

Project Title: Effect of Biochar Application on Soil Fertility and Crop Productivity in Sandy Soils of Happy Valley-Goose Bay, NL

Executive Summary:

Most foods sold in northern and remote communities like Happy Valley-Goose Bay, Labrador are transported from distant places. Handling and long-distance transports diminish food quality and increase price. The long-term, sustainable solution for local food security in such communities is therefore to find ways to produce more local foods and fresh vegetables. Factors hindering successful crop production in the Happy Valley-Goose Bay area include late springs and early fall frosts, high soil acidity, low soil organic matter and a sandy soil texture, which exhibits low cation exchange capacity (CEC), low holding capacity for nutrients and water, and poor soil structure. Among these factors, late springs and early fall frosts can often be addressed by choosing short duration food crops that can be grown during the frost-free days. However, it is not always possible to avoid cold temperatures, because weather patterns are not always predictable. We cannot change soil textures, but there are management practices that can be used to enhance retention of nutrients and water, to increase soil organic matter content and CEC, to improve soil structure and to reduce soil acidity.

Biochar (a carbonaceous material produced through pyrolysis of biomass) is a unique material that when applied as soil amendment can effectively improve the physical, chemical and biological properties of soil, and thereby solve many of the soil limitations stated above. Biochar is persistent in soils and its beneficial effects are longer lasting when compared to other forms of organic matter such as manure. In this study we evaluate the effectiveness of biochar as a soil conditioner and fertility enhancer and ascertain its nutrient-supplying capability when applied singly or in combination with fish meal. We also compared different rates of biochar application on soil health and crop productivity in the sandy soils of Happy Valley-Goose Bay, NL.

In this present study we did not observe any significant positive effect of biochar on soil temperature or moisture holding capacity. Soil pH and Mehlich 3 extractable Ca, K, Mn and P in experiment one and Mehlich 3 extractable K and Mn in experiment two were significantly increased by biochar application. Biochar also slightly improved soil CEC, organic matter content and extractable concentration of Zn and sulphur. Although biochar application had significant positive effects on a number of soil properties, singly applied biochar was unable to help in crop establishment, plant growth or crop yields. The preliminary results revealed that biochar application can significantly increase plant growth and biomass yield only when biochar is applied along with fishmeal and fertilizers. However, it is essential to continue the research for a number of years to verify the results that we have obtained in the first year (2013) before making any recommendations regarding the use of biochar for the enhancement of soil quality and crop productivity.

Background and Rationale for Investigation:

The Soil and Land Management Division of the Department of Forest Resources and Agrifoods, Government of Newfoundland and Labrador identified late springs, early fall frost, low soil organic matter, sandy soil texture and low soil pH as the primary problems related to crop production in the Happy Valley-Goose Bay area (Department of Forest Resources and Agrifoods, 2002). The maximum

production potential of a particular crop depends on many factors, broadly classified as climatic factors (precipitation, air temperature, relative humidity, light, altitude, latitude, wind velocity and its distribution etc.), soil factors (nutrients, pH, depth, organic matter, water holding capacity, texture, structure, CEC and base saturation, soil temperature, tillage, drainage, slope etc.) and crop factors (crop species/variety, planting date, seed quality, seeding rate/row spacing, evapotranspiration, insects, disease, weeds) (Havlin et al. 2005). Of these factors, we generally do not have control over climatic factors, but soil and crop factors can be effectively managed and improved to maximize crop productivity.

Organic matter is a crucial constituent of soils, and impacts their physical, chemical and biological properties. A carbon content of 2% (3.4% soil organic matter) has been identified by the European Commission as a critical figure for sustainable crop production (Hanegraaf et. al. 2009). However, the organic matter content of the sandy soils of the Happy Valley-Goose Bay region is below this threshold, varying generally between 0.75-1.5% (Department of Forest Resources and Agrifoods, 2002). Sandy soils are known to have very limited water holding capacity compared to fine textured clay-based soils as the surface area of clay particles can be as much as 10,000 times higher than same weight of medium sand (IPNI, 2006). The low water holding capacity of soils means that drought is often a problem for successful crop production and can compromise the economic viability of agricultural operations.

Soil organic matter (SOM) has other inherent advantages, being fundamental to building needed soil structure as it provides proper cementing material required for the grouping of primary particles to secondary aggregates (or peds). A carbon content of less than 2% (a measure of SOM) is reported to cause a significant decline in the structural stability in many soils found throughout the United States and Canada (Loveland and Webb, 2003). This is of particular significance to commercial operations, and measures aimed at enhancing soil structure through the incorporation of SOM become especially important.

Finally, soil type also impacts nutrient availability, nutrient retention and cation exchange. In sandy soil, SOM content is the main source of nutrients and therefore, the soil's ability to supply essential nutrients is low. Moreover, this soil has lower nutrient retention capacity compared to clay or to soils with higher SOM content. In particular, nutrient cations are retained by negatively charged sites in clay or SOM where the total negative charges in soil are comprised of 'permanent charge' (resulting from the isomorphous substitution of a lower charged ion for a higher charged ion), variable charge or pH-dependent charges (resulting from increasing soil pH). At acidic soil pH, $\text{Al}(\text{OH})^{2+}$ ions occupy the negatively charged sites and make them unavailable for other cations, while also possibly affecting root development (Brady, 1990). For these reasons, the relative contributions of clay and SOM to cation-exchange capacity are of interest to soil scientists considering soil fertility enhancement. It is estimated that each percent of representative clay and SOM on average contributes to 0.5 meq and 2.0 meq, respectively, for clay and SOM (St. Arnaud and Sephton, 1972). Due to cold climatic conditions the mineralization rate of organic matter is expected to be low (Allison and Treseder, 2011) and organic matter will furnish a limited supply of mineral nutrients to the crop. Furthermore, soil organic matter not only supplies nutrients to growing crops, but also acts as a nutrient and energy source for the microbial biomass that is responsible for many processes benefiting higher plants. Positive effects include the decomposition of organic matter, the transformation of organically bound forms of nitrogen, phosphorus and sulphur into plant-available inorganic forms, and biological nitrogen fixation (Brady, 1990).

On the whole, proper soil management/amendment practices must be chosen to improve soil's physical, chemical, and biological conditions, particularly in cold climate regions with less than ideal growing conditions. Biochar (a product obtained from combustion of biomass such as wood, fish meal, leaves, etc. through a process called pyrolysis) has been drawing renewed attention within agricultural communities (Yuan et al. 2011), and potentially holds great promise as soil amendment, within the context of this study.

The use and utility of biochar as a soil amendment is not a new concept. Amazonian dark earths, often referred to as 'terra preta', can be found throughout certain areas of South America and occur as a result of habitational activities or deliberate soil application by Amerindian populations that occurred before the arrival of Europeans (Lehmann et al. 2006; Barrow, 2012). These "islands" of dark earth can be quite large and would have received large amounts of charred materials (i.e. charcoal) as a result of carbon applications (residues of incomplete combustion of organic material). Within these dark soils, up to 60 cm deep, carbon concentrations can be 70 times higher (mean: four times higher) in 'terra preta' soils than in adjacent soils derived from the similar parent material (Glaser et al. 2001). The carbon content of these soils is so chemically and microbially stable that it persists for centuries (Glaser et al. 2001). Importantly, 'terra preta' soils remain very fertile and are characterized by higher (approximately three times higher) levels of soil organic matter (SOM), higher nutrient holding capacity for nutrients such as nitrogen, phosphorus, calcium and potassium, higher pH values and higher moisture-holding capacity than in the surrounding soils (Barrow, 2012). The implications for soil enhancement and crop productivity are huge, with researchers now exploring the potential for copying and reproducing the dark earth soil by introducing carbon-rich materials (i.e. biochar) to less fertile soils, which is essentially the premise of this study. A synopsis of the reported benefits of biochar and supporting research is provided in the following paragraph.

