar as a soil amendment. Matovic (2011) analyzed the Table 1 below which clearly shows the significant carbon sequestration that biochar provides. If 10% of the net primary production (NPP) of the world biomass was made to biochar, it would offset 4.8 GtC/yr, which is approximately 20% more than the 2011 annual increase of carbon, 4.1 GtC/yr, in the atmosphere.

Table 2 - Potentials for worldwide carbon sequestration via biochar production (Matovic, 2011)

Item	Value	Comments
Net primary production (NPP)	60.6 GtC/yr	None
Percentage of NPP for biochar	10.00%	None
Resultant biochar production	3 GtC/yr	Assume 50% of biomass carbon is converted into biochar
Carbon offset via combustible products (60% of 50% biomass)	1.8 GtC/yr	Assume 60% emission displacement efficiency of the combustion portion (50% of biomass). The remaining 40% (1.3 GtC/yr) is used up for running pyrolysis.
Annual increase in atmospheric C due to fossil fuels and cement industry	4.1 GtC/yr	Amount of CO_2 that remains in the atmosphere, out of the total of 7.2 GtC/yr released by humans.

Moreover, biochar can also reduce nitrous oxide (N_2O) emissions, which is a greenhouse gas (GHG). Biochar-conditioned soils have less need for fertilizers (Maraseni, 2010). As fertilizer causes excessive N_2O emissions, and that they are far more potent than CO_2, it is another benefit from biochar that helps sustain our environment. Soils that are mixed with biochar reduce N_2O emissions by 50-80% (Rondon, Ramirez, & Lehmann, 2005). Also, producing biochar is making beneficial use of agricultural waste. The waste has potentially no other use, and if it were to be decomposed naturally, it would emit methane (CH_4), another potent GHG, into the atmosphere. By using agricultural waste, biochar is reducing CH_4 emissions.

2.4 POSSIBLE CONSEQUENCES

Along with many benefits of using biochar, there are possible unintended consequences. Recent studies have reported that using biochar as a soil amendment reduces the efficiency of pesticides and herbicides applied (Kookana, Sarmah, Van Zwieten, Krull, & Singh, 2011). The Figure 2 below shows the result of a test conducted by Yang, Sheng, and Huang (2006). The picture clearly shows that the efficiency of the herbicide reduces as the application rate of biochar made of wheat straw increases.

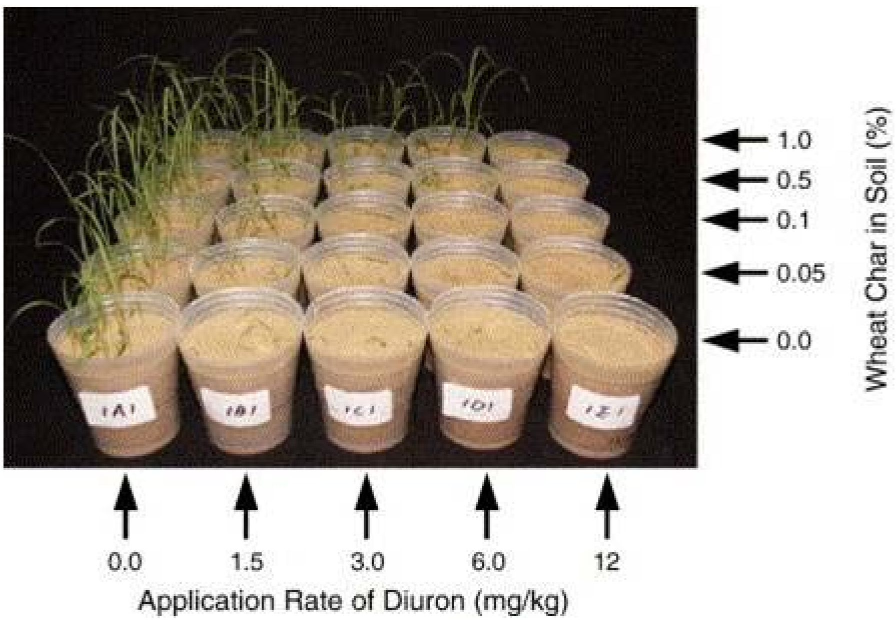

Figure 4 - Photograph of barnyard grass growth in soils with different application rates of diuron herbicide and wheat-straw biochar four weeks after planting (Yang et al., 2006)

Other unintended consequences include rapid changes to nutrient availability, pH, and electrical conductivity. It is recommended that one carefully considers these before applying to soils (Kookana et al., 2011).

