Innovation & Entrepreneurship (I&E) at Yukon College

Pyrolysis for remediation of slash piles in Yukon: use case, and equipment options

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1. INTRODUCTION

1.1 Background

Yukon Government Agriculture Branch (YG AB) expressed the need to explore the possibility of enhancing slash pile management through pyrolysis –heat transformation of biomass into biochar in an oxygen-deficient environment. Slash piles are produced on clearing forestland for agriculture. They are made up of woody material, and typically contain a non-negligible quantity of rocks and soil. In Yukon, slash piles have historically been considered as ‘’waste’’: no particular value was seen in the biomass, and they can take up to 20-30% of the cleared space (Land Resource Stewardship Division, 2003 *in* Lucas, 2019b). Current management practices come down to open burning. This releases CO_2 to the atmosphere, is increasingly seen as a waste of resources, and produces smoke –which has led to more and more concerns in terms of health, esthetics, and harmonious cohabitation in Yukon in recent years (Lucas, 2019b). Over the 1986-2018 period, approximately 15,000 ha have been made available for farmland development by YG (Lucas, 2019a).

The demand for agricultural land remains high, and YG AB has a mandate to continue releasing land for agriculture. For instance, 3 lots of 63 ha currently are currently being cleared as part of the Murray agricultural subdivision development, west of Whitehorse. This project has the potential to release over 75,000 tonne of CO_2, which is equivalent to 12.6% of the annual greenhouse gases (GHG) emissions for the whole territory (Lucas, 2019, pers. comment). Moreover, a large quantity of slash in variable state of decay currently sits in piles across the territory, resulting from recent and ongoing field clearing.

YG AB also has a responsibility to develop environmental, economic, and socially responsible methods of land clearing and food production. Consequently, the Branch is interested in productive non-polluting uses for slash piles. This project proposes pyrolysis as a remediation measure to slash production upon land clearing in Yukon, and usage of biochar end-product as agricultural soil amendment to enhance productivity.

A main benefit of using pyrolysis is that it produces biochar, which can be used to enhance agricultural soils productivity. Another major benefit is that it would drastically decrease emission of GHGs (e.g. CO_2) and contribution to climate change that can be incurred by slash production and burning, as it locks up carbon in biochar. In theories, carbon pricing schemes are meant to curb such emissions by helping the development of alternatives. The recent legislation however does not apply to activities related to land clearing. If the carbon pricing scheme applied to land clearing, the ‘’carbon tax’’ cost of land clearing would be greater than the value of the land (Lucas, 2019a). That would sure decrease slash-and-burn practices precipitously, but also potentially incur a burden to land clearing that could further slow down agriculture development in the Territory. Although debatable, the burning of wood upon land clearing is thus officially considered carbon neutral in Yukon. Nevertheless, pyrolysis is recognized as carbon-negative (IPCC, 2018), and carbon credits can be claimed against usage of biochar in agricultural soils (e.g. ECOERA). Incidental end-products such as heat, syngas, and bio-oil also are produced by pyrolysis. Depending on their quantity, quality, and the capacity to harness them, these incidental end-products can be as much of additional value-added resources and potential revenues. Also, last but not least, pyrolysis equipment exist that release very little or no smoke at all.

All in all, pyrolysis has the potential to take what is presently considered a "waste" product, the removal of which causes significant pollution, and changing it to a valuable soil amendment with significant pollution reducing capability. This new approach to slash management is making major strides towards circular economy and the adoption of the 6th Hannover principle: 'Eliminate the concept of waste – Evaluate and optimize the full life-cycle of products and processes, to approach the state of natural systems, in which there is no waste' (McDonough, et al., 2003).

Pyrolysis can be conducted at all sorts of scales, from a backyard kiln processing a few kilograms of biomass per day to a big plant capable of processing 10s of thousands of tonnes per year. A variety of equipment has been developed, each with a specific set of features (e.g. pyrolysis conditions, throughput capacity, biochar yield, energy consumption/recovery). Open-source models and commercially available devices exist throughout the world. For instance, SESM (2016) identified >1000 companies active in the sector worldwide or which have been active in recent years. In Yukon, at least one pyrolysis unit was tried, with mixed results (YC, 2012; YC, 2014). Among this variety of equipment, some might be better suited to the context of slash management in Yukon and where the end-product biochar is used as an agricultural soil amendment[1].

1.2 Objectives

The overarching goal of this project is to identify an optimum type of equipment for conducting pyrolysis in the context of management of slash piles in Yukon and where the end-product biochar is used as an agricultural soil amendment. The identification of an optimum pyrolysis equipment is an incremental/iterative process, i.e. it requires stepwise decision making. This study aims in narrowing-down the options to only those that have a reasonable chance of satisfying the requirements.

The specific objectives of this project are to (1) define the use case and its requirements (2) turn up existing equipment that could potentially meet these requirements, and (3) evaluate equipment to narrow-down the options to only those that have reasonable chances of meeting the requirements.

1.3 Target audience

This document will be of interest to agriculture and forestry practitioners, especially authorities, regulators, educators, farmers and land developers in Yukon.

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[1] Mention of trade names or commercial products in this study is solely for the purpose of providing specific information and does not imply recommendation or endorsement.

1.4 Acknowledgements

This project was initiated by Jonathan Lucas –Manager of the Agricultural Lands Unit at Yukon Government Agriculture Branch (YG AB). It was conducted by Michel Duteau –Owner/Operator at Duteau Bioresource Contracting (Yukon), under the supervision of Eoin Sheridan and Alessia Guthrie –Project Innovation Officers at Cold Climate Innovation (CCI; Yukon College). Generous support, orientations, advice and review were also provided by various stakeholders.

2. METHODOLOGY

The use case and its requirements were defined though collection of information from relevant stakeholders (e.g. YG AB, Yukon pyrolysis and biochar pioneers) and published documents.

A review of pyrolysis equipment that could respond to the identified use case requirements was conducted, with an emphasis on identifying features that could further clarify use case requirements. Open-source and commercially-available pyrolysis models and devices from around the world were explored. The main source of information was the Internet, starting with databases published by biochar organizations such as the International Biochar Initiative (IBI, 2015), the United States Biochar Initiative (USBI, 2019), BioEnergy Lists (2019a and 2019b), the Pacific Northwest Biochar Initiative (PNWBI, 2015), and Pyrolist (2019). Individual equipment provider websites were further examined to gather preliminary information on each piece of equipment.

The suitability of equipment was evaluated using an analytical grid to measure fit to the use case requirements and compare broad categories of equipment.

3. RESULTS

3.1 Use case

3.1.1 Slash piles in Yukon

3.1.1.1 Slash generation

Slash piles are produced when clearing forest to create field space or when putting previously cleared land back into production. When YG AB releases a lot for soil-based agriculture, at least 53% of the area must be cleared in order to qualify for title transfer (YG, 2006). The native thin and fragile topsoil and duff layer is left on site as much as possible, and the residual trees/vegetation and roots are pushed in mounds or rows with a dozer after salvageable matter (timber and firewood) has been removed.

Slash piles are mainly made up of woody biomass, but typically contain a non-negligible incidental quantity of soil and rocks, as it is very difficult for machinery to completely separate them from woody materials and leave them in the field. The material is of varying sizes, e.g. stumps, root balls, full length trees and debris. The character of the material also varies, with some pieces being green, others fully dry or coming from old growth, yet others in different states of decomposition or damp from rain or snow.

Much like tropical rainforest, the majority of the carbon and nutrients of a Yukon forest is contained in the biomass, rather than in the soil. Whatever has not been removed through timber and firewood harvest thus remains in the slash.

Typical mixed coniferous and deciduous forest density in Yukon is 120-480 tonnes of wood/ha (YG Forestry Branch *in* Lucas, 2019a). Due to small trunk diameter inherent to northern, dry forests, a significant proportion of this biomass is deemed non-salvageable: ~100 tonne/ha (Lucas, 2019, pers. comment). As merchantable timber/firewood currently is rarely efficiently salvaged, slash production upon agricultural land clearing currently is 100-300t/ha (Lucas, 2019, pers. comment). A fair estimate is 200 tonne/ha (Lucas, 2019a) –which is much higher that the 40-100 tonne/ha that can be observed in southerly boreal jurisdictions (Isbister, 2017).

Over the 1986-2018 period, YG has made over 15,000 ha of Crown land available for agriculture development –or 450 ha/yr on average (Lucas, 2019a). The release of agricultural land has been slower in recent years. For instance, 1,171 ha has been titled between in the 2010-2012 period (Ball et al. 2013), at an average of 390 ha/yr. Based on the 2010-2012 period and assuming that the cleared proportion is the minimum requirement (53%) and that 200 tonnes of slash are produced per hectare of cleared land, it can be estimated that 200 ha of cleared land is produced per year, generating 40,000 tonnes of slash per year -which could be cut in half if merchantable wood was harvested efficiently.

3.1.1.2 Current management practices – burning

Slash piles can occupy up to 20-30% of the cleared space (Land Resource Stewardship Division, 2003 *in* Lucas, 2019b). This represents a significant loss of cultivable space, and little value has historically been seen in this material. Farmland developers thus prefer to destroy slash piles as soon as possible. Part of it is occasionally left to decay, but the bulk of slash piles in Yukon currently is destroyed by on-site open burning: slash-and-burn (see pictures in Appendix 1.A, p.92).

On-site burning has the advantage of leaving ash behind, which can be beneficial for agricultural soils –slash pile burn sites often create the most productive areas of a field. This is especially true where nitrogen is not a limiting factor. The nutrient content of ash (0-1-3; Lucas, 2019a) otherwise is of very limited use. For instance, Yukon soils typically are nitrogen-deficient, and nutrient contribution of ash would only be beneficial where supplemented with nitrogen fertilizer. Ash also contains calcium at a rate of 20% volume (Lucas, 2019b). Like lime, ash can increase soil pH and be an advantage where soils are on the acidic side. In most areas of Yukon however, soils already are on the basic side of the arable range. Applying ash would thus in these cases only further depart soils from optimum, unless counteracted with an acidifying agent such as elemental sulfur or ammonium sulfate. The main contribution of ash to Yukon soils actually comes from its increasing of the soil's cation exchange capacity (CEC[2]), which improves the availability of nutrients to crops.

Open burning produces smoke (Figure 3 and Figure 4). It also releases dioxins and mercury (Roach, 2019, pers. comment). Localized smoke can cause health issues and irritation for neighbors for weeks whilst windrows smolder away (Johnson, 2011). This has historically affected harmonious cohabitation in Yukon, and complaints are on the rise (Lucas, 2019b). In some jurisdictions, open burning is outright outlawed. In others, emission of smoke is restricted. For instance, BC Government recently adopted a new 'Open Burning Smoke Control Regulation', which maintains air protection measures and strongly encourages alternatives to burning (BC Gov, 2019). In Yukon, a permit is required if the emissions exceed 40% opacity (YG, 2014). These initiatives can make open burning costly and sometimes difficult to permit but have contributed to the development of alternatives, such as pyrolysis.

For every tonne of wood burnt an estimated 2 tonnes of CO_2 are released to the atmosphere (Agroforestry Research Trust *in* Lucas, 2019a). CO_2 is a potent greenhouse gas (GHG). It also fosters ocean acidification. The global atmospheric concentration of CO_2 has risen 40% since preindustrial era and continues to rise (IPCC, 2014). This atmospheric CO_2 increase has unambiguously been demonstrated to result from human activity and to be the cause of observed climate change through the greenhouse effect (IPCC, 2018). In Yukon, climate change is palpable, with a 2°C increase in average temperatures and a full 4°C increase in winter temperatures over the last 50 years (YG, 2019a). This is twice as fast as in southern Canada (YG, 2019a), which overall is warming

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[2] Cation Exchange Capacity (CEC) reflects the number of cation binding sites. It is a measure of the soil's capacity to ''hold'' and ''release'' positively charged ions. Many nutrients are cations (e.g. NH_4^+, K^+, Ca^{2+}, Mg^{2+}, Zn^{2+} and Cu^{2+}). CEC thus limits leaching of nutrients –especially water-soluble ones, and nitrogen in particular– and improves their availability to plants. CEC generally is higher in soils with finer texture (clays rather than sand) and with higher organic content. CEC is highly dependent on pedogenesis and can be improved through agricultural practices such as amendments.

up twice as fast as the global average –making the warming rate of Yukon roughly three times that of global mean temperature (GC, 2019). Climate change has massive, unpredictable, and costly consequences, such as degradation of permafrost with effect on infrastructure, shorter extent and duration of snow and ice cover, affected precipitation patterns, and ecosystem shifts. The effects are slated to amplify and diversify should GHG atmospheric concentrations continue to rise or be maintained. Considering the estimated 200 tonne/ha slash produced, the offgassing of CO_2 upon clearing forestland for agriculture in Yukon amounts to 400 tonnes/ha (Lucas, 2019a). For instance, the Murray agricultural subdivision development has the potential to release a minimum of 40,000 tonnes of CO_2 (if only the minimum 53% is cleared) and up to 75,600 tonnes of CO_2. This would represent 12.6% of the total territory's GHG emissions for one year (600,000 tonnes of CO_2/yr; YG, 2018a).

Burning also releases toxic components (e.g. dioxins). It also is seen as a missed opportunity, as organic matter is sent away to the atmosphere while organic matter is highly sought after for maintenance and improvement of Yukon agricultural soils.

3.1.1.3 Risk management

A variety of options have been proposed to improve land clearing practices and mitigate the impacts of slash. Avoidance measures tackle the issue before it rises by cutting down the quantity of slash to contend with. Reduction measures are presented that would have less detrimental effects than current open burning slash management practices. Pyrolysis is proposed as a remediation technique to correct the situation and stop damage, possibly reversing past damage.

Avoidance – efficient timber/firewood salvaging and usage

Efficient salvaging of merchantable wood could possibly cut down the quantity of slash that is produced from current 200 tonnes/ha down to 100 tonnes/ha (Lucas, 2019, pers. comment). Even if continuing with slash-and-burn, salvaging wood more efficiently would potentially cut the inconvenience in half (i.e. GHG release, smoke production, and waste of resources).

However, salvage costs time and money, and the value of timber and firewood is variable. For instance, non-coniferous species are often considered "valueless", and the quantity of trees to contend with in the relatively short period allocated for land development seems to sometimes be overwhelming; other landowners and land developers appear to see value in all trees (Lucas, 2019b).

Currently, title transfer agreement documents used by YG AB upon release of forested land to develop agricultural land require that merchantable wood be salvaged. YG Forest Management Branch (FMB) regulations also direct this requirement. In practice, wood salvaging does however not appear to be common and the requirement is rarely inspected and enforced (Lucas, 2019b). A number of explanations have been posited for this. For instance, there is not a clear, common definition for ''merchantable''.

Development of a single definition for ‘merchantable’ wood (e.g. >3” diameter at breast height –DBH) as well as enforcement of current legislation could do much to improve timber/firewood salvaging (Lucas, 2019b). Also, woodland geared towards clearing for agricultural development should be assessed for merchantable wood, perhaps again by YG FMB (Lucas, 2019b).