Biochar application increases soil organic carbon levels (McHenry, 2011; Kwapinski et al. 2010) and improves soil structure (Glaser et al. 2002). Its application improves the soil's ability to retain moisture (Laird et al. 2010a; Steiner et al. 2007), prevents nutrient leaching (Taghizadeh-Toosi et al. 2012; Spokas et al. 2012; Ding et al., 2010) and increases cation exchange capacity (Clough and Condron, 2010; Inyang et al. 2010, Yuan and Xu, 2011). Application of biochar reduces aluminum toxicity (Van Zwieten et al. 2010) and bioavailability of heavy metals (Mendez et al. 2012), increases soil pH (Yuan and Xu, 2011; Deal et al. 2012), supplies essential plant nutrients and decreases the need for chemical fertilizers (Bird et al. 2011; Glaser et al. 2002). Biochar improves the biological condition of soils (Kwapinski et al. 2010; Lehmann et al. 2011), increases soil microbial biomass and supports beneficial organisms like earthworms (Lehmann et al. 2011). The conversion of biomass to biochar reduces greenhouse gas emissions (Lehmann, 2010; Wang et al. 2011) and helps in sequestering atmospheric carbon in to the soil (Lehmann, 2007; Bolan et al. 2012).

Thus biochar has the potential for broad application in carbon sequestration, reduction of greenhouse gas emissions, remediation of heavy metal toxicity, supply of plant nutrients, retention of nutrient elements and soil conditioning (i.e. providing favourable physical, chemical and biological condition for optimum crop growth). The broad objective of this project is to thoroughly study the benefits of biochar application on soil health and crop productivity in the sandy soils of Happy Valley-Goose Bay, NL. One aspect of this project will be to examine the positive effects of biochar on soil pH, water/nutrient retention, soil structure and the growth and yield of representative crops. The second aspect would be to evaluate the nutritional value of biochar by comparing it with fish meal, which is commonly used by local farmers at present. The other aspect is to define the amounts of supplemental applications of fishmeal and/or fertilizer needed for the biochar application to maximise crop productivity and soil quality.

Funding and Partnerships:

This project has been solely funded by Agriculture Research Initiative. However, we have received some in-kind support from Desmond Sellars who provided the land for experimentation and equipment for preparing the land, and also helped in sourcing fish meal, setting up experiments and collecting soil and plant samples.

Methods and Implementation:

Experiment 1: Soil fertility enhancement through biochar, fishmeal and chemical fertilizer application.

The objective of this experiment was to evaluate the effectiveness of biochar as a soil conditioner and fertility enhancer and to ascertain its nutrient-supplying capability when applied singly or in combination with fish meal or chemical fertilizers we initiated an experiment titled .

Location:

The area selected for the experimentation is located within a designated agricultural area of the Happy Valley metropolitan area. The research was conducted at the Southern area of Lot 5 (Agricultural Lease 133 309).

Crop and experiment management:

We originally planned to grow red beet as a test crop. Beet seeds (variety: Detroit Dark Red) were purchased from Vesseys. The seeds were sown June 23, 2013, using a 2-rows hand seeding device (JP-3/Jang Automation Co., Ltd) with an inter-row spacing of 30cm. The seeds were placed at a depth of approximately 2 cm, with a rate of 16 seeds per meter. Thinning was planned to adjust the population to the final desired 6 plants per meter of row (a plant density of 200,000 plants per hectare) at the 4 real leaf stage. Because of seedling disease the seeds of same variety were reseeded on July 3, 2013, following earlier seeding procedures. But again, the seedlings were infected with the same disease. Very few seedlings survived in the earlier stage, and we arranged supplemental irrigation as the upper soil layer was dry due to a lack of rainfall during that time. All these efforts were not successful enough to have sufficient healthy seedlings in the experimental plots, so we decided to grow another crop (canola) which farmers grow as a leafy vegetable which could be harvested within the remaining crop growing season. The seeds of canola were seeded on July 15, using a JP-3 hand seeding device with 30 cm row-spacing. The experimental plots were covered by row cover to protect the plants from insect attack.

Experimental Design and Treatments:

This experiment studied the effects of a number of soil amendments and their interactions. The test crop (i.e. canola) plots were exposed to different combinations of biochar, chemical fertilizers and fish meal. Biochar was added and incorporated in the soil (10-15 cm in depth) at a rate of 20 t of C per ha, in a dry basis (it had 4% water content and 70% C content). The biochar, chemical fertilizer and fish meal were applied to the experimental plots before crop seeding on June 22, 2013. Incorporation of biochar, chemical fertilizers and fishmeal was done using an engine-tiller (208cc Engine, Rear Tine Tiller/Craftman ®). The experiment was set in a randomized block design in which every block consisted of 10 treatments, and there were five blocks. The layout of the experiment is shown in 'Figure 1' and the description of treatments is as follows:

- 1) **Control (C):** no biochar, chemical fertilizer or fish meal was applied.
- 2) **Biochar (B):** only biochar @ 20 t C/ha was applied.
- 3) **Chemical Fertilizer full rate (1F):** Chemical fertilizer @ 175-118-128 lbs/acre for N, P₂O₅ and K₂O, respectively (no biochar or fish meal were applied)
- 4) **Fish Meal full rate (1M):** Fishmeal @ 2 t/ha (no biochar or chemical fertilizer were applied).
- 5) **Chemical Fertilizer half rate (1/2F):** Chemical fertilizer @ 87.5-59-64 lbs/acre for N, P₂O₅ and K₂O, respectively (no biochar or fish meal were applied).
- 6) **Fish Meal half rate (1/2M):** Fishmeal @ 1 t/ha (no biochar or chemical fertilizer were applied).
- 7) **Biochar + Chemical Fertilizer full rate: (B+1F)**

- 8) **Biochar + Chemical Fertilizer half rate: (B+1/2F)**
- 9) **Biochar + Fish Meal full rate: (B+1M)**
- 10) **Biochar + Fish Meal half rate: (B+1/2M)**

Note: To obtain the full rates (175-118-128 lbs/acre for N, P₂O₅ and K₂O, respectively) or half rates (87.5-59-64 lbs/acre for N, P₂O₅ and K₂O, respectively) of chemical fertilizer we bought 3 bags of fertilizer with different rates (20-10-5, 24-4-12 and 12-24-24 for N, P₂O₅ and K₂O, respectively) and mixed them at 1:1:1 ratios.

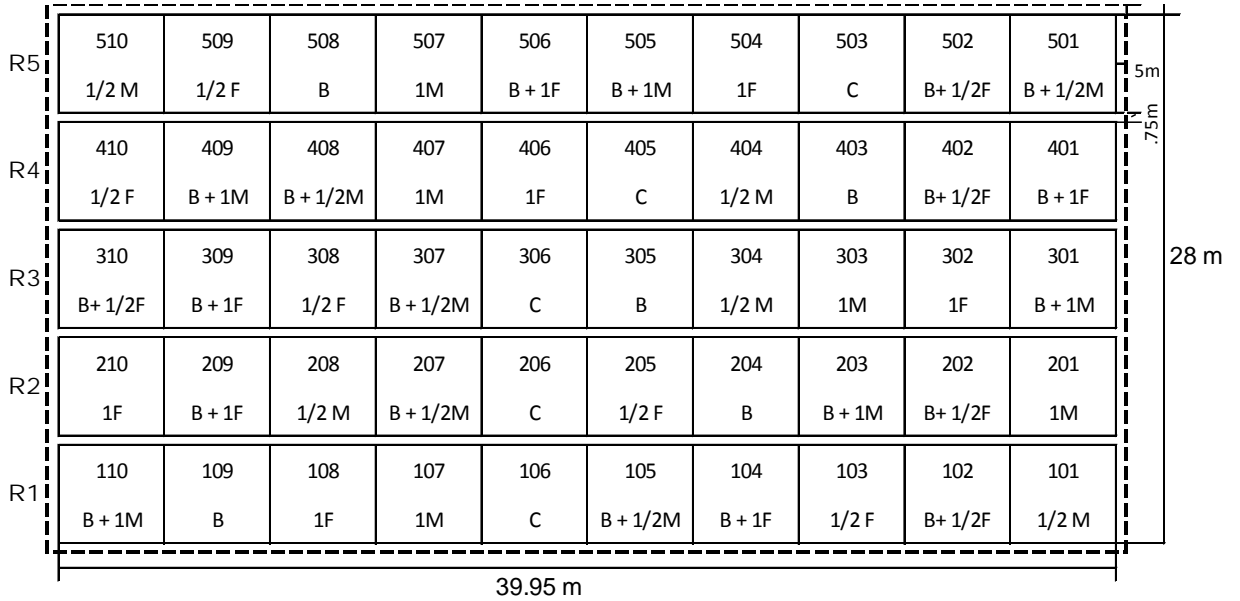


Figure 1: Layout showing the distribution of treatments for experiment 1 in the field

Measurements:

Initial soil characterization: Before soil amendment, seven sub-samples were collected from each plot (at 0-15 cm depth) and the sub-samples were mixed to get a composite sample for each plot. A grand composite sample was made by mixing a portion of soil from each plot. Ten randomly collected subsamples from 15-30 cm and 30-45 cm depth were mixed separately to obtain a composite sample for each depth. The composite samples were analyzed to determine texture (the grand composite sample was used for 0-15 cm depth), organic matter, pH, CEC, EC, P, K, Ca, Mg, Fe, Mn, Zn, Cu and B.