3.0 ECONOMIC ASSESSMENT

The second part of the triple bottom line assessment is to analyze the economic viability of using biochar as the new soil amendment at UBC Farms. This includes doing a cost analysis of implementing biochar, and comparing it with the possible economic return associated to compensate for the costs incurred.

We discuss the different ways biochar can be of financial value to us and then calculate the returns possible if we implement it at UBC Farms. The cost analysis encompasses gauging the market price of biochar, excluding the transportation costs associated. We then add in the cost associated with the application of biochar and devise the most economical option.

We conclude by comparing the costs and returns associated and stating the short term findings.

3.1 ECONOMIC RETURNS

We analyze three different avenues of financial returns that the use of biochar offers UBC Farm. They are as follows:

i. Through Carbon Sequestration: In this section we evaluate the carbon sequestered when we use biochar instead of agricultural lime. We calculate the value of carbon offsets using a price range of $1/Metric Ton (MT) to $31/MT CO_2, assuming that carbon offset trading is permissible using biochar application as a sequestration technique. The C content of biochar varies, based on the feedstock used in its manufacture. Biochar obtained by using a woody feedstock has higher carbon content (80%), as compared to that obtained by using a leafy feedstock (60%). Accordingly, .61 to .80 MT of carbon (2.2 to 2.93 MT of CO_2) is sequestered for every MT of biochar applied. Using the highest carbon content (80%) of biochar (wood feedstock based) and the price range of C offsets, we obtain the approximate value of C sequestration at $2.93 to $90.83 per metric ton of biochar (Galinato, Yoder, & Granatstein, 2010).

ii. Through Avoided Emissions: Biochar has liming qualities that are essential for the growth of crops that require a more basic soil, i.e. soil with a higher pH. These qualities make it possible for biochar to replace agricultural lime as a soil amendment. This helps us avoid CO_2 emissions at a rate of 0.059 metric ton C (or 0.22 metric ton CO_2) per ton of limestone (West & Mcbride, 2005) resulting in avoided emissions in the value range of $0.22-$6.82 per metric ton of lime (Using the CO2 offset price range of $1 (decided in CCX, 2008) to $31/MT CO2 (decided in ECX, 2008)).

iii. Returns from Crop Production: Assuming that the UBC Farm uses biochar as a substitute for agricultural lime, and considering three biochar price scenarios, we assess the potential economic returns. For sandy soils, we require 17MT/acre of biochar to provide the same quality of liming as provided by .54 MT/acre of agricultural lime (Collins, 2008). Thus biochar might not be economically feasible as just a pH adjusting agent.

3.2 APPLICATION COSTS

In this section we compare the variable costs associated with the two popular methods of application of biochar, the broadcast and disk method and the trench and fill method.

The cost of broadcast and disk method (C_a) is the sum of the costs of disking (D) and the cost of biochar application (A_a):

$$C_a = D + A_a,$$

where A_a is a function that considers labor costs (l_a), fuel costs (f_a) and maintenance costs (m_a)

$$A_a = t_a * (l_a + f_a + m_a)$$

Disking is a common agricultural practice for which rates are published from region to region. Here we assume a disking rate of $15 per acre.

The cost of trench and fill method (C_b) is the net sum of the cost of trenching (T) and the cost of application of biochar (A_t).

$$C_b = T + A_t$$

where $T = t_{tr} (l_{tr} + f_{tr} + m_{tr})$ and $A_t = t_a (l_a + f_a + m_a)$.

Note: All values of the variables used are attached in Appendix B.

The findings suggested that the broadcast method (rates ranging from $29-300/acre for application rates of 2.5 to 50 tons/acre) would be more economical than the trench and fill method (rates ranging from $26-1,280/acre for rates between 5-75 tons/acre). (Wills & Arnott, 2010)

3.3 ECONOMIC VIABILITY

Assuming the production of winter wheat, we calculate the profits obtained:

Profit = Revenue + CO_2 offset value – Total Cost – Ag Lime Cost – Biochar Cost (Galinato et al., 2010)

Table 2 - Projected profit given various CO_2 offset prices and biochar prices in the growth of winter-wheat (Galinato et al., 2010)