Efficient wood harvesting could benefit from considering the salvage costs as part of the credits that are allocated in the calculation of what a prospective agricultural land owner needs to put-in prior to title transfer (Lucas, 2019b). Salvage costs could for instance be generalized as a cost per acre depending on the assessed wood density. This may however increase the development costs to such an extent that the costs of other developments (e.g. building a barn) could fall outside the required credits, potentially slowing down agriculture development.

Should more beneficial use markets exist for biomass, wood would most certainly be salvaged more efficiently. Main usage for wood in Yukon currently is for heating homes and buildings through combustion. The contribution of biomass to heating energy already is higher in Yukon (18%) than in the rest of Canada (4.5%), but opportunities for energy generation still are vast (Duteau, 2016). YG released in 2016 its ‘’Biomass Energy Strategy’’ (YG, 2016) supporting heat and power generation from biomass. For instance, public buildings in Whitehorse have been converted to biomass energy in the last few years. In Teslin, a biomass-fuelled district heating system was installed in 2018 which serves 10 commercial buildings and saves up to 120 000 litres of fuel per year; Teslin Tlingit Council also is working on producing biomass electricity (CBC, 2019). Other projects exist in Haines Junction and Watson Lake. A variety of research projects currently are exploring the possibilities for communities such as Old Crow, Pelly Crossing and Dawson City, as well as for school buildings (YG, 2018b). Techniques more efficient than combustion exist in extracting energy from wood, include gasification and combined heat and power (CHP, aka cogeneration); these techniques however might be much more technologically challenging than combustion. With the implementation of YG (2016)’s Biomass Energy Strategy and support of this young but promising industry, value of wood as an energy feedstock is expected to increase. The sheer distances and associated transport costs are however major obstacles to the development of this industry in Yukon. Transport must be minimized, and perhaps on-site energy generation options would be better suited.

Reduction – decreasing the impacts of slash

A number of practices have been proposed to better manage residual slash pile material and reduce the negative impacts of open burning. Some of them are alternative destruction measures, but some of them intend to tap into the value of the biomass.

Closed burning

Alternatives to open burning exist in closed/controlled burning devices such as incinerators and air curtain burners –which do not release smoke. For instance, city of Whitehorse now manages part of its combustible material with a curtain burner in order to limit smoke production upon burning in populated areas. The deployment of such technology for management of slash piles in Yukon however appears unrealistic, considering the quantity of slash to contend with and prohibitive costs that scaling-up would require.

Hill mounds, tilled chips, and mulch

Alternative options making use of residual slash pile material on-site have been proposed. One of them is hügelkultur. This technique is based on the integration of branches and small trunks in mounds to build plant beds; the efficacy of this technique for productivity improvement has however yet to be documented in a peer-reviewed scientific study.

Other options include chipping and integrating the biomass into the soil or using it as top mulch. If the chips come from branches, it is known as ramial chipped wood (RCW)/'bois raméal fragmenté (BRF)'. The overall impact of these techniques in terms of soil productivity is however highly debated and should thoroughly be investigated before broad-scale deployment in the Territory.

On the one side, any organic material has the possibility of generating a cascade of beneficial effects concurring to the improvement of soil productivity, possibly leading to higher crop yields by providing SOM and some nutrients (Figure 1, p. 10).

On the other side, input of organic matter with labile[3] carbon can have detrimental effects on nitrogen availability, especially when not compensating with nitrogen input[4]:

- Input of labile carbon fosters microbial activity, which can lead to nitrogen immobilization[5]. The onset, intensity, duration and reversibility[6] of immobilisation can be influenced by the conditions (e.g. temperature, type of microorganisms present in the soil). In some conditions, immobilisation leads to denitrification, with a net loss of nitrogen[7].

Moreover, input of organic matter with labile carbon can have detrimental effects on pre-existing SOM:

- Input of labile carbon can initiate a priming effect whereby the rate of mineralization of pre-existing SOC (especially less labile forms) is increased because of increased availability of easily degraded carbon, which stimulates microbial activity (microbial respiration), leading to loss of pre-existing SOM (Luo et al., 2011; Singh and Cowie, 2014; Zimmerman et al., 2011).

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[3] Labile: easily mineralized, especially by microorganisms; labile carbon is rapidly cycled.

[4] Woody material is typically high in carbon but very low in nitrogen (C:N ratio >100:1).

[5] Immobilization refers to the process by which nitrate and ammonium are taken up by soil organisms (all living things require N, therefore microorganisms in the soil compete with crops for N). Immobilized nitrogen is unavailable to crops, and is also protected against leaching.

[6] Once the carbon is mineralized and microorganisms die, the organic N contained in their cells is converted back to plant-available nitrate through the mineralization and nitrification process –releasing the nitrogen back for crops' usage.

[7] Denitrification occurs when the soil is saturated (water-logged, anaerobic conditions) and bacteria use nitrate (NO_3) instead of oxygen gas (O_2) as the terminal electron acceptor for their respiration, releasing nitrogen gases (N_2O and N_2) to the atmosphere (Larney and Angers 2012; Gao and DeLuca, 2016).

These detrimental effects have been observed to increase with organic matter application rate (Abbruzzini et al., 2017), and would be smaller if the carbon was more recalcitrant[8] (Atkinson et al., 2010; Luo et al., 2011, Zimmerman et al., 2011).

That being said, it is believed that the relatively recalcitrant nature of a majority of the carbon contained in woody biomass can reduce the probability of these detrimental effects from occurring. A majority of the carbon contained in woody biomass is indeed included in lignin, which is relatively recalcitrant as opposed to cellulose or hemicellulose which are more labile, such as in herbaceous plants. Lignin however still is degradable –albeit on a relatively longer time scale, and woody biomass still contains hemicellulose and cellulose, thus a non-neglectable labile carbon content/fraction. It is also posited that Yukon's climate (cold temperatures) could potentially slow down microbial processes enough to further decrease the risk of these detrimental effects from occurring. Isbister (2017) produced a thorough literature review on the subject and recommended investigating the value of these techniques in the Yukon context for slash management. Experimentations might proceed in 2019, pending on financial support.

In an environment that already is extremely low in nitrogen and SOM, such as is typical of Yukon soils, these potential hazards have to be considered with great attention. As nitrogen often is the very limiting factor in Yukon soils, the negative effects could trump the benefits if the hazards were confirmed, with woodchip incorporation effectively decreasing soil productivity rather than improving it. Nitrogen fertilization could always be considered so as to compensate for labile carbon input and keep the C:N ratio within acceptable range.

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[8] Recalcitrant: resistant to mineralization, especially microbial degradation. Recalcitrant is the opposite of labile.

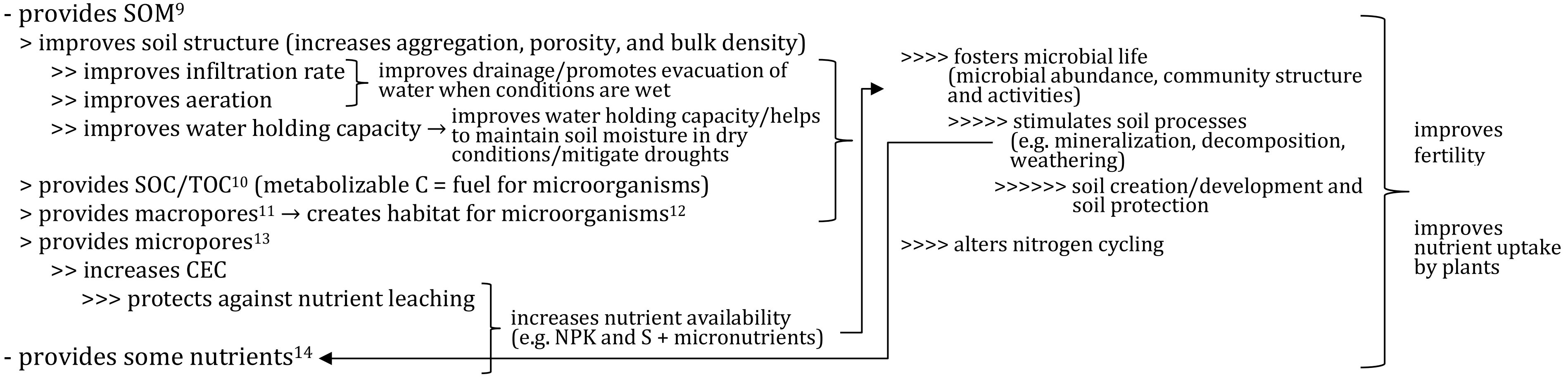

Figure 1. Effects of organic matter on soils, possibly leading to higher crop yields.

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[9] Soil Organic Matter (SOM) reflects the presence of plant and animal residues at different stages of decomposition in the soil. It includes wood debris (fresh, decomposing or charred) and substances synthesized by soil organisms and plants themselves. It is expressed as % of topsoil on a weight basis. SOM is a key aspect of the soil ecosystem and directly or indirectly governs almost all soil properties. For instance, SOM is critical in maintaining moisture-holding capacity and as such has tremendous positive effects on soil productivity. It also provides habitat for microorganisms performing soil processes and contributes CEC. SOM is highly dependent on pedogenesis and agricultural practices such as fertilizers and amendments (e.g. solid manure and compost provide SOM).

[10] Soil Organic Carbon (SOC) is the measurable portion of SOM and is a key indicator of soil fertility.

[11] Macropores are important for plant root penetration, microorganism populations residing within the organic matter particle, mobile soil solution movement and interaction with soil particles.

[12] Beneficial microorganisms include arbuscular mycorrhizal fungi, bacteria such as rhizobium, pseudomonas and bacillus, and symbiotic N_2 fixing bacteria and free-living N mineralizers such as *Bradyrhizobiacea* and *Hyphomicrobiacea*, both of which contribute to crop N nutrition.

[13] Micropores are important for water-holding capacity and for surface binding of cations and anions (Atkinson et al. 2010).

[14] Any organic material contains varying amounts of nutrients. For instance, the nutrient content of woody material (e.g. woodchips) or its products (e.g. biochar) is very small. The overall effects of organic matter addition can greatly be enhanced by co-fertilization or ''spiking'' the organic matter.

Another major potential hurdle with transforming slash piles into woodchips or shreds for usage in agricultural soils is the ‘dirty’ nature of the slash pile material: rocks and soil could indeed pose an unbearable stress onto the equipment. The variety in size and character of the material could pose further challenges. The equipment can also be very expensive to acquire, with heavy maintenance costs. Three large mobile chippers have been identified in the territory at the moment (Isbister, 2017): one based in Haines Junction (Bear Creek Logging), one based in Watson Lake (Biomass North), and one based in Whitehorse (Castle Rock Enterprises). The throughput capacity of Bear Creek Logging’s chipper (Bandit 3680 Beast Grinder) is 50 tons an hour (CBC, 2018). The capacity of these three pieces of equipment is said to be such that they can handle some amount of rock, stones and earth mixed with wood: the mineral elements become chipped and mixed with the chipped wood, returning any top soil that would have been scraped off by ‘’less careful’’ landclearing (Lucas, 2019, pers. comment). This capacity to handle contaminated material should thoughtfully be scrutinized, as it can have a significant impact on the cost and feasibility of chipping or shredding slash piles in Yukon.

Nevertheless, these techniques have the advantage of not producing smoke. Isbister (2017) also affirmed that incorporating woodchips into soil is a most economical method of managing slash pile material in the Yukon context. While possibly valid for ‘clean’ material, the latter affirmation appears to perhaps deserve further scrutiny, taking into account chipping costs –especially when dealing with ‘’dirty’’ material, and comparing the cost of this reduction measure to those of the proposed remediation measure (i.e. pyrolysis). It should also be noted that these practices are a missed opportunity in terms of GHG entrapment: upon decay (order of 100 year), wood matter will virtually release all carbon it contained, doing nothing to hamper and adapt to climate change, quite possibly directly contributing to it.

Whatever the verdict, only so much wood matter can be ploughed into the soil, 20-50 tonne/ha in the best-case scenarios (Isbister, 2017). Meanwhile the quantity of slash to contend with is expected to be 100-200 tonnes/ha, depending on efficiency of wood recovery. Alternatives are thus needed for the remainder.

Energy generation

With the emergence of a biomass energy industry in Yukon, it is conceivable that not only ‘merchantable’ wood (e.g. > 3’’ DBH), but the entirety of slash pile material could have value as bioenergy feedstock. Residual slash pile material however suffers from having a lower bulk density than timber/firewood; to be transported off-site, it would have to be chipped or shredded so as to increase its bulk density and limit transport cost. On-site small-scale energy generation options might be more realistic.

In any case, many biomass energy technologies also require biomass to be comminuted to chip-size, or at least shredded –which could be challenging in the case of residual slash pile material as exposed above (e.g. ‘’dirty’’ slash pile material can be very hard on the machinery).

3.1.2 Remediation – pyrolysis

Pyrolysis of slash piles is proposed as a remediation measure to stop and possibly reverse the negative effects caused by slash and its current open burning management practices. A risk management approach commands prioritizing avoidance, and whatever cannot be avoided should be remedied. Reduction measures should be preferred only when remediation is unreasonable. For instance, should the cost of pyrolysis not be justifiable in the face of environmental, social and economic benefits, a cheaper reduction measure should be considered –if it exists. As a corollary, synergies can stem from using both remediation and reduction measures should reduction be cheaper. For instance, tilling chipped material into the ground could be prioritized for dealing with the ''cleaner'' part of slash pile material if it turned out to be cheaper, and the rest (the ''dirtier'' part, contaminated with rocks and soil) could be pyrolyzed.

3.1.2.1 General process, and key determinants

Pyrolysis is a thermochemical process whereby heat is applied to organic material for a limited period in a near-zero oxygen environment[15]. Biomass thus is ''cooked'', not burnt or combusted –oxidation is minimal. Biomass is more or less rapidly heated to high temperatures (200-1000^{o}C), left to carbonize over a matter of seconds to hours, then quenched to stop further degradation –typically using water. The limitation of oxygen in the system prevents the complete burning, capturing much of the carbon the original feedstock contained into the solid biochar end-product. It is well-established that residence time (speed of pyrolysis) and highest treatment temperature (HTT, treatment temperature) are key determinants of the pyrolysis process: along with the feedstock nature, they determine the type, quantity and quality of the end-products (Lehman and Joseph, 2015). For a same feedstock, differing pyrolysis conditions can render biochars with radically different characteristics.

3.1.2.2 Biochar yield

The main end-product of pyrolysis is biochar, a solid carbon-rich material that can for instance be used as an amendment to improve agricultural soil productivity. Pyrolysis also delivers a liquid by-product (bio-oil) and a gaseous by-product (syngas); heat also is expelled. For any given feedstock, the balance between biochar, heat, bio-oil and syngas is set by the conditions under which pyrolysis was operated (e.g. speed, temperature). Depending on the feedstock and pyrolysis conditions, approximately 1/3 of the original feedstock is turned into biochar; the rest is turned into by-products and heat. On a weight basis, biochar yield can be 7-20% of the original biomass. Considering current typical slash production upon land clearing in Yukon (200

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[15] A wide definition of 'pyrolysis' can include the following processes (SESM, 2016):

- Torrefaction (product = torrefied biomass or bio-coal)
- Pyrolysis (also known as carbonization)
- Slow Pyrolysis (product = biocarbon, charcoal or biochar)
- Fast Pyrolysis (product = bio-oil or pyrolysis oil, plus some biochar)
- Gasification (product = producer gas or syngas, plus some biochar).

tonne/ha, 40,000 tonne/y), biochar production could be 14-40 tonne/ha, or 2,800-8,000 tonne/y; with the implementation of improved merchantable wood (timber and firewood) salvaging measures, this would be cut in half, but still considerable (7-20 tonne/ha, or 1,400-4,000 tonne/yr).