Moisture holding capacity: Soil sampling for the determination of moisture content was done at the end of the season. The purpose of this measurement was to study the effect of biochar on the soil’s water-holding capacity. Three sub-samples were randomly taken from control plots (no biochar, no fertilizer and no fishmeal) and biochar-only treatments at a 0-15 cm depth between 12 and 24 hours after a heavy rain, to make sure that soil at that depth is saturated. Samples were collected in separate glass containers for each plot. Glass containers with moist soil were weighed, then dried in a drying oven until the weight of the container plus dry soil reached a constant weight. The moisture content of the soil in each sample was then calculated using the following formula.

$$\% \text{ moisture} = \{[(\text{container plus moist soil}) - (\text{container plus dry soil})] / (\text{container plus dry soil} - \text{empty container})\} \times 100$$

Harvesting: Harvesting was done on August 26, 2013. A wooden frame (inside area: 2m x 1m) was placed at the centre of the experimental plots and the above-ground portion of the canola plants inside the

frame (total area 2m²) was reaped. The yield was then calculated from the green weight for each plot. A number of plants from each plot were taken for the determination of nutrient elements. After recording the green weight and keeping samples for chemical analysis, the experimenter returned the remaining plant materials to their respective plots.

Season end soil characterization: Soil samples from 0-15 cm and 15-30 cm were collected after harvesting was completed. Seven sub-samples were collected from each plot at each depth and mixed to get a composite sample for each depth. The composite samples were analyzed to determine their content of organic matter, pH, CEC, EC, P, K, Ca, Mg, Fe, Mn, Zn, Cu and B.

Experiment 2: Effect of biochar rates on soil fertility and crop productivity in sandy soils of Happy Valley-geose Bay, Labrador.

The objective of this experiment was to study the response of crop yield and, soil properties and nutrients movement in the soil to increasing rates of biochar application.

Location:

The area selected for the experimentation is located within a designated agricultural area of the Happy Valley metropolitan area. The research was conducted at the Southern area of Lot 5 (Agricultural Lease 133 309).

Crop and Experiment Management:

Red beets variety Detroit Dark Red (Veseys Seeds) was seeded on June 21 using a 2-rows hand seeding device (JP-3/Jang Automation Co., Ltd) with an inter-row space of 30 cm. Seeding was done at a depth of approximately 2 cm, at a rate of 16 seeds per meter of row and after emergence, at the 4 real leaf stage, thinning was done to adjust the population to the final desired 6 plants per meter of row (16.6 cm inter-plant distance). That plant pattern was expected to result in a density of 200,000 plants per hectare, but because of seedling disease the number of healthy plants per row was less than we expected, and the plants were not uniformly distributed in the plot. The plots were kept weed-free manually.

Experimental Design and Treatments:

All experimental plots received a basal chemical fertilizer dose of 175-118-128 lbs/acre for N, P₂O₅ and K₂O, respectively. To obtain this dose, 3 bags of fertilizer with different rates (20-10-5, 24-4-12 and 12-24-24 for N, P₂O₅ and K₂O, respectively) were mixed at 1:1:1 ratio. Fertilizer was uniformly distributed in the plots and incorporated at a 10-15cm depth with an engine-tiller (208cc Engine, Rear Tine Tiller/ Craftman ®).

In this experiment, the effects of different rates of biochar were evaluated. Biochar was added at a rate of 0, 10, 20, and 40 tonnes of C per ha, on a dry basis (the biochar contained 4% moisture and 70% C content). The biochar and chemical fertilizer were applied to the experimental plots before crop seeding on June 20, 2013. Incorporation of biochar and chemical fertilizers was done at 10-15 cm depth using an engine-tiller (208cc Engine, Rear Tine Tiller/ Craftman ®). The experiment was set in a randomized block design for which every block was consisted of 4 treatments and there were four blocks. The layout of the experiment is shown in 'Figure 2' and the description of treatments is as follows:

1. **Control:** no biochar
2. **Biochar:** biochar @ 10 t C/ha was applied
3. **Biochar:** biochar @ 20 t C/ ha was applied
4. **Biochar:** biochar @ 40 t C/ ha was applied.

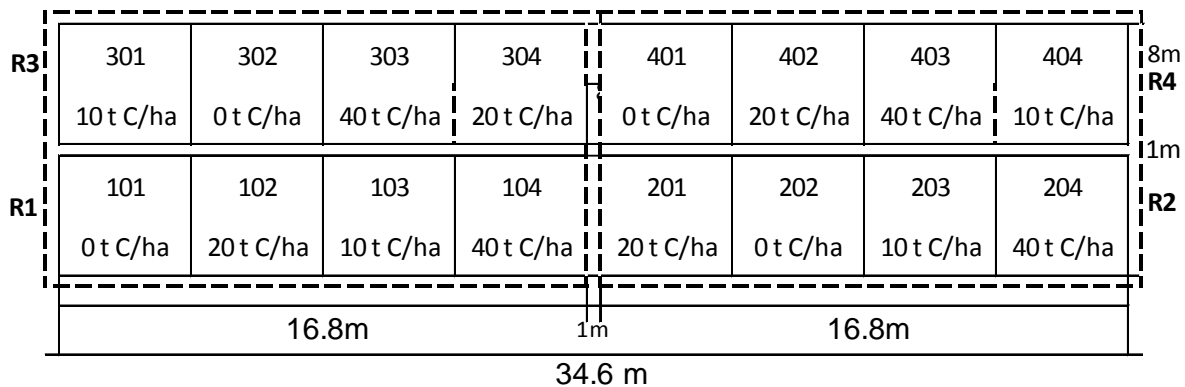


Figure 2. Layout showing distribution of different biochar treatments in the field for Experiment 2

Measurements:

Initial soil characterization: Before the application of biochar and chemical fertilizers, seven sub-samples were collected from each plot (at 0-15 cm depth) and the sub-samples were mixed to get a composite sample for each plot. A grand composite sample was made by mixing a portion of soil from each plot. Ten randomly collected sub-samples from 15-30 cm and 30-45 cm depth were mixed separately to obtain a composite sample for each depth. The composite samples were analyzed to determine texture (the grand composite sample was used for 0-15 cm depth), organic matter, pH, CEC, EC, P, K, Ca, Mg, Fe, Mn, Zn, Cu and B.

Characterization of biochar: About one kilogram of biochar sample was taken from the bag and separated into three portions depending on grain size [biochar powder (< 2 mm), granular biochar (2-8 mm) and biochar chunk (>8 mm)]. All three biochar samples were sent to the lab for chemical analysis. Thermal-gravimetric analysis (TGA) of biochar was performed at the Department of Chemistry, Memorial University (through the courtesy of Prof. Bob Helleur).

Moisture holding capacity: Soil sampling for the determination of moisture content was done on two occasions, during the crop growing season and at the end of the season. The purpose of this measurement was to study the effect of biochar amendment on soil's water-holding capacity. Three sub-samples were randomly taken from each experimental plot at a 0-15 cm depth between 12 and 24 hours after a heavy rain, to make sure that the soil at that depth was saturated. Samples were collected in separate glass containers for each plot. The glass containers with moist soil were weighed and dried in a drying oven until the weight of the container plus dry soil reached a constant level. The moisture content of the soil is then calculated using the following formula.

$$\% \text{ moisture} = \left\{ \frac{[(\text{container plus moist soil}) - (\text{container plus dry soil})]}{(\text{container plus dry soil} - \text{empty container})} \right\} \times 100$$

Measurement of soil temperature: Measurements were taken to study the effect of the biochar on soil temperature at a depth of 2 to 5 cm (i.e., where the seed germinates and where temperature has the greatest impact on the early days of seedling development). Soil thermometers (item # 82084) bought from Vesseys were used to measure temperature at 4 cm depths from 5 spots in each experimental plot. A sunny day was selected for this measurement and data were collected both in the morning and in the

afternoon. Temperature measurement was done only in experiment 2 where different treatments received different rates of biochar.