Scenario	Revenue	CO_2 Offset Value[b]	Total Cost[c]	Cost of Ag Lime[d]	Cost of Biochar[d]	Profit[e]
Without biochar or agricultural lime application	$438	—	$415	—	—	$23
With ag lime application	$694	—	$415	$133	—	$146
With biochar application, *when offset price is $1/MT CO_2 and the price of biochar (P_B) is…*						
P_{B1} = $350.74/metric ton[f]	$694	$90	$415	—	$10,740	-$10,371
P_{B2} = $114.05/metric ton[g]	$694	$90	$415	—	$3,492	-$3,123
P_{B3} = $87/metric ton[f]	$694	$90	$415	—	$2,664	-$2,295
With biochar application, *when offset price is $31/MT CO_2 and the price of biochar (P_B) is…*						
P_{B1} = $350.74/metric ton[f]	$694	$2,799	$415	—	$10,740	-$7,662
P_{B2} = $114.05/metric ton[g]	$694	$2,799	$415	—	$3,492	-$414
P_{B3} = $87/metric ton[f]	$694	$2,799	$415	—	$2,664	$414

Table 2 makes the following assumptions:

a. Biochar or lime application is intended to raise the pH of the soil by 1.5.
b. CO2 Offset Value = 90 metric tons of CO2 offset per acre from avoided emissions of lime and biochar C sequestration * price of CO2 offset ($1 or $31/MT CO2).
c. Excludes the cost of applying lime or biochar to agricultural land (machinery and labor cost).

As observed from the table above, we can draw the following conclusions:

i. For short term economic returns, agricultural lime is a much viable option for UBC Farms.

ii. If agricultural lime is replaced with biochar, UBC Farm will incur losses at either market price of biochar. Results show that a high market price of biochar outweighs the income from carbon offsets.

The only scenario where a profit is obtained is when the offset price is $31/MT of CO_2 and the price for biochar is around $87/ MT (Galinato et al., 2010). These are ideal conditions and if realised, then biochar can be a viable option economically.

Also, the above analysis excluded the cost of application of biochar. We need to take into consideration the cost of application calculated in section 3.2 when doing a complete cost analysis.

4.0 SOCIAL ASSESSMENT

Prior to the use of biochar on the UBC farm, it is necessary to ensure that biochar is not harmful to human health in any way because the potential risk of biochar will be of concern to people who will handle and apply biochar on the UBC farm. Biochar is mostly made from biomass waste materials which include crop residues, animal manures, and food, forestry, industrial, and landfill waste. Waste, in general, is likely to contain contaminants. When a biomass waste material contains high concentrations of contaminants, the biochar that is produced from it would pose health risks. In fact, there has already been much controversy concerning whether biochar contains heavy metals and Polycyclic Aromatic Hydrocarbons, the two most common contaminants found in biomass waste materials.

Sustainability is an important factor to be considered before using biochar on the UBC farm. Due to the facts that sustainability is integral to the well-being of our society today and that UBC is highly committed to promoting sustainability, it is necessary to ensure that biochar is indeed a sustainable type of soil amendment. Theoretically, biochar is a sustainable type of soil amendment because of its ability to be produced using waste.

4.1 POSSIBLE HEALTH HAZARDS

4.1.1 POLYCYCLIC AROMATIC HYDROCARBONS

One type of contaminant that can most likely be found in biochar is Polycyclic Aromatic Hydrocarbons (PAHs). PAHs are toxic pollutants. They are of concern to human health because they are carcinogenic. High concentrations of PAHs are formed in the process of the incomplete combustion of organic material. Since pyrolysis is not combustion, biochar is unlikely to have a high concentration of PAHs. Researches show that during the pyrolysis of biomass, low concentrations of PAHs are usually formed at temperatures between 350 ºC and 600 ºC (Helferty, 2009). The proposed temperature for the pyrolysis of biomass is approximately 500 ºC for most types of biomass (Helferty, 2009). This implies that the PAHs content found in most types of biochar would be of low concentration. In addition, after numerous tests that were performed in the past, it was found that the concentrations of PAHs in different types of biochar typically ranged from 3 to 16 $\mu g/g^{-1}$, which is way lower compared to 28 $\mu g/g^{-1}$ in the char obtained from burning pine trees (Sohi, Krull, Capel, & Bol, 2010, p. 61). Numerous test results also show that increases in pyrolysis time and temperature cause PAH concentrations to decrease (Hale et al., 2012). People are exposed to low concentration of PAH everyday; Barbeque, smoked foods, coffee, and cigarettes are few common sources of PAHs. Just like any other contaminant, PAHs are poisonous if you are excessively exposed to it. Otherwise, PAHs are generally safe for human health. Since the concentration of PAHs can be reduced by appropriate selection of operating conditions such as pyrolysis speed and temperature range, biochar with negligible PAH content is achievable (Shackley et al., 2010). Consequently, PAHs in biochar do not threaten human health.