3.1.2.3 Feedstock possibilities

A wide variety of biomass can be pyrolyzed. Underutilized forestry residues such as those of Yukon slash piles can advantageously be pyrolyzed into biochar, transforming ''waste'' into value-added resources. Many other types of biomaterial can be pyrolyzed such as beetle-killed and fire-damaged trees, sawmill wastes (e.g. sawdust), food/agriculture by-products (e.g. straw, corn stovers, rice husk), manure, and animal rendering waste (e.g. fish or mammal bones; bonemeal). In some circumstances, pyrolysis can be used to transform construction and demolition (C&D) residues, municipal solid waste (MSW), or even tires. Naturally, the char that is produced from those streams has restricted usage (e.g. it cannot be used in agriculture) and will in most cases be disposed of as waste.

3.1.2.4 Biochar stability and longevity

Stability and longevity of biochar depends on the nature of its carbon content. The vast majority of biochar's carbon is in very recalcitrant forms. This 'pyrolytic carbon' cannot easily be degraded and will last for a time scale on the order of centuries to millenia (Jeffery et al. 2011; Lehman et al., 2006). For instance, biochar produced 7,000-8,000 years ago in Southern America still persists in what has been called '*terra preta*' (Glaser and Birk, 2012; Glaser, 2006; Glaser et al., 2001). The exceptional recalcitrance of pyrolytic carbon comes from its structural arrangement at the molecular level: the structure is highly aromatic, meaning that the carbon molecules are flat, ring-shaped and have resonance bonds. Pyrolytic carbon is thus similar to graphite, but with some covalent bonding between its graphene sheets as a result of imperfections in its production. This arrangement is more stable than other geometric or connective arrangements with the same set of atoms and shields pyrolytic carbon from microbial degradation and mineralization.

Nevertheless, any biochar contains a fraction of 'volatile matter', which is made up of carbon that can escape in a matter of a few hours to a few months and can easily be degraded or used up by microorganisms. It also contains 'labile' carbon, which can be degraded by microorganisms over the course of days to years. The exact overall stability and longevity of biochar's carbon content is specific to the feedstock and pyrolysis conditions under which it was produced (e.g. speed and temperature). For instance, higher pyrolysis temperatures have been demonstrated to render biochars with less labile carbon, and highest recalcitrance.

3.1.2.5 The role of pyrolysis in fighting climate change

Pyrolysis can transform into pyrolytic carbon up to 50% of the carbon the original feedstock contained –which carbon once was removed from the atmosphere via photosynthesis. Pyrolysis can thus effectively remove carbon from the immobilization-respiration-mineralization cycle and lock it up in a solid, stable end-product that can last for millenia.

Sequestering up to 50% of the carbon contained in the biomass means that pyrolysis can effectively eliminate 50% of the GHG emissions incurred upon current clearing practices in Yukon. For the comparison, only 3% of the original feedstock's carbon remains in ashes after combustion, and only <10-20% would remain after 5-10 years decomposition of wood, for instance when tilling woodchips into the ground (Lehman et al., 2006). Not only can pyrolysis mitigate GHG emissions, pyrolysis can remediate existing excessive atmospheric CO_2 if performed on dedicated biomass that would be grown for that purpose, which is known as 'carbon scrubbing'. This technique could eventually lead to compensation for past fossil fuel emissions. Depending on the overall stability of its carbon content, the carbon dioxide equivalency of biochar is 2.4-3, meaning that 1 tonne of biochar can sequester the global warming potential of 2.4-3 tonne of atmospheric CO_2, for thousands of years (SESM, 2016). Whether used to cut GHG emissions or to remediate existing CO_2, pyrolysis can be a powerful ally in mitigating climate change and adapting to it.

This carbon-sequestering potential has conducted IPCC (2018) to officially recognise pyrolysis as one of only six carbon-negative processes, and biochar as a carbon sink. As an indication, carbon offset initiatives such as displacement of fossil fuel energies with renewable ones are at best carbon neutral –which can lead to savings on carbon taxes. Carbon credits, in the context of a carbon market, could generate a non-neglectable revenue. For instance, carbon credits traded for ~CAD $20/tonne as of April 2019 on such voluntary cap-and-trade markets as the European Union Emissions Trading System or the Western Climate Initiative, and its value is expected to rise until atmospheric CO_2 drops significantly (Carbon Tracker, 2018). To the best of the author's knowledge, Australia is the first and still the only country where carbon credits can be claimed against biochar production and usage on a national cap-and-trade carbon market (Australia Government, 2019). However, such biochar-borne credits can already be claimed on a variety of volunteer carbon trading platforms (e.g. carbon future, Puro.earth, ECOERA, NORI and others conforming to the 'Gold Standard').

3.1.2.6 Smoke emission, and other pollutants

Complete and effective pyrolysis virtually produces no smoke and as such has a high potential to improve neighborly relations. Steam sometimes is released, depending on how dry the feedstock is –but smoke normally is minimal. Ash can sometime be produced, and pyrolysis does generate some pollutants –such as tars, phenols, and carbon dioxide– but at far lower levels than burning. Incomplete or ineffective pyrolysis can however still release smoke, for instance containing airborne particles and Volatile Organic Compounds (VOCs).

3.1.2.7 Pyrolysis co-products, and the first law of thermodynamic

Although external heat needs to be applied to initiate the process, pyrolysis is overall an exothermic reaction. Energy is expelled in the form of heat, and is also contained in the solid, liquid and gaseous end-products. Depending on their quantity and quality and on the advancement and efficiency of the equipment with which pyrolysis is conducted, the energy-carrying by-products can be captured for use or to provide a revenue stream. In the real world though, harnessing by-product energy can prove technically challenging. Moreover, additional heat often is required to maintain the treatment temperature, due to imperfect conservation of heat in the system. For instance, equipment often requires propane or electricity to sustain high process temperatures.

The low-grade heat that is lost from the system can advantageously be recovered for drying next feedstock or heating a building or greenhouse. It has also been demonstrated that heat can be harnessed to generate electricity. Integrating a Rankine cycle unit (organic or not) or a sterling engine to a pyrolysis unit have been demonstrated to be practical means of harnessing incidental heat generated by pyrolysis and converting it to work power and ultimately into electricity. This electricity can be transformed back into heat energy to help maintaining the high pyrolysis temperatures. It could also be used to charge up batteries. In Yukon, electricity generated by small-scale operations can be fed for profit into the grid, granted that quantities suffice (≥30 kWh); for instance, the starting price can be 16 cents per kilowatt-hour (Gignac, 2019). Nevertheless, the most energy-efficient practice is to limit heat loss as much as possible, for instance through thorough insulation of the pyrolysis chamber and heat transfer form pyrolyzed material to the incoming material. Also, it has been demonstrated that energy outputs can be extremely variable, generally following feedstock variability in terms of size and character (WSP, 2014).

Bio-oil is produced upon condensation of liquid fractions. It is similar to bunker fuel or heating oil, with roughly half the calorific value of diesel, at ~26,800 MJ/m^3. It can be collected to be subsequently used as energy source off-site. For instance, it can be used for heat in a burner or boiler. Recent breakthroughs (e.g. catalytic conversion) have also proven the feasibility of converting bio-oil into second generation biofuel, such as ethanol, green gasoline, or green diesel. In turn, this biofuel can be used for work in a combustion engine (e.g. flex/diesel engine), or even a fuel cell.

Syngas is an important energy carrier. It is similar to natural gas and is made of oxygen and hydrogen. Where technically feasible, it can be collected and burnt to generate heat on-site and contribute to sustaining the process temperature. Although more technically challenging, syngas can also be collected to fuel a genset on-site and produce electricity (WSP, 2014). Even more challenging would be the recovery of syngas for off-site usage, or transformation of syngas into liquid biofuel (e.g. Fischer-Tropsch process). If not used, the syngas must be flared so as to avoid safety issues and assuage CH_4 into less harmful CO_2 in terms of GHG effect.

The biochar end-product also contains energy. However, usage of biochar as an energy source seems unrealistic in Yukon conditions, given the high market value of biochar, which is driven by its other beneficial usage (e.g. soil amendment).

3.1.3 Biochar end-product

Biochar is a general term to describe the charcoal-like solid that is obtained from pyrolysis of biomass (Lehman, 2015). It differs from charcoal mainly in that it is not used as fuel/energy carrier. All biochars are not created equal –much like plastics, they can have vastly varying characteristics which determine properties and the specific applications that can be made. Biochar currently sells for approximately €350-400 on the European market.

3.1.3.1 Common characteristics and specific properties

A common feature with all biochars is that it is a very porous material: it has an exceptionally high specific surface (10-400 m^2/gram)[16], with lots of macropores and micropores. It is relatively light, with a bulk density of 80-320 kg/m^3 (typically ~250 kg/m^3); for the comparison, bulk density of woodchips typically is ~380 kg/m^3. Native moisture content is effectively 0%. In other words, biochars normally are ''bone dry''. However, they can hold a great deal of moisture –which is a very important data to take into account when assessing quantities of biochar by weight (Major, 2010). Biochars generally keep the shape of the original biomass but are very brittle and crumble easily. Bigger pieces can easily be crushed, and smaller particles can easily be ground to a powdery granulometry. Biochars are mainly made up of carbon, but also contain ashes and volatile matter. Some minerals (e.g. nutrients, metals) can remain from the original feedstock and be integrated in the carbon matrix, or part of the ash.

The specific set of properties of a unique biochar is conferred by the interaction of a specific feedstock with the unique set of pyrolysis conditions under which it was produced (e.g. speed, temperature –see point 3.2.2 below). One of the principal challenges in pyrolysis is generating a consistent biochar that responds to a precise use case: slight changes in reaction conditions and feedstock can result in biochars with radically different properties.

3.1.3.2 Possible applications

The varying properties of specific biochars determine the specific applications that can be made. Some biochars can be used as an amendment to increase productivity of agricultural soils (Atkinson et al., 2010; Lehmann, 2006). Similarly, some can be used in horticultural potting mixes, for instance as a replacement for coconut coir. Others can be used as an inoculant carrier upon seed coating with plant-beneficial microorganisms (e.g. rhizobium, arbuscular mycorrhiza) as an alternative to peat moss, which is a non-renewable resource (Glodowska, 2014). Other possible

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[16] Specific surface area: surface area per unit volume, aka surface-area-to-volume ratio,

agricultural applications include silage additives, feed-additives, and medical applications (EBF, 2019). Activated, some biochars can be used as an alternate to activated carbon, for instance as filter media for air treatment or water treatment. Yet other biochars can replace carbon black in industrial manufacturing (e.g. color pigment, reinforcing filler in tires and other rubber products). With high adsorption ability, some biochars can be used to immobilize heavy metals, pesticides, herbicides, and hormones; prevent nitrate leaching and faecal bacteria into waterways; and reduce N_2O and CH_4 emissions from soils. Micobiome-harboring capacities can also give some biochars the potential to foster hydrocarbon breakdown and to promotes revegetation; some have successfully been used in clean-up efforts and in remediation/reclamation of mines and industrial sites.

3.1.3.3 Biochar as an agricultural soil amendment

The successful use of biochars as an amendment to improve soil productivity leads to improved crop yields, and by extension profitability of agriculture. Biochars are however not a panacea. Inconsistent results have been observed, as well as negative effects too. In the most extreme examples, crop productivity has been reported to decrease by as much as 55 % and increase by as much as 220 % (Atkinson et al. 2010; Jeffery et al. 2011; Lehmann et al. 2006). Effectivity of a biochar in enhancing soil productivity depends first and foremost on its specific properties (determined by feedstock and pyrolysis conditions under which it was produced), then on the conditions under which it is used, including limiting conditions such as nutrient limitations.

Effects and mechanisms leading to them

The way that biochar can affect soil processes and ultimately can improve soils productivity has been thoroughly examined and is well documented (e.g. Cai et al., 2016, Głab et al., 2016; Gul, S., et al., 2015; Lehman and Joseph, 2015; Lehmann et al., 2006; Liang et al., 2006; Spokas et al, 2011; Zimmerman et al., 2011). The interactions however are complex and antagonistic effects are at play (Figure 2, p. 18). Nitrogen cycling is particularly affected, with many features affecting its overall availability (e.g. CEC, water holding capacity, VOCs). Biochar is able to resorb a quantity of water and solved nutrients, which equals the fivefold of its own weight (Scheub et. al. 2016). One of the major benefits of biochar is that it can significantly reduce nitrogen fertilizer needs, and associated costs (Backer, 2016; Clough and Condron, 2010). Of non-neglectable interest is the fact that the presence of toxicants (e.g. PCBs, heavy metals) in biochar can have serious detrimental effects and has been linked to decreased productivity (e.g. Dutta et al., 2017; Lehman and Joseph, 2015).

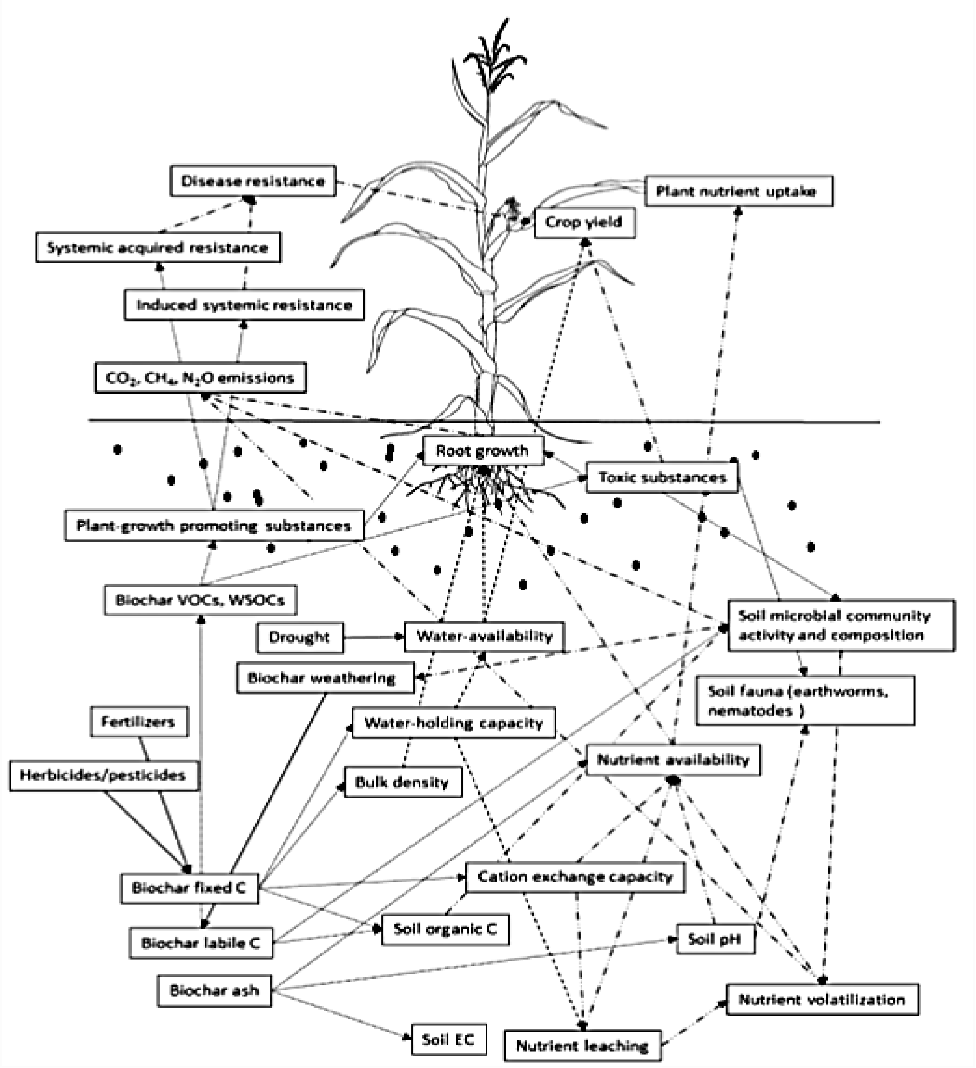

Figure 2. Summary of biochar effects on plant and soil properties using corn as a model crop. Arrows, dashed dots: direct effects of biochar properties; dash double dot: indirect effect of biochar chemical properties; solid: external effects that influence biochar-soil-plant relationships. In addition to the factors shown in the diagram, soil texture, organic matter concentration, pH and nutrient availability influence this relationship. (adapted from Backer, 2016).