Harvesting the crop: Harvesting was done on September 15, 2013 and all plants in the experimental plots were harvested to calculate the yield. Plants were separated into leaf and root portions and weighed separately, soon after harvest. A number of whole plants (leaves plus roots) were weighed and kept for chemical analysis. After the fresh weight was recorded, and samples were kept for chemical analysis, the leaves were returned to the respective plots and roots were retained.

Season-end soil characterization: Soil samples from 0-15 cm and 15-30 cm were collected after harvesting was completed. Seven sub samples were collected from each plot for both depths and the sub-samples were mixed to get a composite sample for each depth. The composite samples were analyzed to determine organic matter, pH, CEC, EC, P, K, Ca, Mg, Fe, Mn, Zn, Cu and B.

Results and Discussion for Experiment 1

Initial soil characteristics: The initial (i.e before applying any amendment) soil properties at three different depths are presented in Table 1. The soil of the experimental site has a coarse texture, highly acidic pH and low organic matter content. The subsoil is coarser than the top soils. Soil acidity decreases with increasing soil depths where the pH of 0-15 cm depth soil is 0.3 units lower than that of 30-45 cm depth soil. The soil organic matter content and CEC also decrease with increasing soil depths. The CEC of all the three soil layers are very low (<7 Cmol/kg). There are distinct differences in nutrient concentrations among the soil depths. In general upper soil layer has more available nutrient concentrations than the lower soil layers (0-15 cm > 15-30 cm > 30-45 cm). Available concentrations of all the nutrient elements in 15-30cm and 30-45 cm depth are extremely low except Fe (very high) and B (high). The Mehlich 3 extractable concentrations of P, Ca, Mg and K in upper soil layer (0-15cm) can be considered below optimum, very low to medium low (Sims and Gartley, 1996).

Table 1: Initial soil characteristics for experiment 1

Parameters	0-15 cm	15-30 cm	30-45 cm
Texture	Loamy sand	sand	sand
Soil pH	4.7	4.8	5.0
O.M. (%)	2.7	1.71	1.15
CEC (Cmol/ kg)	6.3	4.59	3.47
Ca (ppm)	166.0	60	23
Mg (ppm)	71.0	30	16
K (ppm)	26.0	16	10
P (ppm)	26.0	28	23
Fe (ppm)	719.0	709	677
Cu (ppm)	0.2	0.18	0.30
Mn (ppm)	7.0	3.0	1.2
Zn (ppm)	1.2	0.64	0.40
B (ppm)	1.7	1.6	1.5

Nutritional properties of biochar and fishmeal: The biochar used in this study contained 3% moisture, 8% ash and 19% volatiles (as per TGA results). Nutrient concentrations in biochar varied depending on

the grain sizes for all the elements except for Co (Table 2). In general coarser materials had higher nutritional values. Concentrations of P, K, Ca and Mg in fishmeal were much higher than those in biochar.

Table 2: Nutritional properties of different biochar and fishmeal

Sample ID	P	K	Ca	Mg	Fe	Mn	Zn	Cu	Co
	%					ppm			
Biochar (ground)	0.01	0.10	0.42	0.03	0.03	160	20	3	1
Biochar (granular)	0.03	0.25	0.96	0.06	0.04	361	44	4	1
Biochar (chunk)	0.04	0.26	1.25	0.09	0.13	494	52	5	1
Fishmeal	>1.00	>1.10	3.66	0.27	0.06	14	79	9	1

Moisture retention capacity: Moisture content determined by gravimetric methods shows no significant difference between biochar and control plots. Variation in moisture contents among the same treatment plots was remarkable (Table 3).

Table 3: Effect of biochar on moisture retention capacity of soil

Treatment	Soil moisture (%) \pm S.D
Control	37.53 \pm 6.13
Biochar	38.31 \pm 7.75

Effects of different amendments on soil properties: A number of soil properties (pH and Mehlich 3 extractable Ca, K, Mn and P) were significantly ($p < 0.0001$ for all except P ($p < 0.05$)) affected by different soil amendments (Table 4). In general, soil pH increased 0.1 unit because of biochar application whereas fertilizer and fishmeal application tend to decrease soil pH up to 0.3 units. Results from a number of field and greenhouse experiments report an increase in soil pH due to biochar application (Deal et al. 2012; Yuan and Xu, 2011; Yuan et al. 2011). There was a small increase in soil organic matter content in biochar and fishmeal treatments. There was variation in CEC among the different amendments with no distinct trend. However, Deal et al (2012) and Van Zwieten et al (2010) in their pot experiment observed a slight increase in CEC due to biochar application. The Mehlich 3 extractable nutrient concentrations in different amendments were generally higher than the control with exceptions in Fe, Cu and B. The concentrations of basic cations (Ca, Mg and K) in biochar treatments were generally higher than the other soil amendments (fertilizer and fish meal). Similar results of increased base cation concentrations were also reported in earlier literature (Yuan et al., 2011). The soils in fishmeal treatments were found to have more available base cations except K than the fertilizer treatments. Available P concentrations in biochar treatment were as good as the full fertilizer and full fishmeal treatments. Available Mn concentrations in biochar treatments were noticeably higher than the control, fertilizer and fishmeal treatments. The available Zn concentrations in biochar amendment were slightly better than the control or other soil amendments. There was a small increase in available S concentrations due to soil amendments but the difference between the different amendments was very small. Laird et al (2010b) observed an increase in Mehlich 3 extractable P, K, Mg and Ca with biochar amendment, which supports the preliminary results of this multi-year study.

Soil pH ($p < 0.01$), CEC ($p < 0.01$) and Mehlich 3 extractable Ca ($p < 0.01$), K ($p < 0.0001$) and S ($p < 0.01$) were significantly affected by different soil amendments (Table 5). The effects of soil amendments on 15-30 cm depth soils were very similar to those on 0-15 cm depth soils which is due to the fact that the applied soil amendments were also mixed in to the 15-30 cm depth soils during incorporation, or washed down later on by rainwater.

Table 4: Soil characteristics at 0-15 cm depth after one year of cropping

Treatment	Soil pH	O.M. (%)	CEC (Cmol/ kg)	Ca	Mg	K	P	Fe	Cu	Mn	Zn	B	S
				(ppm)									
C	4.8	2.9	7.3	163	62	21	22	507	0.42	4.5	0.84	1.25	7.18
B	4.9	3.6	7.9	308	90	51	28	526	0.31	8.6	1.20	1.35	8.53
1F	4.5	2.7	6.3	173	64	58	35	498	0.38	4.6	0.82	1.22	8.32
1M	4.6	3.3	7.7	251	91	30	33	539	0.22	5.6	1.08	1.32	8.56
1/2 F	4.7	2.9	8.6	195	79	36	27	559	0.52	4.8	0.85	1.40	7.36
1/2 M	4.6	2.8	7.3	186	68	24	27	551	0.35	4.6	0.90	1.39	7.82
B + 1F	4.8	3.0	7.1	274	72	81	31	558	0.39	7.4	0.87	1.44	8.84
B + 1M	4.9	3.1	7.6	332	80	52	34	543	0.33	8.3	1.09	1.41	9.22
B+ 1/2F	5.0	3.2	7.3	342	94	62	29	525	0.76	8.9	1.13	1.32	8.18
B + 1/2M	5.0	2.7	6.0	236	64	45	23	510	0.36	6.5	0.80	1.30	8.48