4.1.2 HEAVY METALS

Aside from PAHs, another kind of contaminant that usually appear in biochar is heavy metals. Heavy metals include cadmium, copper, chromium, lead, zinc, mercury, nickel, and arsenic. Human bodies require certain amounts of some heavy metals, such as zinc and copper for good health; however, others, such as mercury, lead, arsenic, and cadmium provide no benefits to human health. Also, excessive amount of heavy metals ingested can poison the human body and damage the organs. Some biomass feedstocks are found to contain heavy metals (Lehmann & Joseph, 2012). Given that they are grown in non-contaminated soils, the concentrations of heavy metals in them are low even after they are converted to biochar; however, even low concentrations of heavy metals are harmful to human health because the human body is unable to eliminate them (Suruchi & Khanna, 2011). In addition, some landfill waste and industrial waste such as sewage sludge are commonly found to contain high levels of heavy metals; therefore, it is necessary to understand the biomass feedstock used to produce the biochar that we consider purchasing. Consequently, a careful selection of biochar is necessary to avoid using biochar that contain heavy metals at the UBC farm.

4.2 SUSTAINABILITY OF BIOCHAR

The UBC farm is currently using compost on most of its production fields. Some of the compost used is produced on site and is made primarily from green organic waste such as crop residues. Similar to compost, biochar can be produced by using organic waste; however, we are not looking into producing our own biochar on site because of economical reasons. The primary reason is that pyrolysis plants are generally expensive to operate and maintain, relative to the cost of buying biochar. Instead, we will be buying biochar from local companies. Because local companies are likely to produce biochar using local organic waste, by buying biochar from them, we indirectly reduce the amount of organic waste being sent to our local landfills. This helps UBC in promoting sustainability. On the other hand, if we buy biochar that is not made from organic waste but from unprocessed feedstock like virgin timber, then we no longer are promoting sustainability. The use of unprocessed feedstock to produce biochar involves land clearance which may release the carbon dioxide stored in soils. In this case, the use of biochar might possibly emit more carbon dioxide than it sequestrates carbon dioxide (Woolf, Amonette, Street-Perrott, Lehmann, & Joseph, 2010). Consequently, since producing biochar from organic waste does not pose risks to the environment such as deforestation, it is most sustainable to use organic wastes for the production of biochar. Also, buying biochar made from organic waste is the best way for UBC to promote sustainability.

5.0 CONCLUSION

After a comprehensive triple bottom line assessment, we can make a final recommendation in the use of biochar as a soil amendment at the UBC Farm. According to our research so far, biochar can be used as a successful soil amendment based on its proven environmental and social benefits. Its ability to provide superior water and nutrient retention can be of great value to the Farm, given the presence of sandy soil. Its ability to reduce GHG emissions also makes it a superior choice as compared to agricultural lime. Given the use of processed organic waste as feedstock, biochar can be used to reduce waste going to landfills and thus promote sustainability. Also, using feedstock devoid of heavy metals and toxic materials can ensure that the biochar used is healthy for handling and socially sustainable. Economically, biochar does not seem to be a good replacement for agricultural lime as the costs associated exceed the revenue generated by selling carbon offsets. But over the long run, given a small size field of application, it might be possible to break even with the cost of implementing biochar. This is after taking into consideration the longer lifetime of biochar and also the projected rise in the prices of carbon offsets. We can also offset the high prices for biochar by taking into consideration the money saved on the decreased use of nutrient supplements every year. The viability of biochar also lies in the ability to value the monetary loss incurred by its implementation against its environmental and social benefits.

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APPENDIX A

The following is an email conversation with Jessica Dennis, the lead researcher on the UBC biochar project:

Hey APSC 262 folk and Veronik,

I have answered the first two questions - for the last question financial records and application rates are needed and I do not have easy access to these.