Uncertainties remain on the implications of each effect and how each effect is modulated (extent, rate, etc.); inconsistent performance results perhaps reflect this incomplete knowledge. The following is a description of the consensus on how biochar properties can interact with soil particles, microorganisms, water and fertilizers to modify the physical, chemical, and biological properties of soil, and ultimately improve productivity.

SOM and nutrients contribution

Like any organic material, the application of biochar as a soil amendment contributes SOM and nutrients, which can trigger a cascade of effects that can ultimately lead to increased crop yields (see Figure 1, p. 10). The consensus about how biochar modulates the effects of organic material addition on soils, and key difference with woodchips includes the following:

- The vast majority of biochar's carbon is in very recalcitrant forms ('pyrolytic carbon'), as it has a highly condensed aromatic molecular arrangement (like graphite). Conversely, the labile fraction typically is very low. The extent of the labile fraction can be evaluated by measuring the hydrogen to carbon (H:C) ratio. The lower the H:C ratio, the higher the stability and recalcitrance. For the comparison, plant macromolecules such as cellulose and hemicellulose have a high H:C ratio, as they contain a lot of easily metabolizable carbon. Meanwhile, lignin has an aromatic molecular arrangement, therefore lower H:C ratio than other plant macromolecules; the structure however is not condensed, therefore lignin's H:C ratio still is fairly high. Biochars have an H:C ratio < 0.7 (IBI, 2015b, EBF, 2019), and well carbonized biochars can have an H:C ratio of 0.3 (Backer, 2016). Low labile fraction limits the hazards that it could otherwise bring, *a fortiori* when the C:N ratio is high (e.g. N immobilization, depletion of pre-existing SOM; see point 3.1.1.3 above for details). Correspondingly, biochars with higher labile carbon fractions (higher H:C ratio) have been observed to act as a nitrogen sink, therefore decreasing overall plant productivity. Backer (2016) also observed that biochars with low lability help plants develop longer root systems and therefore higher resilience to drought and nutrient stress. A low lability also is indicative of stability in soil, and longer C sequestration. The exact recalcitrance of biochar's carbon is determined by the feedstock and pyrolysis conditions (see point 3.2.2 below).
- The ''habitat'' feature of biochar is especially important: the exceptional specific surface area with large number of macropores make it an excellent habitat for soil inoculants and organisms already present in the soil. In that sense, biochar can be considered "a hotel for microbes" and its effects have been compared to those of an ''artificial reef'' in supporting lifeforms. For instance, Mia et al. (2014) observed that biochar increases nodulation by N-fixing bacteria in crops such as pea, soybean and red clover, leading to increased crop yields.
- The CEC increase feature also is very important, as it has a major impact on prevention of nutrient leaching and improvement of nutrient availability to plants –especially nitrogen (Van Zwieten et al., 2010). The exceptional specific surface area with large number of micropores boosts CEC, and ash content also contributes CEC. For instance, Laird et al. (2010) observed that biochars can increase soil CEC by up to 20%. CEC increase is long-lasting and could be virtually permanent but is thought to possibly deteriorate as the biochar ages. CEC increase might be less significant in higher pH soils. The effects of CEC increase are expected to be magnified on coarse-textured soils (like most Yukon soils), where nutrient retention is inherently low. CEC increase is not as high with wood-based biochars as it could be with biochars that have higher ash content, for instance manure-based (Singh, et al, 2010).
- The capacity of biochar to retain the soil solution within its pores also is major: this feature protects available nutrients (e.g. NO_3-N, NH_4-N and P) from loss via

volatilization and leaching, while maintaining them accessible to plant roots (Knowles et al. 2011; Yao et al. 2012). Overall, Ding et al. (2010) observed a 15.2% reduction in NH_4-N leaching in the presence of biochar.

- The effect on water balance also is major, especially in dryer climates (like in Yukon). Peake et al. (2014) indicated that biochar application could increase water holding capacity by over 22 %. The effects of an increased water holding capacity is much more important in coarse-textured soils (such as Yukon), where water retention is inherently low (Basso et al., 2013).
- Biochars can contribute nutrients, depending on the feedstock and pyrolysis conditions. For instance, nutrients contained in ashes can contribute to fertility; nutrients integrated in the carbon matrix however are not plant-available and cannot contribute to fertility (Chan et al., 2008). In any case, any nutrient contribution is short lived (1-2 seasons), especially compared to the quasi-permanency of the effects brought by the SOM content of biochar. The effects will dissipate with time because nutrients get used up, depleted and taken out of the system as crops are grown and harvested. Moreover, the effects of any nutrients can be counteracted by the presence of labile carbon (see point 3.1.1.3). In the case of wood-based biochars, they generally contain very little nutrients and contribute very marginal plant nutrition, as woody material is very nutrient-poor (Atkinson, 2010). More specifically, the N contribution of wood-based biochar is negligible. Incidentally, low-N biochars can exacerbate the hazards that could be born by the presence of any labile carbon.

pH

Biochar can have an effect on soil pH. This effect, in turn, can change the speciation of nutrients and their availability to plants, which is critical for plant growth. Biochar pH is closely related to feedstock type and conditions under which it was produced see point (see point 3.2.2). Wood-based biochars' pHs can range 4-9, but typically are on the basic side (Enders et al., 2012). The effect of biochar on soil pH is thought to diminish as the biochar ages in the soil (Cai et al., 2016). As biochar typically is on the basic side, it typically increases the soil pH. For instance, Laird et al. (2010) reported an increase of almost 1 pH unit upon application of wood-based biochars in agricultural soils. Where undesirable, this effect can be counteracted with an acidifying agent such as elemental sulfur or ammonium sulfate. Activation of biochar is also known to decrease its pH.

VOCs and WSOCs

Volatile organic compounds (VOCs) are a vast category of organic compounds with common feature that they are easily volatilized as gases or vapor. Water soluble organic compounds (WSOCs) are hydrophilic compounds with varying aromaticity and molecular weights. VOCs and WSOCs include both human-made and naturally occurring chemical compounds.

Pyrolysis like any heat treatment of organic matter operates the breakdown and rearrangement of the original chemical structure of the feedstock, which generates a complex mixture of organic compounds –among which VOCs and WSOCs (Spokas, 2011). When the liquid or gas phases are allowed to recondense, some VOCs and

WSOCs can become sorbed onto the biochar (Buss and Mašek 2014). VOCs become part of the overall biochar's ''volatile matter content'', and their composition has recently been termed the "volatilome" (Ghidotti et al. 2017a). Production conditions determine the initial volatilome, but storage conditions can lead to some losses, and VOCs migrate quickly out of the biochar upon soil application, making them bioavailable (Backer, 2016).

The variety of VOCs and WSOCs that can be found on biochars is vast. For instance, Spokas et al. (2011) identified over 140 sorbed VOCs on biochar surfaces. Ghidotti et al. (2017b) detected thousands WSOCs in water extracts of biochar. Some of these compounds can become available in soil. The effects of biochar-associated VOCs and WSOCs are varied, and are receiving more and more scrutiny (Backer, 2016). Some are positive, some are negative; some of these compounds can promote plant growth, others can be phytotoxic. VOCs and WSOCs are now believed to play an important role in crop response to biochar soil amendments, independently from effects happening in the soil/improvement of soil productivity.

Phytohormones used by plants to communicate are VOCs. Plants use ppm-level VOCs to modulate plant processes (e.g. seed germination), to communicate with other plants (e.g. invasive plant responses), to send signals to microorganisms (e.g. nutrient cycling), and to send messages to animals (i.e. herbivore resistance). Many of these VOCs are produced in the rhizosphere, and their effect is called ''soil volatilomics''. For instance, giberelline stimulate shoot elongation, seed germination, and fruit and flower maturation; cytokinins are involved in cell growth and division; and ethylene stimulates/regulates the ripening of fruit, the opening of flowers, and the abscission (or shedding) of leaves. Other plant hormones produced in the rhizosphere can directly inhibit/stimulate microbial processes or influence the ability of macroorganisms to participate in biotic and abiotic reactions known to influence soil quality, for instance C and N cycling (DeLuca et al. 2015; Spokas, 2011). Some VOCs and WSOCs found with biochars can mimick those plant hormones (Dutta et al., 2017). Experimental results suggest that biochar, through VOCs and WSOCs, can stimulate defense response, induce resistance, and directly stimulate plant growth –independantly from effects happening in the soil/improvement of soil productivity (DeLuca et al. 2015; Ghidotti et al. 2017a; Rombolà et al., 2015; Spokas et al. 2011). For instance, results by Bruun et al. (2014) suggest that root growth may directly be stimulated by VOCs and WSOCs brought by biochars.

Another type of VOCs are the karrikins; they result from the combustion of cellulose and lignin, and are known to stimulate seed germination after a forest fire. Kochanek et al. (2016) detected their presence in biochars, and demonstrated that their presence in biochar effectively stimulated seed germination. Backer (2016) suggested that ''it is possible that similar mechanisms may also strengthen plant responses to abiotic stresses such as drought or nutrient deficiency thereby reducing their negative impacts on yield.''

Also, experimental results suggest that biochar-associated VOCs and WSOCs such as benzene, ethylene, carboxylic acids, furans and polyphenols are able to modify microbial diversity, abundance and activity in the rhizosphere, leading to changes in nutrient cycling (Backer, 2016; Ding et al., 2016). Additionnally, VOCs and WSOCs contained in biochars provide metabolizable C which microorganisms may use as fuel to operate carbon and nitrogen cycling, indirectly affecting plant growth (Zimmerman, 2011).

By contrast, some VOCs found with biochars can be phytotoxic; these include hydrophilic biodegradable compounds, low molecular weight organic acids, and penols. McClellan et al. (2007) found that some residual volatiles on biochar proved toxic to plants. The presence of toxic biochar-associated VOCs has been linked to decreased seed germination and crop yields in a number of studies (e.g. Gonzaga et al., 2017; Rajkovich et al., 2012). Specifically, biochar-associated carboxylic acids and phenolic and organic nitrogen compounds have been implicated with reduced plant germination and growth (Buss and Mašek, 2014; Rombolà et al., 2015; Spokas, 2011). Other suspects include guaiacol, levulinic acid, glycolic acid, acetic acid, glycoaldehyde dimer, catechol, volatile fatty acids, and other nitrogen-containing organic compounds. VOCs that may be present with biochars and that are known to have bactericidal or fungicial effect include phenolic and polyphenolic compounds such as cresols, xylenols, formaldehyde, acrolein, and other toxic carbonyl compounds (Ding et al., 2016; Lehman and Joseph, 2015). Other VOCs that may be present with biochars are known to be toxic to aquatic life (Bastos et al, 2014). The exact identity of VOCs or group of VOCs that can be present with biochar and that cause toxicity remains unclear, as well as the duration of their effects (Backer, 2016). What is known for sure is that incomplete pyrolysis has been associated with the release of toxic VOCs (Gonzaga et al., 2017).

The overall contribution of VOCs and WSOCs to soil productivity and plant yield remains elusive (Spokas, 2011). The diversity of VOCs from one biochar to the other –even for biochars produced from same feedstock under (apparently) same conditions– could partially explain the observed variability in soil and plant response upon biochar application. Spokas (2011) affirmed that ''It is important that the presence of individual VOC compounds and the combined effects of these compounds be elucidated because their presence may cause diverse responses from biochar additions to soils or other growth media.'' Furthermore, Guidotti et al. (2017a) affirmed that ''the presence of potentially harmful compounds in biochar […] highlights the importance of controlling the biochar production process.''

Of significant interest is the fact that some VOCs and WSOCs are dangerous to human health or cause harm to the environment. Harmful VOCs and WSOCs typically are not acutely toxic but have compounding long-term health effects.

PAHs

Polycyclic aromatic hydrocarbons (PAHs) are a particular category of VOCs. A distinguishing feature is that they are made up only of hydrogen and carbon (''hydrocarbons'') and that they are composed of multiple aromatic rings, i.e. benzene rings. This group is represented by more than 100 different compounds. Naphtalene is the simplest example of a PAH (two benzene rings), and pyrene, phenanthrene and anthracene are other common examples of PAHs.

PAHs are phytotoxic. The presence of biochar-associated PAHs has clearly been associated with inhibition of germination and growth (Buss and Mašek, 2014; Rombolà et al., 2015). The co-occurrence of other VOCs may further amplify the phytotoxic effects of PAHs (Dutta et al., 2007). Furthermore, the presence of PAHs poses a threat to human health: they are known to have toxic, mutagenic, and carcinogenic effects (Dutta et al., 2007). Humans can become exposed to biochar-associated PAHs through direct inhalation or through ingestion of fruits or vegetables grown on a biochar-amended media (Dutta et al., 2017). PAHs are persistent, and as such are renown as one of the most difficult organic contaminants to treat (Dutta et al., 2007).

Biochars can serve as a sink for PAHs and have been successfully used to help in remediating PAH-contaminated soils (Beesley et al., 2011). However, heat treatment of biomass like pyrolysis also has the potential to release PAHs. Incomplete pyrolysis (e.g. traditional kilns) has been associated with biochars with increased levels of PAHs (Gonzaga, M.I.S. et al., 2017). For instance, De la Rosa et al. (2019) observed that wood-based biochars produced via traditional kilns had double concentration of PAHs compared with wood-based biochars produced with more advanced reactors (e.g. kilns, bath reactor, rotary reactor).