Table 5: Soil characteristics at 15-30 cm depth after one year of cropping

Treatment	Soil pH	O.M (%)	CEC (Cmol/ kg)	Ca	Mg	K	P	Fe	Cu	Mn	Zn	B	S
				(ppm)									
C	4.8	1.8	3.6	71	24	14	17	546	0.43	2.4	0.45	0.98	6.2
B	4.9	2.1	5.4	116	30	26	20	634	0.27	4.2	0.55	1.08	7.4
1F	4.6	1.5	3.1	64	23	23	21	529	0.35	2.0	0.36	0.93	6.1
1M	4.8	2.0	4.4	87	29	16	23	638	0.42	2.6	0.53	1.16	7.0
1/2 F	4.8	1.8	4.0	76	27	17	22	598	0.49	2.7	0.41	1.10	6.4
1/2 M	4.7	2.2	5.7	106	36	18	23	590	0.34	3.5	0.63	1.06	7.3
B + 1F	4.9	2.0	4.6	122	29	36	19	616	0.28	3.9	0.50	1.14	7.4
B + 1M	4.9	2.1	4.7	131	31	26	26	606	0.41	4.6	0.58	1.03	7.3
B+ 1/2F	4.9	1.9	4.7	115	30	26	24	593	0.35	4.5	0.54	1.09	6.8
B + 1/2M	5.0	1.7	4.4	99	26	21	21	545	0.49	4.1	0.49	0.96	6.6

Effect of biochar on plant growth and yield:

The growth and yield of canola plants was significantly ($p < 0.0001$) affected by different soil amendments. The germination of seeds in control and biochar treatments was very poor; the growth of seedlings was so stunted that at the end of cropping season there were no green plants to harvest (Figure 3). The inhibited growth of canola plants in the fertilizer and fishmeal treated plots where no biochar was applied resulted in very low yields. Conversely, growth of canola plants was very good when biochar was applied along with fertilizer and fishmeal. The highest green yield of 14.2 t/ ha was noted in B+1M treatment followed by 12.3 t/ha and 8.1 t/ha recorded in B+1/2F and B+1F treatments, respectively (Figure 4). The positive effect of biochar on plant growth and biomass yield has been reported by a number of researchers (Deal et al., 2012; Uzoma et al., 2011; Kimetu et al., 2008; Lehmann et al., 2003).

However, the variability in growth among the replications was so high that the difference in green yield between half and full doses of fertilizers plus biochar treatments were statistically insignificant. These results suggest that application of biochar can help in crop establishment, growth and plant yield on the sandy soils of Happy Valley-Goose Bay only when supplementary fertilizer or fishmeal is added. The reason for this huge variation in fertilizer plots (B+1F and B+1/2F) is not clear, but partly could be related to the dose of fertilizers which was based on the requirements of beet crops.

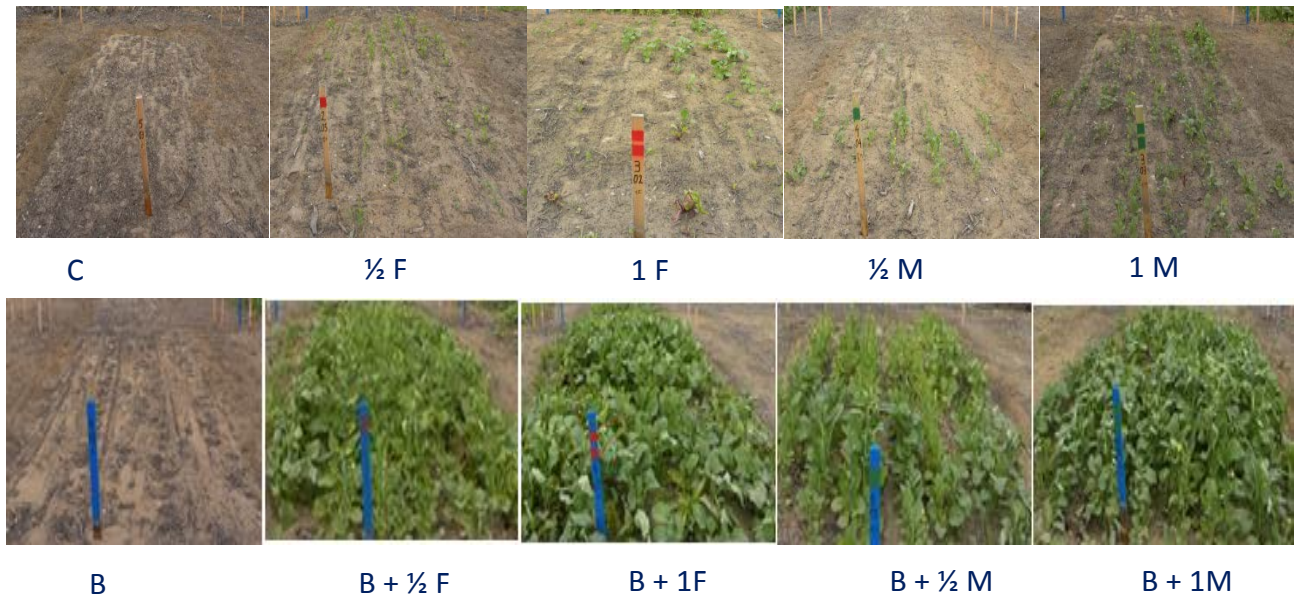


Figure 3: Canola greens in different amendment treatments at harvest

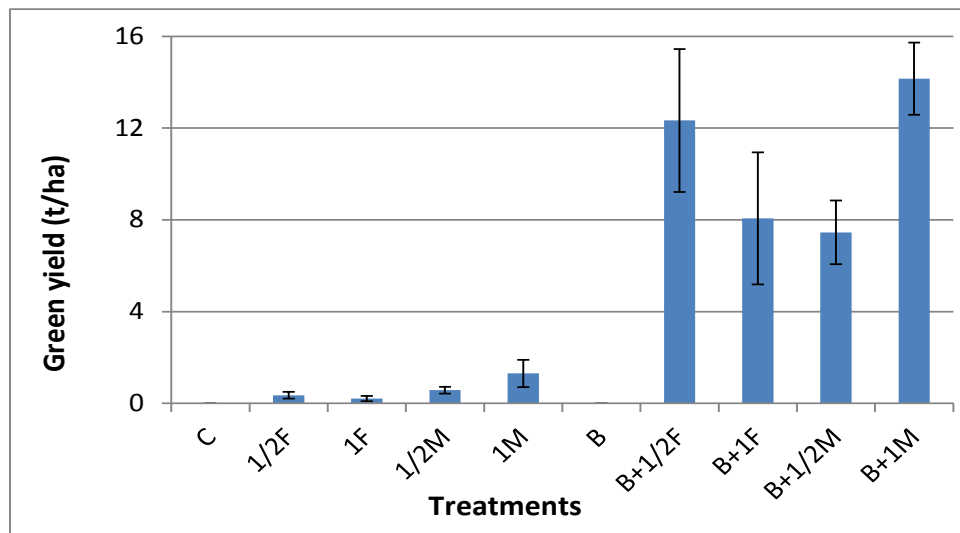


Figure 4: Effect of different soil amendments on the yield of canola green. Error bar represents \pm SE (n=5)

Mineral nutrition: Nutrient concentrations in canola green were affected by biochar application (Table 6). The concentrations of K and B were found to be increased due to biochar applications whereas the opposite trend was observed for N, Ca, Mg, Mn and Zn concentrations.