1. What kinds of soil amendment were previously used at the UBC farm?

The UBC Farm uses compost on the majority of its production fields. Some of the compost is made on site and is made from crop residues and organic material from the UBC Farm as well as a selected donated organic residues from campus.

Some compost is also purchased from a supplier in the Fraser Valley to supplement the compost produced on site. The compost produced on site is not very high in nitrogen (a limiting nutrient as you likely know) due to the fact that the feedstock is primarily green material (not manures). Hence the purchased compost may be mushroom manure or poultry litter based manure.

The UBC Farm also uses other amendments where needed. Lime is widely spread as the soil pH tends to be slightly acidic and it is beneficial to raise the pH for crop production. Lime is also a source of calcium. (Biochar could potentially, in theory, reduce need for lime as most biochar is slightly alkaline)

Blood meal (powder form) or fish fertilizer (liquid) may used on crops that are very high nutrient users and/or at at a stage in a crops lifecycle where larger amounts of nutrients are need - example just before bloom or fruiting of a plant.

2. What challenges are they facing that we are considering to make the switch to Biochar?

The UBC Farm is not considering a switch to biochar. We are considering supplementing our current amendment regime with biochar in hopes that biochar may improve the retention and uptake of nutrients (UBC has sandy soils) and may potentially reduce the amount of annual nutrient inputs added to the soil. Biochar is not a very good source of plant nutrient and biochar does not replace other soil amendments. Biochar improves soil properties that are in turn beneficial to crop growth rather than directly adding nutrients that are available to plants. If you would like further information on the effects of biochar on soil properties and crop growth I can recommend some litterature on the subject.

3. How can we investigate the cost for the soil amendments that UBC is currently using? It would be useful for us to compare it to the cost of using biochar.

This question I would direct to Tim Carter (tim.carter@ubc.ca) the field manager at the farm who does the ordering. or perhaps Natalie Yuen for financial records.
Need to figure out:
Cost of compost on site = cost of labour to make this compost =
Cost of purchased compost =
Cost of lime =
Cost of other mineral nutrients spread (Boron,?) =
Cost of blood meal, or fish fertilizer used =

I am not sure if annual data is available on average cost of soil amendments for one season. Alternatively, Tim could perhaps provide you with some rates of application and cost of amendments either per hectare or acre and you could do a cost estimate based on an area of application and then compare to estimated amount of biochar you would add to that same area? Depending on your project details - you could maybe even narrow it to a particular crop (ideally beets cause that is what we will be adding biochar to this summer, and figure out cost of amendments added per area of beet crop at UBC Farm.

Please feel free to send along other question.
Cheers,
Dennis

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APPENDIX B

Table 1: Variable Values in Cost Estimation using Broadcast and Disk Application.

Variable	Definition	Units	Notes:
t_b	Total time	hours	s/r
s	Saturation rate	Tons/acre	Ideal rate unknown
r	Discharge rate	ft^3/minute	$8.9ft^3$/minute[a]
l_b	Labor	$/hour	$12/hour[b]
f_b	Fuel	$/hour	17.42[c]
m_b	Maintenance	$/hour	$3.97/hour[c]
A_b	Application Cost for Broadcast	$	$A_b = t_b * (l_b+f_b+m_b)$
D	Cost of Disking	$	$15[d]
C_b	Total cost – broadcast app.	$	$C_b = A_b + D$

Table 2: Variable Values in Cost Estimation using Trench and Filling application.

Variable	Definition	Unit	Notes
s	Saturation Rate	Tons/acre	Ideal rate unknown
d	Trench depth	ft	1-2'
n	Number rows/ acre	n/a	Depends on *s*, *d*.
r_t	Trenching/application rate	ft/minute	Between 12-20'/minute
t_{tr}	Time - trenching	hours	
$l_{t,a}$	Labor cost of trenching, application	$/hour	Both based on custom rate for high level tractor operator in Western Colorado[a]
f_{tr}	Fuel cost for skid steer	$/hour	7.2 ga/hour * $2.50/ga = $18.00[b]
m_{tr}	Maintenance for skid steer	$/hour	$4/hour; estimated from average maintenance cost over 1,000 hours[c]
T	Subtotal cost for trenching	$	
f_a	Fuel cost of tractor/applicator	$/hour	$17.42/hr[d]
m_a	Maintenance for tractor	$/hour	$3.97/hour[e]
A_t	Subtotal cost for Application	$	
C_t	Total cost Trenching Process	$	