Salinity and PCBs

The mineral content of biochar reflects the background geology where the feedstock was grown. Like any minerals, Na and Cl contained in the feedstock can remain in the biochar end-product. Feedstocks high in Na can induce salinity stress in plants (Rajkovich et al., 2012). High salinity can also increase the probability of producing polychlorinated biphenyls (PCBs). Backer (2016) noted that ''it remains unclear how biochar salinity and nutrient concentrations interact with VOCs and WSOCs in biochar to produce plant growth effects.''

Heavy metals

The presence of heavy metals has also been observed to cause detrimental effects and decreased productivity and may present a long-term soil contamination problem (Kookana et al.2011; Hale et al.2012). Biochars indeed concentrate minerals present in the feedstock, and as such could carry heavy metals. Over and above the influence of the background geology, species accumulate heavy metals differently. For instance, willows tend to accumulate cadmium. The accumulation of heavy metals in the foodchain should be of especial concern. Much like salt, presence of heavy metals cannot be prevented if present in the feedstock. However, application rate can be adapted.

Usage conditions affecting effectivity of biochar in enhancing soil productivity

Usage conditions include time since application, the way it was applied, as well as the local conditions. A solid body of literature has validated the effectivity of biochars in enhancing soils productivity in varying usage conditions (Barrow, C. J. A. G., 2012; Jeffery, S., et al., 2011; Spokas, K. A., et al., 2012).

Time since application and temperature

The early effects of biochar can vary considerably. For instance, the presence of nutrients can have very rapid, but short-lived effects (~1-2 seasons). Effects other than nutrient input are known to be slow in coming, tend to improve with time for a certain period, then stabilize and can persist for a very long time, cogently on a scale of centuries to millenia (Major, 2010). This long-term persistence is a major difference with other organic soil amendments (e.g. woodchips) or with fertilizers, which partly explains the relatively high market value of biochar ($500-1000/tonne).

Slow response reflects the fact that many effects of biochar are microbially-mediated, and microorganisms take time to colonize biochar (Joseph et al., 2010). Biochar also goes through 'ageing' once put in the soil, a process by which some oxidation takes place; Cheng et al. (2008) noted that a huge knowledge gap exists in the understanding of how ageing impacts the integrity of biochar, which will impact its longevity. As far as impact of temperature goes, it is known that cold temperatures slow down microbial colonization, which delays early response of biochar (Cheng and Lehman, 2009) and slows down ageing (Cheng et al., 2008). Consequently, the effects of biochar can be slower in coming in a colder climate and evolve differently.

Application rate and technique

Major (2010) mentioned that a minimum application rate from which improvements of soil productivity have been observed is 5 tonnes/ha, and improvements have been observed for applications of 50 tonnes/ha and even higher. It is said that the poorer the soil, the less biochar needed to see an effect. Where several rates have been tested, results often are better at higher application rates (Major, 2010). However, decreasing productivity has been observed with incremental rates (e.g. 100-200 tonnes/ha); the reason for this decrease is unknown, but is believed to perhaps be related to salinity (Major, 2010).

A commonly used default application rate is 10 tonnes/ha, but this is arguably more of a rule-of-thumb than a science-based standard. Like any soil amendment, biochar application rates should be calculated by an agronomist based on both the receiver (site-specific soil properties and crop needs) and the specific amendment's properties (e.g. nutrient content, pH, CEC, see point 3.2.1 below). In clear, site-specific soil conditions should be observed to better align the prescription and determine the application rate of a biochar with known properties.

However, 'insufficient field data [still] is available to make general recommendations on biochar application rates according to soil types and crops' (Major, 2010). It can be expected that in a near future, like other soil amendments, a calculation chart would be available for experts to use in calculating application rate. Until then, application rate must be based on best professional judgement, taking into account past results and regional trends in similar conditions. Wherever possible, different application rates should be investigated on a case specific basis to determine the optimum biochar application rate.

The grain size of the biochar particles and effectivity of integration in soil also are important application conditions. For instance, comminuted biochar is more effective than bulky chunks, and full integration of biochar in the soil bed enhances the response as compared to surface application.

Biochar can be handled/delivered by bag or in bulk by truck. Biochar can be applied on an agricultural field using standard solid manure spreader; biochar should be wetted to limit flying away and to improve consistency of dosage/application, and promptly tilled into the ground (Major, 2010). It is recommended that biochar be integrated into the soil to a depth of 60-100 mm (Major, 2010).

Local conditions

The soil conditions (e.g. texture, structure, pH, CEC, salinity, nutrients content and speciation) and climate (temperature patterns, precipitations) under which a biochar is used have been shown to be key determinants in the effectivity of a specific biochar. For instance, Jefferey et al. (2011) found that crop productivity did not increase upon application of a biochar on fine soils, whilst it increased 10% when the same biochar was applied on medium and coarse soils. Moreover, agricultural practices (e.g. fertilization, irrigation, tillage, rotations) have a role to play, and the response will be different for every crop type. Given the sheer variability of all these factors, it is understandable that inconsistent results have been observed, even in the case of a same biochar. For instance, soil conditions can tremendously vary from one site to another, even in an otherwise relatively homogeneous region (see point 3.1.3.4 below for Yukon specificities).

Interactions with fertilizers

Most biochar materials are not substitutes for fertilizer, and cannot be expected to be effective in improving soil productivity under otherwise limiting conditions, e.g. insufficient N. It is however well documented that biochar can improve nutrient usage and that synergies can stem from the interaction of fertilizers with biochars: the benefits of using biochars and fertilizers together are higher than those brought by using them alone (Lehmann et al., 2003; Cantrell et al., 2012). In particular, biochar increases responsiveness to N fertilizer, and generally diminishes the fertilizer requirements (Glaser et al., 2002). Biochars can advantageously be applied in combination with compost or manure, or spiked/charged with synthetic fertilizer prior to application. It can also be used as a feed or silage additive or added to the litter or manure for supplementary benefits (Joseph et al., 2015).

3.1.3.4 Effectivity of biochar in enhancing agricultural soils productivity in Yukon

Although proven time and again in a variety of conditions (e.g. soils, climate) and for a variety of crops the world over, confirmation that biochar can improve productivity of agricultural soils in Yukon remains elusive. Very few studies have been conducted on the subject despite the high potential, solid supporting body of literature, and the interest from the farming community. To this day, results are fragmentary and remain inconclusive.

Current state of the knowledge

For instance, Drury (2014) did not find any increase in productivity 1-3 years into application of biochars on Yukon agricultural soils (Orthic Eutric Brunisols with varying site-specific properties). Invalidating results have also been observed. Biochar was applied at a rate of 10-30 tonne/ha, with and without NPK and S fertilization. The biochars used in this experiment originated from woody and manure feedstocks and were obtained locally by slow pyrolysis under unreported conditions (e.g. residence time, temperature, oxygen level). They were produced under similar conditions, and from same equipment as woody and bonemeal feedstock biochars used by Karppinnen (2018) and for which properties are presented in Table 5 (Appendix 1.B, p. 94). Lability of the carbon content (H:C ratio), salinity and presence of potential toxicants (e.g. PAHs, VOCs, PCBs, dioxins/furans) were not reported.

Nevertheless, anecdotal evidence exists, and some Yukon farmers and gardeners observed that biochar has improved the productivity of their agricultural soils. Also, the efficacy of biochar in improving revegetation of mine tailings when combined with compost in Yukon conditions has been documented by Nordin (2015). Likewise, the efficacy of biochar in enhancing hydrocarbon degradation has been documented by advanced studies taking place in Yukon and similar conditions (e.g. Greenland and Nunavut; Karppinen et al., 2019, Karppinen, 2018). And the efficacy of biochar in enhancing agricultural soils productivity has been documented in conditions similar to those prevailing in Yukon (e.g. northern China: Yang et al., 2015, Yao et al., 2017, Wang et al., 2016; Zhang et al., 2014). It could also be argued that agricultural conditions in Yukon are not so different from those of more temperate zones of Canada, where the efficacy of biochar has abundantly been demonstrated (e.g. Ahmed, 2016). In Northern Russia, historic biochar-amended soils ('plaggen soils') similar to those of terra preta have been documented and are known to have been built for soil productivity enhancement purpose (Hubbe et al., 2007). Same for the Illinois Plains (Krug et al., 2003). Sheridan (2019) suggested that further agricultural field trials would highly benefit from prior identification of desirable biochar properties and suitable production methods –which this study aims in providing. In any case, Atkinson (2010) mentioned that 'Biochar effects […] are highly variable and site-specific research is needed to determine impacts on crop yields.'

3.1.4 Conditions under which agriculture is practiced in Yukon which might affect effectivity of biochar

Agriculture conditions in Yukon are challenging. Climatic conditions are a challenge in and of itself, but the main challenge is with soil conditions. Agriculture is practiced all over the southern part of the Territory, where conditions are better suited.

3.1.4.1 Climate

Yukon climate is continental and generally semi-arid, with cool, short summers. Summer temperatures in Southern Yukon can reach 30°C, with 80-90 frost-free days depending on the location (YG, 2018c). Long summer days with greater photoperiod boost GDD[17] and allow for growing many of the same crops as in the Canadian prairies. Typical precipitations during the growing season (May to September) are low, at 156-196mm, with lots of nuances depending on the location. Irrigation practices can somewhat compensate for low precipitations.

Precipitations and temperatures have been observed to be on the rise as a consequence of climate change (YG, 2019a). Although unpredictable and threatening many other aspects, this possibly could enhance general agriculture conditions in Yukon, for instance hastening soil processes and increasing GDDs.

3.1.4.2 Soils

Yukon soils generally bear very poor native productivity. They often are limited by nutrient availability and low SOM. The deficiencies often are so important that soils need be 'built' to be able to support agriculture. Most soil deficiencies can be corrected with soil amendments and fertilizers. Those deficiencies however often are hard to address, given the high needs and the prohibitive cost of fertilizers and of amendments in Yukon. Locally-made biochar could compensate some of that.

The following is a description of general soil conditions in Yukon. Table 6 (Appendix 1.C, p. 95) provides a summary of soil condition trends by region. Over and above generalities, it is important to keep in mind that site-specific conditions vary tremendously and can evolve with agricultural practices. YG (2019c) offers soil analysis services to uncover these. Table 7 (Appendix 1.D, p. 96) presents examples of criteria that can be used for evaluating soil properties.

Sound prescription of soil amendments and fertilizers need be calculated taking into account site-specific conditions. In the absence of soil test data, information contained in Table 6 and Table 7 can be used to estimate soil conditions and help in better aligning amendment and fertilizer application rates to soil needs.

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[17] Growing degree day (GDD) reflects the accumulation of heat and the classic measure reflects the the number of days above 5°C.

Pedogenesis

Yukon lies within the ''Pacific Cordillera'' physiographic region, characterized by rugged mountains, high plateaus and river valleys. The last glaciation that ended 10,000 years ago affected over two-thirds of the Territory. Affected regions saw their pre-existing soils scraped and covered with barren glacial deposits (Matheus, and Omtzigt, 2012). Soils that evolved only since are said to be very 'young' in geological terms. They evolved under cool and dry conditions with short summers and are said to be 'immature'. They are shallow and weakly developed: coarse texture, weak structure, and poor nutrient content. Soils that were not affected by the last glaciation such as those of the Klondike region are not much better developed, as they also evolved in mostly cold and dry conditions, often being underlain with permafrost (Matheus, and Omtzigt, 2012).

Cold and dry conditions hamper soil development in that it slows down microbial activity and chemical reactions –which are the drivers for mineral weathering, organic matter decomposition (Matheus, and Omtzigt, 2012). Mineral weathering, on top of contributing to refinement of texture, is the process by which minerals are released from rocks to create a sufficient pool of available nutrients.

Soil types

Predominat soils in the southern half of Yukon and where agriculture is practiced are Brunisols (closely equating to Cambisols; YG, 2019b). They are described as 'mildly weathered mineral soils' (Scudder, 1997). The most common subgroup of Brunisols in Yukon is Eutric Brunisols; Dystric Brunisols also exist but are less common. A typical agricultural soil in Yukon is Orthic Eutric Brunisol (Drury, 2014). Agriculture in Yukon now is mostly practiced on fluvial deposits in river valley bottoms (Yukon, Takhini, Dezadeash, Pelly, Steward, Liard).

Soil texture, and CEC

Granulometry of Yukon soils is generally coarse (gravel and sand). Fluvial deposits in river valley bottoms tend to be finer textured: they contain more silt and can be described as 'very fine sandy loams' to 'silt loams' (YG, 2018c). Clay is seldom present in Yukon soils; exceptions include the Takhini and Dezadeash valleys, where clays originate from glacial Lake Champagne. In general, finer grains have higher CEC.

Soils structure, SOM, and CEC

Yukon soils are said to be 'non-cohesive' and have weak structure: they have poor shear strength, which can be observed on how a handful can run relatively easily between the fingers (Matheus, and Omtzigt, 2012). Good structure fosters aeration, water retention, and root penetration. Structure is partly related to texture but depends a lot on the organic content. For instance SOM typically is <5% in native Yukon agricultural soils, which is considered low and below target to sustain agriculture. Soils with <6% SOM generally are considered carbon-deficient and as such have higher potential of benefiting from biochar addition (Pensulo, 2012). SOM also contributes CEC. Soils with a history of burning tend to have a higher recalcitrant

SOC content. Within floodplain areas, mixed layers of organic and mineral material are present throughout the profile (Matheus, and Omtzigt, 2012). Yukon forest soils usually have a very thin top layer of organic material, which needs to be treated with utmost care upon land clearing (YG, 2018c). Even after incorporating this layer, organic material content is often insufficient to sustain agriculture. CEC typically is very low, due to coarse granulometry and low SOM.

Structure, SOM and CEC can be corrected with large quantities of organic matter amendments (e.g. woodchips, biochar, compost, manure, 'green manure'/tilled-in cover crops). It is important to keep in mind that input of labile carbon is susceptible of immobilizing nitrogen and fostering nitrogen loss due to increased microbial activity. Organic matter with lower labile carbon fraction, such as biochar, is less susceptible of causing such issue. Nitrogen depletion can be compensated with addition of large quantities of nitrogen fertilizer.

pH

pH is typically on the higher side of the arable range, with notable exceptions (e.g. acid soils in the Klondike river valley). Alkaline soils can be acidified with application of elemental sulfur or ammonium sulphate. The latter also contributes nitrogen fertilisation. Conversely, acid soils can be treated with lime to increase pH.

Salinity

Localized salinity issues have been observed, for instance northwest of Whitehorse along the Alaska Highway and in the Takhini Valley (Matheus, and Omtzigt, 2012). Fertilizers tend to increase salinity, as many of their components essentially are salts. Salinity can be treated with elemental sulfur amendments (which also lowers pH). Salinity is measured as Electrical Conductivity (EC).

Nutrients content and speciation

Yukon soils typically are deficient in macronutrients (NPK and S; YG, 2019b). While nitrogen usually is the main limiting factor, phosphorus can also be growth-limiting as it tends to be low in most regions (Matheus, and Omtzigt, 2012). Potassium and Sulfur vary according to local geology, and sometimes are limiting (Matheus, and Omtzigt, 2012). Micronutrients such as boron have also been shown to be limiting in some soils (Matheus, and Omtzigt, 2012). Other nutrients of importance include Mg and Ca. The availability/speciation of existing nutrients (e.g. total N, NH_4, NO_3, available P, extractable K) depends on the prevailing physico-chemical parameters (e.g. CEC, pH, salinity).