Table 6: Nutrient concentrations in canola green (above ground plant part) at different soil amendment

Treatment	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B
	%						ppm				
1F	6.43	0.67	4.94	1.03	0.66	0.34	226	12.2	194	47	13
1M	6.81	0.52	2.78	1.07	0.69	0.56	235	12.8	152	57	13
1/2 F	5.73	0.56	4.22	0.93	0.74	0.32	183	11.3	122	44	13
1/2 M	5.06	0.43	3.43	0.80	0.54	0.44	321	14.5	95	47	15
B + 1F	5.68	0.67	6.99	0.92	0.46	0.46	318	18.8	154	46	36
B + 1M	4.84	0.58	5.44	0.78	0.38	0.45	232	11.9	108	42	37
B+ 1/2F	3.37	0.51	5.67	0.66	0.33	0.33	102	10.0	90	35	34
B + 1/2M	3.72	0.44	5.06	0.64	0.27	0.40	192	10.7	77	34	34

Results and Discussion for Experiment 2

Initial soil characterization: The initial (i.e before applying biochar and fertilizers) soil properties at three different depths are presented in Table 7. The soil of the experimental site has a sandy texture, acidic pH and low organic matter content. The soil is sandy where subsoil is coarser than the top soils. Soil pH decreases with increasing soil depths where the pH of 0-15 cm depth soil is 0.3 units higher than that of 30-45 cm depth soil. The soil organic matter content and CEC also decrease with increasing soil depths. Although the CEC of the surface soil the highest among the three soil layers, it is not sufficient enough to support optimum crop growth, as this soil has low water and nutrient holding capacity (IPINI, 2006). There are distinct differences in nutrient concentrations across the soil depths. In general the availability of nutrients is higher in upper soil layers than the lower soil layers (0-15 cm > 15-30 cm > 30-45 cm). Available concentrations of all the nutrient elements in the sub soil layers (15-30cm and 30-45 cm depth) are extremely low except Fe (very high) and B (high). The concentrations of four major elements (P, K, Ca and Mg) in the top soil layer (0-15cm) can be categorized as low, very low, low and medium low, respectively for P, K, Ca and Mg (Sims and Gartley, 1996).

Table 7: Characteristics of initial soil for experiment 2

	0-15 cm	15-30 cm	30-45 cm
Texture	Loamy sand	sand	sand
Soil pH	5.1	4.9	4.8
O.M. (%)	2.8	2.17	1.12
CEC (Cmol/ kg)	8.1	5.1	3.5
Ca (ppm)	278.6	136	34
Mg (ppm)	74	41	17
K (ppm)	33	22	10

P (ppm)	28	30	24
Fe (ppm)	613	821	776
Cu (ppm)	<0.1	<0.1	<0.1
Mn (ppm)	7.1	4.6	2.1
Zn (ppm)	1.3	0.80	0.45
B (ppm)	2.0	1.9	1.8

Moisture retention capacity: Moisture contents determined by the gravimetric method in two different dates are presented in Table 8. The soils that received higher biochar doses retained more moisture, but the difference was not statistically significant. It is unclear why there was notable variation in moisture contents within the same treatment plots (Table 8). The positive effects of biochar on moisture retention have been reported by a number of researchers (Karhu et al., 2011; Laird et al. 2010b). Novak et al. (2009) relates increased water holding capacity by biochar to its type, especially the feed stock and pyrolysis temperature used in the biochar product. Sohi et al (2010) noted that the surfaces of low temperature biochar can be hydrophobic and may thus limit the retention of soil water content. We sampled soils after 12-24 hours of heavy rain assuming that the soil was fully saturated, but the huge difference in moisture content between the two sampling dates suggests that soils might have not reached to saturation while the samples were taken. We plan to install a mini weather station to record weather related data and soil moisture/temperature sensors coupled with data loggers to different experimental plots to monitor moisture and temperature in soil during the whole cropping season.

Table 8: Surface soil moisture content at two different dates

Treatments	Mean soil moisture (%)	
	1st sampling	2nd sampling
0 t C/ha	21.8 ± 2.6	32.2 ± 6.1
10 t C/ha	20.4 ± 1.9	31.0 ± 5.2
20 t C/ha	23.6 ± 3.2	34.8 ± 2.6
40 t C/ha	24.2 ± 3.9	35.8 ± 5.8

Soil temperature: The soil temperature data presented in Table 9 are statistically similar. Biochar, because of its colour, is expected to change the albedo of the soil surface and increase the capture of radiation, thereby increasing its temperature. As the temperature was measured twice (morning and afternoon) in a single day, it is unwise to draw any conclusion from this result. Therefore, for the next year we have plan to measure temperatures throughout the cropping season using moisture/temperature sensors coupled with data loggers.

Table 9: Effect of biochar rates on surface soil temperature

Treatments	Mean soil temperature (°C)	
	Morning	Afternoon
0 t C/ha	24.6 ± 1.1	30.5 ± 1.0
10 t C/ha	25.3 ± 0.8	30.6 ± 0.3
20 t C/ha	25.5 ± 1.4	30.7 ± 0.8
40 t C/ha	25.4 ± 1.1	30.8 ± 1.0

Effect of biochar rates on soil properties: Most of the properties of the top soil (0-15 cm depth) were not significantly affected by different biochar doses (Table 10), except for K ($p < 0.0001$) and Mn ($p < 0.01$). In some of the parameters, the treatment effect was not statistically different but there was slight increase/decrease in the higher two biochar rates compared to the control. The mean soil pH increased to 0.1 unit at 20 t C/ha treatment and 0.2 units at 40 t C/ha treatment over control. Soil organic matter increased with increasing biochar rates, and the highest organic matter content (3.3%) was measured in 40 t C/ha treatment which is approximately 0.7% higher than the control. Although there was no distinct trend for CEC among the different biochar rates, the highest CEC value of 8.7 Cmol/ kg was measured in 20 t C/ha treatment. Deal et al (2012) and Van Zwieten et al (2010) in their pot experiment also observed a slight increase in CEC due to biochar application. In general, Mehlich 3 extractable concentrations of K, Ca, Mn, Zn and S increased with increasing rates of biochar, where the lowest and the highest measured concentrations were observed in the control and 40 t C/ha treatments respectively. Although there is no trend for available concentrations of P and Fe with increasing biochar rates, the highest P and the lowest Fe concentrations were found at the highest biochar rate (i.e. 40 t C/ha). B concentrations were generally unaffected by different biochar application rates. Laird et al (2010b) observed an increase in Mehlich 3 extractable P, K, Mg and Ca with biochar amendment but found no effect on Mehlich 3 extractable S, Cu, and Zn. Effect of biochar on soil properties at 15-30 cm soil depth are almost similar to that at 0-15 cm depth where only available K concentrations were significantly influenced by biochar application (Table 11).

Table 10: Soil characteristics at 0-15 cm depth in experiment 2 after one cropping season

Parameters	Control	10 t C /ha	20 t C /ha	40 t C /ha
Soil pH	5.1	5.1	5.2	5.3
O.M. (%)	2.6	2.8	2.9	3.3
CEC (Cmol/ kg)	7.9	7.5	8.7	8.4
Ca (ppm)	343	345	447	489
Mg (ppm)	80	77	78	79
K (ppm)	58	69	82	125
P (ppm)	47	41	44	58
Fe (ppm)	676	649	679	628
Cu (ppm)	<0.1	0.16	<0.1	0.25
Mn (ppm)	6.2	6.3	8.7	11.0
Zn (ppm)	0.68	0.76	0.82	1.16
B (ppm)	1.7	1.7	1.7	1.7
S (ppm)	8.4	8.6	9.3	10.4

Table 11: Soil characteristics at 15-30 cm depth in experiment 2 after one cropping season

Parameters	Control	10 t C / ha	20 t C / ha	40 t C / ha
Soil pH	4.9	4.9	5.0	5.1
O.M. (%)	2.0	1.8	2.0	2.3
CEC (Cmol/ kg)	4.6	5.0	5.7	5.4
Ca (ppm)	164	164	181	220
Mg (ppm)	38	37	36	35

K (ppm)	38	47	52	65
P (ppm)	34	28	30	37
Fe (ppm)	699	629	709	635
Cu (ppm)	0.17	0.29	0.26	0.31
Mn (ppm)	4.0	3.4	4.6	5.6
Zn (ppm)	0.53	0.46	0.52	0.82
B (ppm)	1.8	1.6	1.8	1.6
S (ppm)	7.5	7.2	7.7	8.7

Biomass yield: Positive effects of biochar on beet crop growth were observed when biochar was applied at different rates along with a standard fertilizer dose (Figure 5). Beet biomass yield was significantly ($p < 0.01$ for beet and $p < 0.0001$ for leaves) affected by different rates of biochar application. Yield of both beet and leaves increased with increasing rates of biochar (Figure 6). The positive effect of biochar on plant growth and biomass yield has been reported by a number of other researchers as well (Deal et al., 2012; Uzoma et al., 2011; Kimetu et al., 2008; Lehmann et al., 2003). The yield of biomass (beet plus leaves) was only about 0.7 t/ha in the treatment where no biochar was applied (i.e control), which increased to 14.9 t/ha, 22.4 t/ha and 24.7 t/ha with 10 t C/ha, 20 t C/ha and 40 t C/ha, respectively. Although the highest beet and leaf yields were recorded with 40 t C/ ha biochar rate, the increase in yield over the 20 t C/ha biochar rate was not statistically significant. These results suggest that biochar rate of 20 t C/ha could be the optimum dose for the soil under study. Available K and Mn concentrations in soils were significantly increased due to biochar application, but it is beyond the scope of this study to conclude whether positive growth and increased yield of beet crop were related to the increased availability of these two nutrients, or whether other soil properties also contributed. Kimetu et al. (2008) were able to establish that the yield benefits from biochar were in part due to non-nutrient improvements to soil function.