Nutrient deficiencies can be corrected by large quantities of fertilizers (e.g. compost, manure, synthetic fertilizers, 'green manure'/tilled-in cover crops). Precipitations and humid conditions pose a challenge to sustaining the N supply, as NO_3^- is susceptible to leaching, particularly in coarse textured soils such as those of Yukon.

3.2 Use case requirements

The exploration of pyrolysis equipment options with this study is a unique opportunity to align prospective end-product biochar with the general Yukon agricultural soils needs, taking into account the slash management context. The idea of a ''designer biochar'' has been around for a while (e.g. Novak et al., 2009), where biochar properties are tailored through adjustment of pyrolysis conditions[18] to address the specific needs of a particular soil. On that topic, Major (2010) expressed ''To date, actual field data is lacking to address which measurable characteristics of biochar are the most relevant to soil improvement and soil C sequestration, in a range of soil environments and management systems.'' While making strides in that direction, the current reality still is that biochar properties depend on so many factors outside of the equipment itself (esp. feedstock nature and size) and that soils needs vary so much from site to site –even in an otherwise relatively homogeneous region like Yukon–, that it still is difficult to predict the exact efficacy of a biochar based on the equipment that is used and the pyrolysis conditions.

What can be done nevertheless is to aim for a specific set of biochar properties and calculate appropriate application rate accordingly, perhaps supplemented with fertilization. The following is a description of the requirements in terms of the properties the end-product biochar should bear, the pyrolysis conditions that can lead to them, and other factors that should be taken into consideration to narrow-down equipment options to only those that have reasonable chances of responding to the use case.

3.2.1 Desirable biochar properties

Several properties have been identified to evaluate the quality of biochar for use as agricultural amendment. Yukon agricultural soils demand biochars that can increase SOM and trigger the cascade of recognized benefits, without causing harm (e.g. PAHs, pH, salinity, metals). The aspect of nutrient contribution can be ignored, as it is very marginal in any case. Recognized quality criteria exist that can help in evaluating the suitability of a biochar as an agricultural soil amendment and which should be used, with special considerations for the Yukon context.

3.2.1.1 General considerations

The International Biochar Initiative (IBI, 2015b; Appendix 1.E, p. 97) and the European Biochar Foundation (EBF, 2019; Appendix 1.F, p. 100) both developed sets of standards to characterize biochar as an agricultural soil amendment. The two sets of standards differ slightly, and harmonization efforts are underway; a unique industry-wide international standard can be expected in the coming years (EBF, 2019). In the meantime, professional judgement must be exercised in comparing and using them.

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[18] e.g. modifying the residence time or the temperature to influence biochar pH, ash content, or surface area properties.

The standards establish quality criteria (tresholds) for key biochar properties to optimize the benefits as an agricultural soil amendment, as well as measuring protocols so that results can be compared on a same basis. The objectives behind the quality criteria is to foster effectivity of biochars as an agricultural soil amendment while keeping the hazards in check. For instance, they establish a minimum threshold for organic carbon content (Corg) and maximum limits for degree of lability (H:C ratio) and degree of un-carbonized material (O:C ratio), as well as maximum limits for PAHs and heavy metals. The 'safe level' thresholds for toxicants are slightly different from one standard to the other, as well as the measuring protocols (see comparison in Table 8, Appendix 1.G, p. 103).

These standards also establish declaration requirements and labelling formats. For instance, ash content, pH, bulk density and specific surface area must be declared, even though no specific threshold is established. Reporting on properties in a systematic way regardless of feedstock type and production process can help users/buyers in knowing what exactly they are getting and help in calculating proper application rate. It can also help researchers in their ongoing efforts to link specific biochar properties to specific effects.

EBF (2019) standards also prescribe sustainability criteria, e.g.:

- wood feedstock must only be used if appropriate standards, laws or certificates (e.g. PEFC, FSC) can prove that it was obtained through sustainable forest management
- at least 70% of the waste heat must be used, for instance for drying biomass, distant heating, generating electricity or similar sustainable purposes
- the pyrolysis process is compliant with emission standards

Certification programs exist (e.g. IBI, 2013) that can demonstrate that a biochar responds to a specific set of quality criteria. By definition, a certification program is administered by an independent third party (an entity other than the manufacturer, the user, or the legislator/government, in this case). Such certification program can be an opportunity for manufacturers to prove that their product meets well-defined quality standards while giving customers a reliable quality basis. It can also help in (re)building and ensuring the trust between manufacturers and users, especially in a context where biochars with unknown properties have been used and failed to deliver expected results. Many jurisdictions have their own certification requirements, often referencing one or both of the international standards. For instance, Government of Canada requires certification by the Canadian Food Inspection Agency (CFIA)[19] for any biochar that is sold with the intent to be applied as an agricultural soil amendment, as it is now legally considered as a soil

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[19] CFIA administers the certification (GC, 2018), and accredited third-party agencies can provide the certification services (e.g. Centre for Systems Integration, CSI). Alberta Innovates/Technology Future (AITF, 2015) offers assistance in obtaining certification.

''supplement''[20]. This certification program focuses on heavy metals content, with set priority on controlling environmental risk (see comparison of thresholds in Appendix 1.G, p. 103). The manufacturing method and physical characteristics of the final product (e.g. pH) must also be reported. Moreover, if field trials are being conducted, a research authorization (RA) is required from the CFIA. Another example of certification program is those of organic farming certification agencies, who have their own set of standards for application of biochars as agricultural soil amendment.

It is important to note that tests are done on a specific biochar series (e.g. production of 1 day). Consequently, certification applies to a specific biochar, not an equipment or the biochar it can produce in general. The EBF (2019) definition of a ''biochar series'' includes the following:

- 'The pyrolysis temperature in °C do not fluctuate more than 20%. Interruption of the production is allowed as far as the production parameters keep the same after the restart of the production.
- The production period of the series does not exceed one year including any interruption of the production
- The composition of the pyrolyzed biomasses does not fluctuate more than 15% based on the type of feedstock listed in the feedstock positive list.

Once any one of these criteria is not met, the biochar subsequently produced belongs to a new series for which new production records and analyses are required.'

3.2.1.2 Special considerations for Yukon context

Considering the typical soil conditions under which agriculture is practiced in Yukon (see point 3.1.4 above) and that the feedstock would be woody biomass, the following hazards and properties might be of special interest for biochars to be used as agricultural soil amendment in Yukon.

Stability of the carbon content/fraction of labile carbon

Considering the fact that Yukon soils generally have a low nitrogen content (0-3 ppm) and low native SOM content (0-4%) and), the labile carbon fraction (H:C ratio) should receive proper attention and be kept at a minimum. As a reminder, labile carbon carries the hazard of triggering a priming effect leading to loss of pre-existing SOM, as well as the hazard of fostering nitrogen immobilization and nitrogen loss (see 3.1.1.3 ''Risk management''). Labile fraction also decreases the C-sequestration potential. Recognized quality criteria (IBI, 2015b and ECF, 2019) recommend that H:C ratio be <0.7. In the Yukon context, the criteria possibly should be smaller.

Where nitrogen is a limiting factor –which typically is the case for Yukon agricultural soils–, adding biochar cannot be expected to produce any positive result unless supplemented with nitrogen fertilization; any labile fraction can even result in overall

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[20] 'Supplement: 'any substance or mixture of substances, other than a fertilizer, that is manufactured, sold, or represented for use in the improvement of physical condition of soils or to aid plant growth or crop yields' (GC, 1985).

decrease in productivity. Henceforth, biochar used as soil amendment in Yukon should be supplemented by some form of nitrogen fertilization (e.g. manure, compost, synthetic fertilizer).

Salinity

Considering that salinity has been detected as an issue in some Yukon areas, biochar salinity should receive appropriate attention. For instance, locally-sourced woody feedstock could carry salt issues into biochar. This would be of special concern when applying a biochar obtained from a high-salinity area to a soil that already is on the higher range of salinity. Moreover, feedstock with higher salt content would have a higher probability of producing PCBs and dioxins in the biochar.

Salinity of biochar cannot be prevented if present in the feedstock. However, evaluation of the composition of the feedstock might help in predicting influence on biochar content and adjust pyrolysis conditions consequently where possible, or adjust the application rate to the soil's capacity in tolerating salinity. Alternatively, salinity could be counteracted with elemental sulfur (which also lowers pH).

IBI (2015b) prescribes that salinity be measured but does not provide any quality criteria –no more than EBF (2019). As an indication, salinity is considered ''low'' and ''moderate'' in agricultural soils when <1 and 1-5 mmho/cm, respectively (see Appendix 1.D, p. 96). Further scrutiny would likely be beneficial, perhaps to determine a suitable salinity criterion in the Yukon context.

Toxicants/antagonistic compounds

Considering the severity and the near-irreversibility of consequences of applying biochars that contains higher-than-acceptable toxicants, evaluation of these parameters should be a priority. For instance, heavy metals, dioxins/furans, PAHs, and PCBs are known to occur in biochar. Their occurrence depends on the feedstock and the conditions under which the biochar was produced (see point 3.2.2 below). These can have antagonistic effects (damaging the soil productivity), accumulate in the soil, cause a threat to human health, and disseminate in the food chain. IBI (2015b), EBF (2019) and GC (2019) all have sets of quality criteria for these, some taking into account the application rate. While the feedstock is fixed (slash pile material), the concentration of contaminants can be controlled by controlling the operating conditions in the pyrolysis unit. As an upside, experimental results by Buss (2016) and by Weideman et al. (2018) demonstrated that biochars made from woody feedstock (such as that of slash piles) contained significantly less PAHs than straw-derived biochars –almost 7 time less, and 5.8 time less, respectively.

Unfortunately, the analyses for toxicant content can be very expensive. It has been suggested that perhaps a form of leachate toxicity test could be used as a proxy (Nordin, 2019, pers. comment).

Much like salt, presence of heavy metals cannot be prevented if present in the feedstock. However, evaluation of the composition of the feedstock (e.g. salinity, heavy metals) could give insights into composition of the subsequent biochar end-product; pyrolysis conditions could be adjusted where possible (e.g. salinity), or the application rate (e.g. heavy metals).

pH

Considering that some Yukon soils already are on the alkaline side of the arable range and that biochars tend to increase pH, provision should be made to counteract any undesirable pH increase with addition of an acidifying amendment, for instance elemental sulfur (which also tackles salinity) or ammonium sulfate (which also provides nitrogen fertilization).

3.2.2 Optimum pyrolysis conditions

The unique properties of a specific biochar are conferred by the interaction of a specific feedstock with the specific set of pyrolysis conditions under which it was produced. In the current use case, feedstock is fixed: slash pile material. Therefore, the determinants of biochar properties are the pyrolysis conditions under which it is produced, which can be adjusted to optimize the desired biochar product. Speed of pyrolysis and treatment temperature are the key factors. Another very important aspect is the oxygen level in the furnace. Other determinants include the heating rate and the pressure under which pyrolysis was conducted.

Overall, slow pyrolysis conducted at a temperature in the higher range (450-550 ^{o}C) has the best probability of producing an optimum and consistent wood-based biochar that responds to the quality criteria (properties requirements) for usage as an agricultural soil amendment while taking into account the nature of the feedstock, for the reasons exposed below.

Important aspects of the feedstock variability that could influence the pyrolysis conditions include the fact that smaller pieces of dryer material or softer biomass with lower density and higher resin content might tend to increase the treatment temperature and speed up the process, while big or damp, green or rotting material might have the opposite influence (Spokas, 2011).

3.2.2.1 Residence time

Residence time of the biomass in the pyrolysis chamber can vary from seconds to hours; anything shorter than 15 minutes is considered ''fast'' pyrolysis, and anything longer is ''slow pyrolysis''. Other characteristics of fast and slow pyrolysis include the following:

- Fast (rapid) pyrolysis uses moderate to high temperatures. Heating rate is in the order of 1000K/min, and HTT most likely is above 400^{o}C (Brown et al., 2011). Residence time often can be counted in seconds (Brown et al., 2011). It is a more technologically challenging process and typically requires higher capital costs than slow pyrolysis.

- Slow pyrolysis, aka carbonization, is characterized by gradual heating over a wide range of temperatures. The heating rate remains below 100K/min and HTT can remain below 400°C. Residence time is of at least several minutes and often several hours –sometimes days (Brown et al., 2011). Slow pyrolysis is much closer to the traditional charring process used by human for millennia.

One of the main advantages of slow pyrolysis is that it permits various feedstock sizes, moistures and nature's anomalies to be slowly processed into biochar with consistent properties. Over and above quality, product consistency indeed is a special challenge with pyrolysis; the slightest change in pyrolysis conditions and feedstock can render a biochar with radically different properties. This challenge is greatly enhanced when dealing with variability in the feedstock (e.g. size, humidity), such as with slash pile material. Product consistency nevertheless is of utmost importance, especially in the context of usage of biochar as soil amendment.

Slow pyrolysis has also been shown to be able to operate a more complete conversion of the biomass, especially in the face of limitation to heat transfer[21] and kinetics for instance when dealing with big pieces (Bruun et al., 2011). A more complete/effective conversion has a number of advantages:

- Lower probability of producing smoke.
- Lower labile carbon fraction, hence higher durability/recalcitrance of the biochar and lower hazard of causing nitrogen immobilization and depletion of native SOM. For instance, Bruun et al. (2012) found that slow pyrolysis biochar had lower content of un-pyrolzed carbohydrates compared to fast pyrolysis biochar from same feedstock; when applied as a soil amendment, the fast pyrolysis biochar acted as nitrogen sink while the slow pyrolysis biochar actually fostered nitrogen mineralization, and better nitrogen availability.
- Reduced salinity (Backer et al., 2018)
- Less volatile matter content, especially lower volatile organic carbon (VOC) content (e.g dioxins/furans; IBI, 2012, Spokas et al., 2011). For instance, Ghidotti et al. (2017a) found a statistically significant trend between the increasing carbonization and decreasing quantity of all VOC classes, with biochars having high carbonization degree (H:C <0.70) releasing no VOCs at ambient temperatures (25, 50 °C).
- Reduced concentration of PAHs (Weidemann et al., 2018). For instance, Hale et al. (2012) found that biochars produced under slow pyrolysis generally had lower total PAH concentrations (0.07-3.27 µg/g) than those produced under fast pyrolysis or gasification (0.3 µg/g and 45 µg/g, respectively, with maximum levels

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[21] Particle size and physical structure influence the speed in which material is subjected to pyrolysis: in general, lower thermal conductivity of the biomass results in slower heat and mass transfer rate within individual particles. In other words, bigger diameter/size particles (e.g. trees, logs, root balls) will pyrolyze slower than small particles (e.g. woodchips).

exceeding some quality standards). Cole et al. (2012) found results consistent to these. The authors posited that this could result from the fact that slow pyrolysis provides more chance of PAH loss is gaseous forms to the atmosphere whereas in fast pyrolysis the PAHs tend to become sorbed onto the biochar.

Other advantages of increasing residence time on biochar properties include the following (Ippolitto, 2015):

- Increases the carbon content of the biochar, with better carbon sequestration potential (as measured in wt % of dry and ash-free biochar).
- Generally, increases retention of macronutrients (NPK and S) and micronutrients such as Ca and Mg.
- Increases specific surface area.
- Increases CEC

Increasing the residence time generally produce less ash, which is neither good or bad, but depends on the farmer's preference. For instance, farmers planting row crops tend to want the low ash biochar while horticulturalists tend to want the high ash biochar (which has more minerals and brings CEC). Moreover, while ash can provide nutrients, biochars with a high proportion of ash will contain a correspondingly lower amount of fixed C. Manure-based biochars typically have higher ash content than wood-based biochars.

The effect of residence time onto pH depends on the temperature: increased residence time only increases pH at low temperatures (e.g. 300oC, Sun et al., 2016).

The effect of residence time onto biochar yield also is a function of temperature: increased residence time only decreases yield at low temperatures (e.g. 300^{o}C, Sun et al., 2016). At higher temperatures (e.g. 600^{o}C), it has no effect (Sun et al., 2016). Overall, slow pyrolysis tends to favor production of solid end-product (biochar) over syngas and bio-oil, but slow pyrolysis also expels more heat, with a neural overall biochar production (Brown et al., 2010). Increase in heat release reduces the need to apply external heat to sustain the process.

Overall, slow pyrolysis is preferred to fast pyrolysis for yielding good quantities of consistent biochar that is optimal for agricultural soil amendment usage.

3.2.2.2 Temperature

Pyrolysis temperature highly influences the yield and the properties of the biochar end-product (Table 1).

Table 1. Advantages and downsides of increasing pyrolysis temperatures on biochar yield and properties in the context of agricultural soil amendments, taking into account feedstock nature. Arrows indicate direction of the influence, without necessarily indicating extent of influence.

Advantage	Downside	Influence
↓ Biochar yield		
	X	Higher temperatures tend to produce more syngas, to the expense of biochar. A decrease in biochar yield also means a decrease in overall C recovery and C sequestration (Bruun et al., 2011; Ippolitto et al., 2015). For instance, Keiluweitet al. (2010) indicated that temperatures > 550^{o}C decreased C recovery. Zhao et al. (2018) observed a decrease in biochar yield when increasing temperatures 200–700 °C, in 50 °C intervals.
↑ Carbon content		
X		Although less biochar is produced, what is produced has a higher carbon content (Ippolitto et al., 2015). For instance, Zhao et al. (2017) found an increase in C content with increasing temperatures (300, 400, 500 and 600 °C). Zhao et al. (2018) also observed an increase in fixed carbon when increasing temperatures 200–700 °C, in 50 °C intervals. As similar trend was observed by Ding et al. (2016) when increasing temperatures from 300 to 800 °C.
↓ Labile carbon fraction		
X		The ''easily metabolizable'' fraction of the carbon content decreases because of more complete conversion and increased aromaticity (Bruun et al., 2011). For instance, Zhao et al. (2017) found a decrease in H:C and O:C ratios with increasing temperatures (300, 400, 500 and 600 °C). This means that the overall durability of any carbon content is higher, increasing the sequestration potential of any carbon content. This also decreases any hazard brought by labile carbon, esp. decreasing hazard of nitrogen immobilization.
↕ Specific surface area, micropores (and CEC) and macropores		
X	X	For instance, Keiluweit et al. (2010) found that pyrolysis temperatures > 550 ^{o}C produced biochars that generally have high surface areas > 400 m^2/g. In the same way, Zhao et al. (2018) observed an increase in micropores and overall specific surface area, albeit a decrease in average pore size when increasing temperatures 200–700 °C, in 50 °C intervals. Ippolitto et al. (2015) confirmed a trend of increasing specific surface area with increasing temperature. ''Specific surface area of biochar increases with increasing production temperature as a result of micropore formation that arises when fused-ring C compounds develop at high temperatures. However, at temperatures over 600 °C, the surface area tends to decline due to the destruction of micropores, giving way to formation of macropores. (Backer, 2009).''
↓ Volatile matter content		
X	X	Zhao et al. (2017) found a decrease of volatile matter content with increasing temperatures (300, 400, 500 and 600 °C). Zhao et al. (2018) found a similar trend when increasing temperatures 200–700 °C, in 50 °C intervals. Spokas (2011)'s results confirmed the trend. A lower volatile matter content can have the advantage of decreasing the content of easily metabolizable carbon and the hazards it brings, especially nitrogen immobilization (Deenik et al., 2010). It can also decrease the level of harmful VOCs (e.g. Furans, PAHs). A lower volatile matter content however has the disadvantage of decreasing the level of beneficial VOCs.
↕ VOCs		

X	X	No consistent trend relating VOCs to temperature can be found. For instance, Ghidotti et al. (2017a) found that the release of VOCs increased with increasing temperatures.
↓ Dioxins and Furans		
X		Garcia-Perez and Metcalf (2008) found that in the presence of salts/chlorine, high temperatures decrease the probability of producing dioxins.
↕ PAHs		
X	X	No consistent trend relating PAH to temperature can be found. Buss et al. (2016) have attributed this to a simultaneous increase in PAH formation and evaporation from the biochar with increasing temperatures. For instance, Wang et al. (2013) observed that PAHs decreased with temperature increments: biochars produced at 200^{o}C contained large amounts of PAHs, the content still was high at temperatures 300-400^{o}C, but low at temperatures >500^{o}C. Hale et al. (2012) also generally observed decreasing PAH concentrations when increasing temperatures along a 250-900 °C gradient. Contrastingly, Del la Rosa (2019) observed lower PAH concentrations at higher temperatures. Interestingly, Hale et al. (2012) found that the dominant fractions of PAHs in slow pyrolysis biochars are produced between 350 and 550°C. Similarly, Keiluweit et al. (2012) reported that the amount of PAHs in biochars produced between 400 and 500 °C greatly exceeds the quantities in biochars produced from the same feedstocks at higher or lower temperatures.
↑ pH		
X	X	For instance, Enders et al. (2012) observed an increase in wood-based biochar pH values from 5 to 9 when increasing temperature from 400^{o}C to 500^{o}C. In the same way, Zhao et al. (2018) observed a pH increase when increasing temperatures 200–700 °C, in 50 °C intervals. Ippolitto et al. (2015) confirmed that trend. pH levels are not good or bad, but the desired level depends on the soil conditions.
↑ Salinity		
	X	High temperature biochars have high electroconductivity (Ippolito et al. 2015).
↓ CEC		
	X	Overall, it has been noted that CEC decreases with increasing temperatures (Ippolitto et al., 2015).
↓ Nitrogen retention		
	X	For instance, Lang et al. (2005) found that nitrogen losses increased over a temperature range of 300 to 800°C, beginning around 400°C and with half the nitrogen content lost as volatiles by 750^{o}C. Keiluweit et al. (2012) found a similar trend, especially past 550^{o}C.
Nitrogen immobilization		
X		As a side-effect of lower labile content, increasing temperatures decreases N immobilization.
↑ Phosphorus content and concentration		
X		For instance, Zheng et al. (2013) found that P content increased from 0.12 to 0.17% when increasing temperatures from 300 to 600^{o}C –which might be attributed to the loss of carbon and relatively stable P in plant biomass. Zhao et al. (2017) also found an increase in P content when increasing temperatures (300, 400, 500 and 600 °C).
↕ Phosphorus availability		
X	X	While increased temperatures increase the overall P content, the availability of this P decreases, possibly because higher temperatures tend to form more crystallized P-associated minerals. For instance, Zheng et al. (2013) found that increasing the temperature decreases the availability of the P contained in biochars.
↓ Phosphorus sorption		
	X	Independent of P contribution from biochar, P sorption decreases with increasing temperatures. For instance, Morales et al. (2014) found that increasing the temperature (400, 500 and 600 °C) decreased the sorption of P onto biochar, with 4-10 times less at 600^{o}C. This could have implications for P leaching (i.e. leaching increases with temperature), and thus P availability to crops -especially in low fertility soils.
↕ Potassium (K) retention, content and availability		

X	X	No consistent pattern relating temperature to K can be found. On the one side, Zheng et al. (2013) found that K content increased from 3.7% to 5.02% when increasing temperatures from 300^{o}C to 600^{o}C; availability of K increased from 37% to 47% along the same temperature gradient. Zhao et al. (2017) found an increase in K content with increasing temperatures (300, 400, 500 and 600 °C). Ippolitto et al. (2015) confirmed that trend. On the other side, Keiluweit et al. (2010) found an opposing trend, with temperatures > 550^{o}C decreasing K retention. Wornat et al. (1995) identified that K volatilization was initiated at ~400^{o}C.
↓ Sulfur retention		
	X	For instance, Keiluweit et al. (2010) found that S retention decreased with increasing temperatures, especially with temperatures > 550^{o}C.
↑ Other minerals/nutrients		
X		Increases mineral content. For instance, Zhao et al. (2017) found an increase of Fe, Zn, Ca and Mg content with increasing temperatures (300, 400, 500 and 600 °C). Ippolitto et al. (2015) confirmed that trend for Mg.
↑ Ash content and CEC		
X		Higher temperatures tend to favor production of ash, to the expense of biochar. Ash content brings CEC.
	X	However, the total amount of nutrients contained in ash decreases as a result of volatilization at higher production temperatures
↓ CEC		
X		Globally high temperature biochars have lower CEC (Ippolitto et al., 2015).

The overall influence of temperature on biochar yield and properties is complex. Increasing the temperature has advantages. However, this is done at the expense of biochar yield and carbon sequestration (Bruun et al., 2011). Increasing the temperature nevertheless increases the carbon content of biochar and decreases the labile carbon fraction. The overall carbon sequestration potential is thus lower with high temperatures, but more carbon is sequestered per unit weight of biochar, and whatever carbon is sequestered is sequestered for longer. A decrease in the labile fraction also limits the hazards that labile carbon can bring, especially in terms of N immobilization. Increasing temperatures increases ash content. This has the advantage of bringing CEC. However, the total amount of nutrients contained in ash decreases as a result of volatilization at higher production temperatures, with notable exceptions (P, Fe, Zn, Ca, Mg); however, any nutrient contribution from wood-based biochar is marginal, therefore the contribution of nutrients should not be considered important in balancing the choice of a preferred pyrolysis temperature. Lehmann and Joseph (2015) proposed a temperature between 450-550^{o}C to optimize the characteristics of biochar for use as soil amendment. However, this is in the range where Hale et al. (2012) and Keiluweit et al. (2012) found that slow pyrolysis leads to highest PAH concentrations, which compels to thorough monitoring.

3.2.2.3 Oxygen in the furnace

Biochar yield increases with decreasing the oxygen level in the chamber. In other words, the more efficient a production unit is at excluding oxygen, the better the biochar yield (IBI, 2019).

3.2.3 Preferred equipment features

While a variety of pyrolysis equipment exists that can perform pyrolysis under the said optimum conditions (slow pyrolysis at 450-550°C) to render biochars with the desirable properties, some might be better suited to the context of slash management in Yukon. Many technical, financial and socio-economic factors need to be balanced, the importance of which can be weighed on a scale of 0.1 to 1 as suggested below.

3.2.3.1 Technical factors

Technical factors include those determined by the design and operation features and also reflect the environmental impacts.

Does not produce smoke

The desire to quell smoke production involved with current slash management practices was the original driver for this project. Many other aspects are important (e.g. optimum biochar properties), but the base requirement to not produce smoke should never be lost; on a scale of 0.1-1, this factor hits 1.

Capable of performing slow pyrolysis

It has been established that slow pyrolysis –in opposition to fast pyrolysis– has the highest probability of overcoming difficulties brought by inconsistency of the feedstock, and that it favors a more complete/effective pyrolysis and better biochar properties for usage as agricultural soil amendment (e.g. lower labile fraction and PAHs; see point 3.2.2). While not completely obligatory, slow pyrolysis should be a factor of utmost importance (ponderation factor of 0.9).

Capable of performing pyrolysis at 450-550°C

For a same speed of pyrolysis, it has been established that pyrolysis temperatures of 450-550°C have highest probabilities of producing biochars with optimum properties for usage as an agricultural soil amendment. Again, while not completely obligatory, capacity to operate pyrolysis at temperature 450-550°C should be of very high importance (ponderation factor of 0.9). Alternatively, the pyrolysis temperature could be higher than this range rather than lower; higher temperatures might have the advantage, for instance, of producing biochars with lower labile carbon fraction.

Effectively excludes oxygen

It has been established that biochar yield increases with decreasing the oxygen level in the chamber. Given the relatively lower importance of yield, this condition compared to residence time and temperature, it could receive lower consideration than residence time, and temperature (ponderation factor of 0.5).

Features at least a fair level of process control

Slight changes in pyrolysis conditions can render biochars with dramatically different properties. The fact that the feedstock at hand (slash pile material) has so much variability in terms of sizes and character commands fair process control capacities. While the feedstock cannot be adjusted, process control is the only thing whereby adjustments can be made when feedstock variability tends to throw the pyrolysis conditions out of the optimum. A fair process control would include some form of regulation feature, rather than solely rudimentary monitoring devices. For instance, a basic process control would include temperature sensors, and more advanced equipment would also monitor O_2, flow, pressure, combustion, time, etc. in multiple zones. Regulation features can include some form of temperature lever (e.g. thermostat) all the way up to automated systems and HPLCs operated through softwares, whereby autopilot operations adapt to nature's anomalies to produce a biochar with consistent properties. The capacity to operate slow pyrolysis at 450-550°C is nothing without process control. For instance, Guidotti et al. (2017a) affirmed that ''the presence of potentially harmful compounds in biochar [...] highlights the importance of controlling the biochar production process.'' Moreover, EBF (2019) mentions that ''as both biochar properties and the environmental footprint of its production are largely dependent on the control of pyrolysis parameters [...] a secure control system for its production and analysis needs to be introduced.'' Hence this feature receives a ponderation factor of 1.

Can handle feedstock size ≥ or >> woodchips

Many pyrolysis equipment are designed to process only a uniform size of material, often chip-size or less. Nevertheless, pyrolysis equipment exists that can process feedstock of varying sizes bigger than woodchips (e.g. logs). Even better, pyrolysis equipment exist that can process very big material, such as whole trees, stumps and root balls. As exposed in point 3.1.1, chipping, grinding or shredding could prove difficult with the feedstock at hand. Indeed, slash pile material is notorious for containing a significant amount of rocks and soil, which could prove hard on the machinery. The varying character of the material (e.g. some pieces green, others dry or damp or rotting) would compound that situation and render comminution even more difficult. A lot of resources would be required too. For instance, the purchase and operation of a supporting chipping/grinding/shredding unit could prove very expensive (e.g. capital cost, salaries, maintenance, etc.). Bucking up to log or bolt size would still require some resources, but to a very much lower extent, while totally being technically feasible on this type of material (e.g. with a chainsaw). While smaller material can be fed to the pyrolysis unit using an auger, bigger material can be fed semi-mechanically too, for instance using a loader or excavator. If need be soil and rocks can be removed from the final product by floating the biochar. Contrastingly, it has however been observed that total yield (of biochar) is typically higher when feedstock is pre-processed. While not completely indispensable, the capacity to handle bigger material should receive higher range consideration (ponderation factor of 0.7).