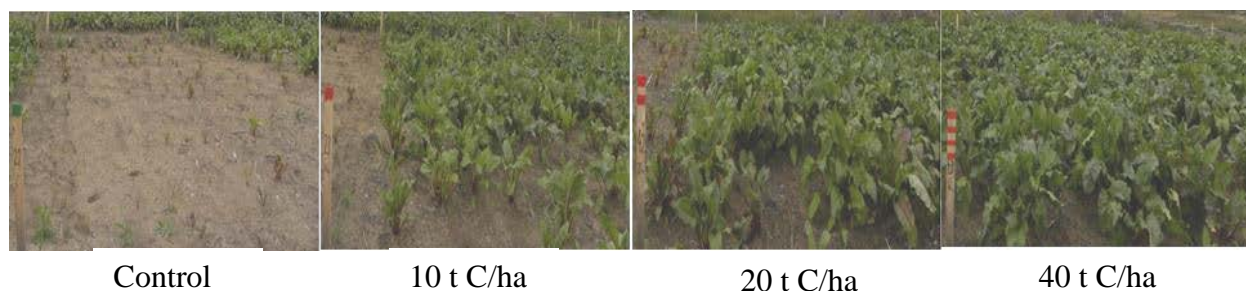


Figure 5: Beet crop in different biochar treatments

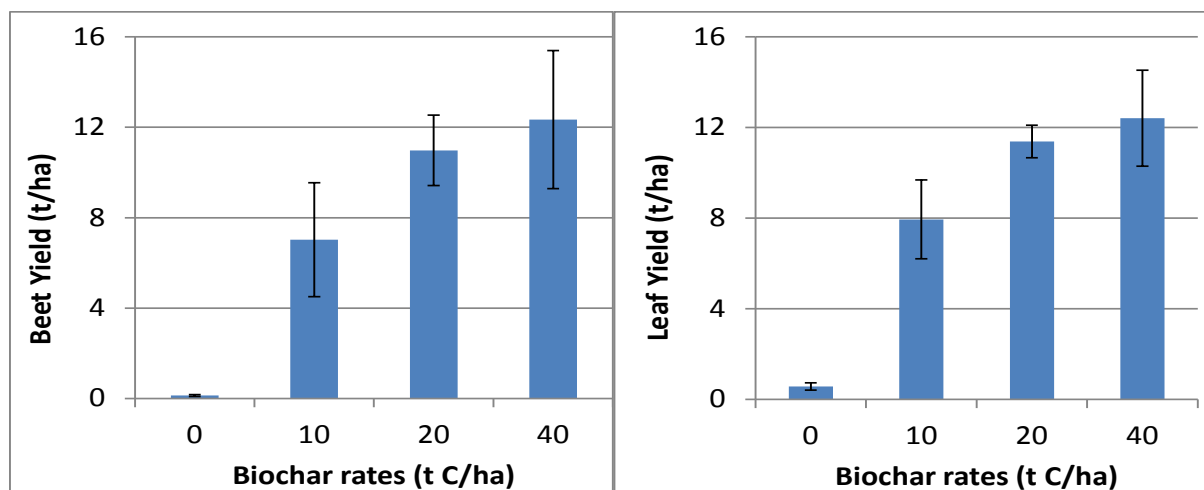


Figure 6: Effect of different rates of biochar on beet biomass yield. Error bar represents \pm SE (n= 4)

Plant concentration: The total concentrations of most of the nutrients in beet plants were affected by biochar application (Table 12). Although there was no clear trend in concentrations of different elements for different biochar doses, the lowest concentration was observed in the highest biochar dose for N, P, Ca, Mg, S, Fe, Cu, Mn and Zn. On the other hand, the concentrations of different elements in the control treatment were generally higher, and the control treatment had the highest concentrations for N, P, Ca, S, Fe and Zn. This result is unexpected, because the available concentrations of most of the nutrients in soil were highest in the highest biochar dose. However, in the highest biochar treatment, the crop biomass production was more than 35 times higher than that of the control, so it is possible that lower tissue concentrations in the highest biochar treatment could be related to the dilution of nutrients in the plant biomass (Jarrell and Beverly, 1981).

Table 12: Nutrient concentrations in beet plant (whole plant) at different biochar treatments

Treatment	N	P	K	Ca	Mg	S	Fe	Cu	Mn	Zn	B
	%						ppm				
Control	4.4	0.64	5.12	1.26	1.05	0.29	709	15.5	468	103	24
10 t C/ ha	4.1	0.41	4.60	0.99	1.08	0.23	274	12.5	445	65	30
20 t C/ ha	4.1	0.44	5.15	1.11	1.24	0.24	256	21.8	722	72	34
40 t C/ ha	3.2	0.35	4.94	0.91	0.80	0.22	188	10.7	431	58	35

Communications and Outreach

Some of the results of this project were presented as a poster titled “Potential for using biochar to improve soil fertility and increase crop productivity in the sandy soils of Happy Valley-Goose Bay, NL” at the 8th Circumpolar Agricultural Conference and UArctic Inaugural Food Summit in Girdwood, Alaska, USA (September 29-October 3, 2013). Newfoundland and Labrador English School District arranged a visit to the experimental site for the students who attended its Science Camp activities 2013, where the principal investigator demonstrated how scientific experiments are conducted and explained the project objectives to the participating students. A news story on this research project was aired on CBC’s *Here and Now* on July 30, 2013. A link for the program is as follows:

<http://www.cbc.ca/player/News/Canada/NL/Here+and+Now/ID/2398842939/?page=3>

Conclusion and Future Recommendations

Soil analytical results show that the sandy soil of the experimental site is very acidic, where surface soil pH is 4.7 and 5.1 respectively for experiment one and experiment two. The soil has a low organic matter content, low CEC and low levels of most available nutrients, except Fe and B. The organic matter content, CEC and the availability of depleted nutrient elements all decrease further with increasing soil depth.

In this present study, we did not observe any positive effect of biochar on soil temperature and moisture holding capacity of soil. As discussed earlier, we plan to modify our methodology on soil moisture and temperature measurement by installing soil moisture/temperature sensors coupled with data loggers in different experimental plots to monitor moisture and temperature in soil during the whole cropping season.

Soil pH and Mehlich 3 extractable Ca, K, Mn and P were significantly affected by biochar application in experiment one, as were Mehlich 3 extractable K and Mn in experiment two. Biochar also slightly improved soil CEC, organic matter content and extractable concentration of Zn and sulphur.

In both experiments, biochar application had positive effects on plant growth and crop yields. However, the results from experiment one shows that singly applied biochar application is unable to support crop establishment, growth and biomass production despite its positive effect on a number of soil parameters. The results underline that the positive effect of biochar on plant growth and biomass yield is only realized when biochar is applied along with a supplemental nutrient source such as fishmeal or fertilizer. In experiment two, biomass yields increased with increasing biochar rates where the highest rates of biochar (40 t C/ha) produced the most biomass, although, the difference in biomass yields between 20 t C/ha and 40 t C/ha was statistically insignificant. This preliminary result suggests that a biochar rate of 20 t C/ha could be optimum for the sandy soils of Happy Valley-Goose Bay. However, we need to continue the experiments over several years to confirm this observation. In the next cropping season, we plan to split each biochar plot into two portions, of which one will receive additional biochar application. This experiment will allow us to see how much biochar can be applied before crop yields decline or its positive effects on soil properties diminish.

References

Allison, S. D., & Treseder, K. K. (2011). Climate change feedbacks to microbial decomposition in boreal soils. *Fungal Ecology*, 4(6), 362-374.

Barrow, C. J. (2012). Biochar: Potential for countering land degradation and for improving agriculture. *Applied Geography (Sevenoaks)*, 34, 21-28.

- Bird, M. I., Wurster, C. M., de Paula Silva, P. H., Bass, A. M., & de Nys, R. (2011). Algal biochar – production and properties. *Bioresource Technology*, 102(2), 1886-1891.
- Bird, M. I., Wurster, C. M., de Paula Silva, P. H., Paul, N.A., & de Nys, R. (2012). Algal biochar: effects and applications. *Global change Biology Bioenergy*, 4, 61-69.
- Bolan, N.S., Kunhikrishnan, A., Choppala, G.K., Thangarajan, R., & Chung, J.W. (2012). Stabilization of carbon in composts and biochars in relation to carbon sequestration and soil fertility. *The Science of the Total Environment*, 424, 264-270.
- Bradey N.C. 1990. *Nature and Properties of Soils*. Tenth edition, Macmillan Publishing Company, New York.
- Clough, T. J., & Condon, L. M. (2010). Biochar and the nitrogen cycle: Introduction. *Journal of Environmental Quality*, 39(4), 1218-1223.
- Deal, C., Brewer, C.E., Brown, R.C., Okure, M.A. E., & Amoding, A. (2012). Comparison of kiln-derived and gasifier-derived biochars as soil amendments in the humid tropics. *Biomass and Bioenergy*, 37, 161-168.
- Department of Forest & Agrifoods (2002). Soils of the Happy Valley East Area, Labrador (*Soil Survey report*). Published by Soil and Land Management Division, P.O. Box 8700, St. John's, NF A1b 4J6.
- Ding, Y., Liu, Y.-X., Wu, W.-X., Shi, D.-Z., Yang, M., & Zhong, Z.-K. (2010). Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. *Water, Air, and Soil Pollution*, 213, 47–55.
- Galinato, S. P., Yoder, J.K. & Granatstein, D. (2011). The economic value of biochar in crop production and carbon sequestration. *Energy Policy*, 39, 6344-6350.
- Glaser, B., Haumaier, L., Guggenberger, G., & Zech, W. (2001). The ‘Terra Preta’ phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, 88,37–41.
- Glaser, B., Lehmann, J., & Zech, W. (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biology and Fertility of Soils*, 35, 219–230.
- Hanegraaf, M. C. (2009). Trends in soil organic matter contents in dutch grasslands and maize fields on sandy soils. *European Journal of Soil Science*, 60(2), 213-222.
- Havlin, J.L., Beaton, J.D., Tisdale, S.L. & Nelson, W.L. (2005). *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. Pearson Prentice Hall, Upper Saddle River, New Jersey.
- Inyang, M., Gao, B., Pullammanappallil, P., Ding, W., & Zimmerman, A. R. (2010). Biochar from anaerobically digested sugarcane bagasse. *Bioresource Technology*, 101(22), 8868-8872.
- IPNI (International Plant Nutrition Institute), (2006). *Soil Fertility Manual*. IPNI, 655 Engineering Drive, Suite 110, Norcross, GA 30092-2837

- Jarrell, W.M. & Beverly, R.B. (1981). The Dilution Effect in Plant Nutrition Studies. *Advances in Agronomy*, 34: 197-224
- Karhu K., Mattila T., Bergstrom & Regina K. (2011). Biochar addition to agricultural soil increased CH₄ uptake and water holding capacity – Results from a short-term pilot field study. *Agriculture, Ecosystems & Environment*, 140:309-313.
- Kimetu J.M., Lehmann J., Ngoze S.O., Mugendi D.N., Kinyangi J.M., Riha S., Verchot L., Recha J.W. & Pell A.N. (2008). Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems*, 11: 726–739.
- Kookana,R.S., Sarmah, A.K., Van Zwieten, L., Krull, E. & Singh, B. (2011). Biochar application to Soil: agronomic and environmental benefits and unintended consequences. *Advances in Agronomy*, 112, 103-143.
- Kwapinski, W., Byrne, C.M.P., Kryachko, E., Wolfram, P., Adley, C., Leahy, J.J., Novotny, E.H., & Hayes, M.H.B. (2010). Biochar from Biomass and Waste. *Waste and Biomass Valorization*, 1, 177–189.
- Laird D.A., Fleming P., Davis D.D., Horton R., Wang B., & Karlen D.L. (2010b). Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma*, 158:443–449
- Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010a). Biochar impact on nutrient leaching from a midwestern agricultural soil. *Geoderma*, 158(3–4), 436-442.
- Lehmann, J. (2007) Bio-energy in the black. *Frontiers in Ecology and the Environment*. 5(7), 381–387.
- Lehmann, J. (2010). *Biochar for Environmental Management : Science and Technology*, Earthscan publications, London.
- Lehmann, J., Gaunt, J. & Rondon, M. (2006). Biochar-sequestration in terrestrial ecosystems- a review. *Mitigation and Adaptation Strategies for Global Change*. 11, 403-427.
- Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., & Crowle, D. (2011). Biochar effects on soil biota- A review. *Soil Biology and Biochemistry*, 43, 1812-1836.
- Loveland, P., & Webb, J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. *Soil and Tillage Research*, 70(1), 1-18.
- McHenry, M. P. (2011). Soil organic carbon, biochar, and applicable research results for increasing farm productivity under Australian agricultural conditions. *Communications in Soil Science and Plant Analysis*, 42(10), 1187-1199.
- Méndez , A., Gomez, A., Paz-Ferreiro, J. & Gasco, G. (2012). Effects of sewage sludge biochar on plant metal availability after application to a Mediterranean soil. *Chemosphere*, 89, 1354-1359.
- Novak J.M., Lima I., Xing B., Gaskin J.W., Steiner C., Das K.C., Ahmedna M., Rehrh D., Watts D.W., Busscher W.J. & Schomberg H. (2009). Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science* 3: 195-206

Sims T. & Gartley, K.L. (1996). Nutrient management-An Overview (Chapter 1). In *Nutrient Management Handbook For Delaware*. Cooperative bulletin no. 59, University of Delaware, Newark, De 19716.

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 05/09*, 64pp.

Spokas, K. A., Novak, J. M., & Venterea, R.T. (2012). Biochar's role as an alternative N-fertilizer: ammonia cap *Plant and Soil*, 350, 35-42.

St. Arnaud, R. J., & Sephton, G.A. (1972). Contribution of clay and organic matter to cation-exchange capacity of chernozemic soils. *Canadian Journal of Soil Science*, 52(1), 124-126.

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macêdo, J.L.V., Blum, W.E.H., & Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil*, 291, 275–290.

Taghizadeh-Toosi, A., Clough, T. J., Sherlock, R.R., & Condon, L.M. (2012). Biochar adsorbed ammonia is bioavailable. *Plant and Soil*, 350, 57–69.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K.Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, 327, 235–246.

Wang, J., Zhang, M., Xiong, Z., Liu, P., & Pan, G. (2011) Effects of biochar addition on N₂O and CO₂ emissions from two paddy soils. *Biology and Fertility of Soils*, 47, 887-896.

Warnock, D.D., Lehmann, J., Kuyper, T.W., & Rillig, M.C. (2007). Mycorrhizal responses to biochar in soil – concepts and mechanisms, *Plant and Soil*, 300, 9–20.

Yu, X., Ying, G., & Kookana, R. S. (2009). Reduced plant uptake of pesticides with biochar additions to soil. *Chemosphere*, 76(5), 665-671.

Yuan, J.-H., & Xu, R.-K. (2011). The amelioration effects of low temperature biochar generated from nine crop residues on an acidic Ultisol. *Soil Use and Management*, 2011, 27, 110–115.

Yuan, J.-H., Xu, R.-K., Qian, W., & Wang, R.-H. (2011). Comparison of the ameliorating effects on an acidic ultisol between four crop straws and their biochars. *Journal of Soils Sediments*, 11,741–750.

Zheng, W., Guo, M., Chow, T., Bennett, D. N., & Rajagopalan, N. (2010). Sorption properties of greenwaste biochar for two triazine pesticides. *Journal of Hazardous Materials*, 181(1–3), 121-126.

Appendices

The appendices are attached as a separate PDF file