Has a throughput capacity that is aligned with the needs

It has been demonstrated that approximately 40,000 tonnes of slash is produced in Yukon on a yearly basis upon land clearing for agriculture (see point 3.1.1). It has also been posited that this quantity could be cut in half (20,000 tonnes/y) if merchantable wood was harvested efficiently. Very few equipment exist that can handle this large quantity of material. The industry generally defines the ''commercial scale'' threshold at 500 ton/day and larger. In order to calculate the throughput capacity of any equipment, it can be assumed that an indoor unit could be operated 1,920 hours per year (8 hours per day, 5 days a week, 48 weeks per year), and that an outdoor unit could be operated 720 hours per year (6 hours per day, 5 days a week, 24 weeks per year) –taking into account the weather conditions in Yukon. It should however be noted that much throughput capacity could be gained from longer shifts or continuous operation. As an indication, 6-8 hours is relatively short for a batch to be processed. As well, throughput increments would not be linear with increasing operational time: longer operational days could bring huge savings on start-up and winding down, even more so with continuous or semi-continuous operation. Realistically, redundancy of up to 3 units of a same equipment could compensate for lower capacity. Conversely, the equipment should not be grossly over-sized. For instance, a throughput capacity higher than 50,000 tonne/yr (25% higher than current slash production) would be an overkill. While important, this feature should receive mid-range consideration (ponderation factor of 0.5) given the fact that other factors that are beyond this study could substantially influence it (e.g. operational time, continuous operation vs. batch-fed).

Overall yield of biochar in the higher range

Equipment exist that have better yield of one or the other end-products (i.e. biochar, bio-oil, syngas, and heat). The equipment should decidedly target biochar production over bio-oil and syngas, with minimal waste heat. Ideally, the overall biochar yield should be in the higher range (≤5:1). Good ratio of biochar produced for a given quantity of feedstock will improve the bottom line. Given the relatively lower importance of this feature compared to those mentioned above, it could receive lower consideration (ponderation factor of 0.3).

Risk of issues with (local) procurement and replacement of parts is low

There are many places where a pyrolysis unit can fail. Every moving part is a potential point of failure, and number of moving parts might give an indication of durability and reliability. Procurement and replacement of parts tends to be an issue with any project in Yukon, due to shear distances involved and availability of qualified technicians. As for any initiative in Yukon, this factor needs to receive utmost attention in the planning process (ponderation factor of 1).

Syngas can be captured and used

Syngas is an important energy carrier in pyrolysis. Capturing this co-product to burn it rather than flaring it can provide heat energy required to sustain the pyrolysis temperature. Supplemental heat energy could also be used for other purposes (e.g. electricity generation). Capturing and using the syngas imparts a non-neglectable technological burden, but tremendously improves the overall energy efficiency of the system. For this reason, it should be given a higher-range ponderation factor (0.8).

Bio-oil can be harvested

Some equipment are capable of harnessing the production of bio-oil, others less. Recovery of bio-oil could enhance overall efficiency, and potentially the bottom line, while reducing pollution emissions. However, capturing bio-oil can incur a technological burden. For instance, ''if smaller on-farm conversion processes are used, then biofuel production is not likely to be cost effective (Sheridan, 2019).'' As this factor is not likely to influence the overall cost/benefit of an equipment, it should receive a lower ponderation (0.1).

<u>Does not cause issues with localized mercury emissions/deposition</u>
Thermal decomposition of wood emits mercury. Volatilized mercury tends to deposit near the emission point, which can lead to a local accumulation (Roach, 2019, pers. comment). For instance, a stationary unit/plant could see an accumulation of mercury in its vicinity. Mercury emissions can be limited by using a 'scrubber'. For instance, an alkaline flue gas scrubber made of charcoal filters can retain mercury. Ultimately, mercury deposition can be monitored using passive sampling methods (McLagan et al., 2018). Given the severity of the consequences of mercury contamination onto the environment and to public health, this factor should receive relatively high ponderation (0.6).

3.2.3.2 Financial aspects

<u>Capacity to forego transportation of the material over long distances</u>
Land clearing is bound to continue all over the southern half of Yukon, which encompasses huge distances. Transporting large amounts of biomass to a central location is costly, relies on fossil fuels, and results in the emissions of GHGs (Dennis, 2011). In the bioenergy realm, a general rule is that biomass cannot be transported more than 100 km before the cost of transportation exceeds the value of the energy in the biomass. As well, shipping the end-product biochar can be expensive, and especially counterproductive if shipping back to the agricultural field it originated from. For instance, Roberts et al. (2009) observed that 'the transportation distance for feedstock creates a significant hurdle to the economic profitability of biochar-pyrolysis systems; biochar may at present only deliver climate change mitigation benefits and be financially viable as a distributed system.' Transporting the pyrolysis equipment rather than the feedstock biomass and end-product biochar would minimize the costs, usage of fossil fuels, and GHG emissions. In any case, if need was to arise to transport biochar to another application location, it would be much cheaper to transport than the feedstock it originated from, as it has a much lower volume and mass, and low bulk density. For all these reasons, the capacity to forego transportation should receive highest consideration (ponderation factor of 1). Another option could be 'purchasing or building a pyrolysis machine for shared regional production', for instance when the regional amount of biomass justifies (Dennis, 2011).

<u>CAPEX is limited</u>
Costs for capital investment/expenditure (CAPEX) includes unit cost and the expenditures to transport a unit to Yukon. This aspect can tremendously vary among pyrolysis units, from a few hundred dollars to millions. The value of a pyrolysis equipment should however be based first and foremost on the capacity to produce

biochars with desirable properties, than take into account overall benefits. Moreover, the likelihood of capital investment being supported by public instances is high. This factor should thus receive a mid-range ponderation (0.5), even though these costs can be very high.

Cost for O&M are limited

The cost for operation and maintenance (O&M) can also tremendously vary. As a gross figure, pyrolysis is typically operated for $500-4,500 per tonne of feedstock. O&M costs will likely have to be assumed by the equipment owner, and possibly transferred to the client (e.g. pyrolysis service buyer, biochar buyer). This factor should thus be given a relatively high ponderation (0.8).

Capital risk is low

Vendors exist that offer to rent their equipment, greatly limiting the capital risk as compared to equipment purchase. As well equipment exist that could be easier to resell and have higher resale:original value ratio should the need arise. For instance, modular equipment is easier to dismantle and resell than equipment that would be built on-site. Given the sums at play, this factor should receive highest ponderation (1).

Scalability

The scaling of pyrolysis equipment to the need (20,000 tonne/yr) would benefit from a staged process, where units are incrementally implemented so as to limit the risk and allow for in-course adaptative management. Equipment exist that are easier to add to one another than others (ponderation factor of 0.9).

3.2.3.3 Socio-economic factors

Socio-economic factors include those determined by logistics and reflect the social impacts.

Higher impact on Yukon economy

The relative impact on Yukon economy can be evaluated by comparing the O&M cost to the capital cost: an equipment that has higher O&M than CAPEX has a higher impact on Yukon economy. As the impact on Yukon economy is a strong basis for any public instance to contribute to capital investment, this criterion should be given maximum ponderation (1).

Higher impact on rural development

Job creation and business for the local shop(s) can impact the local development. For instance, a centralized system would mainly have an impact only in the one location where the plant would be located, quite possibly the capital (Whitehorse). As rural development also is a strong basis for any public instance to contribute to capital investment, this criterion should be given maximum ponderation (1).

Siting and permitting is easy

The siting of a pyrolysis equipment could require all sorts of permits, which could defer the implementation. For instance, the siting and permitting of a stationary equipment could prove difficult. This factor should receive lower ponderation (0.2).

It is easily/quickly commissioned

Implementing a pyrolysis equipment in Yukon could take a few months to 10s of years. For instance, mobile equipment could be easier/quicker to commission than stationary equipment. This factor should receive lower ponderation (0.2).

Expertise needed for commissioning currently exists in Yukon

Commissioning would be much easier and faster if the skills required for installation and start-up commissioning are aligned with current availability in Yukon. Skills can always be built, for instance for O&M, but any pyrolysis project would tremendously benefit from having pre-operation skills already existing. This factor should be given a high mid-range ponderation (0.6).

The equipment is safe to operate

Potential safety issues include high temperatures and release of gases. Health issues could also arise from the presence of volatile matter. The safety of equipment should be thoroughly evaluated, and receive commensurate consideration, i.e. ponderation factor of 1.

3.3 Pyrolysis equipment

Pyrolysis as a process is not difficult and has been mastered for thousands of years. Humans have been designing, using, and improving pyrolysis equipment ever since. Recent advances allow for more accurate control of the pyrolysis conditions, make the process more energy efficient, reduce pollutant emissions, and improve biochar yield and quality; some advances bolster the capture and usage of value-added co-products such as heat, bio-oil and syngas. These recent advances are reflected in the variety of models and types of units that are now available. Among the variety of pyrolysis equipment that exists, some might be better suited to the conditions of slash management in Yukon where the end-product biochar is used as a soil amendment to enhance productivity.

3.3.1 General principle

Pyrolysis is typically performed in a kiln or in a retort where the biomass is contained, oxygen is excluded, and a vent allows gases to escape (Brown, 2012). As biomass is heated, gasification gets initiated; with the release and combustion of syngas, heat is generated and the process becomes self-sustaining and residual heat is released. The process ends with quenching of the material (rapidly cooling it down) at the end of the residence time so as to stop further degradation. Quenching typically is performed using water.

Pyrolysis can be operated at scales ranging from a large engineered industrial-scale plant capable of turning out 10,000 tonnes of biochar per year to a backyard kiln producing just a small amount of biochar each day. Example of technologies include drum pyrolyzers, rotary kilns, screw pyrolyzers, flash carbonizers, fast pyrolysis reactors, gasifiers, hydrothermal processing reactors, and wood-gas stoves. This project is exploring all scales of production, and embraces the variety of models, types, units, and technical aspects that currently exist.

3.3.2 Equipment evolution

Following realization of the potential of pyrolysis in fighting climate change and the potential of biochar to enhance agricultural soils productivity, much attention has been given to the subject in recent years –by the scientific community and private ventures alike. This interest fostered a tremendous evolution in the equipment that can be used for pyrolysis. Many models have been proposed, developed and tested. Some have failed. For instance, SESM (2016) identified >1000 companies around the world that have at some point offered a pyrolysis equipment in recent years, many of which are Canadian. Numerous companies however actually only exist on paper –or on the Internet, despite claims of being at ''commercial stage''. Indeed, there are a lot of ''pie-in-the-sky'' companies out there, and professional judgement must be exercised in analyzing available information. Although a technology may look good on paper, it is no proof that it works in the real world or can be scaled up for commercial operation.

Garcia-Perez et al. (2010) described the situation in the following terms:

> ''The potential for biochar […] production has enticed many entrepreneurs to develop their own businesses, but lack of technical skills frequently results in highly polluting and inefficient systems. Those interested in commercializing biochar […] technology and developing production facilities are often unaware of available designs and existing regulations that exist. The diversity of situations in which pyrolysis can be applied (different feedstock, scale, capacity, use of mobile or stationary units) as well as the diversity of products that can be obtained from this technology is vast. This makes it very difficult to find an exclusive design that is sustainable across all the potential applications.

SESM (2016) aptly self-declared this situation in the following terms:

> 'This menagerie of [pyrolysis] wizardry is filled with creative technical marvels, but the developers are afflicted with "technical blindness" (from the euphoria of their invention), and they refuse to see the economic reality. The graveyard of [pyrolysis] technologies is littered with good intentions and even great technologies; the monument to their passing is only a dead website. Why do so many new technology companies become zombie ventures? More projects fail because of management than the technology itself.''

3.3.3 Equipment currently available

The following is the result of the literature review that was conducted to appreciate the breadth of the variety of equipment that is available at the moment in view of narrowing down the options to only those that have highest chances of responding to the use case requirement: management of slash piles and usage of biochar as an agricultural soil amendment in Yukon. Any equipment available throughout the world, of any scale, either open-source models or commercially-available units were explored.

A list was built (Table 2), mentioning the name of the model/unit and the manufacturer or source of the model as the case may be. The list was not intended to be exhaustive, but to give a portrait of the variety of options available at this point in time and allow for discerning general patterns in terms of fit to the preferred equipment features. Only those equipment that can process woody material were kept. Equipment that did not respond to that criterion (e.g. only processing agricultural or food waste) or which are not currently available (e.g. for whom the manufacturer seemed to no longer be active or not in the business of supplying equipment) are included in Appendix 1.H, (p. 104). Preliminary information that could inform on fit to the technical, financial and socio-economic factors was collected (e.g. pyrolysis conditions, throughput capacity, biochar yield). Wherever possible, the table was populated with these, along with key benefits and challenges that could eventually help in analysing the value of equipment. Hyperlinks were included in the table, for instance to manufacturer webpage, presentation videos, and images.

Three broad categories with commonalities in terms of technical, financial and socio-economic factors were discerned, and any equipment was aggregated/classified along those lines:

- Low tech/pop-up oven and kilns

These are small-scale open-source and commercially-available model and templates for simple, backyard-type systems that can be custom-built from easily available material. A kiln is a kind of oven, a thermally insulated chamber,that produces temperatures sufficient to complete some process, such as drying, or chemical change. A kiln may be internally or externally heated. A retort is an airtight vessel in which substances are externally heated, usually producing gases to be collected in a collection vessel, or for further processes. Options include buying a unit from a vendor, building a unit from a published design/model, or developing one's own unit. This category includes equipment that is not engineering, such as mounds or pits, as well as rudimentary oven and kilns. Some are impermanent (not meant to be durable) yet others are more durable and can be either stationary or moved around with a pickup truck. Most of these are batch-fed. Their primary design function typically is the production of biochar, and they typically do not burn the pyrolysis gases.

- Mobile units

These are commercially-available equipment that are transportable/portable, i.e mounted or mountable on a towable trailer. They can be on wheel or tracks and can be self-propelled/move around autonomously or require a loader or tractor to be moved around. This category includes kilns and retorts, as well as entire sites with temporary buildings that can be relocated as needed.

- Stationary units

These are large-scale units that are built on-site from modules or from a model. It includes big plants and industrial-scale units.

Table 2. Presentation of existing pyrolysis equipment that potential could be used for slash management in the Yukon context, with features that can inform on fit to the use case requirements.

Type/Company, region, and contact person	**Model**	**Pyrolysis conditions**		**Operation**							**Capital cost** (CAD, approx..)	**Other notes** (OPERATION/DESCRIPTION, KEY BENEFITS, CHALLENGES, ADDITIONNAL END-PRODUCTS[22])
		Residence Time (S or F)[23]	Temperature	Feedstock size capability (≤ or >, or >>)[24]	Feed rhythm/ Frequency (B or C)[25]	Throughput capacity		Yield (efficiency)		Process Control (N/R, F, or A)[26]		
						native units	on a yearly basis[27]	Absolute (native units)	Relative (ratio of feedstock to biochar, on a weight basis)			
Low Tech/pop-up oven & kilns												
No container	Earthen Kilns: Pit/trench kilns Cone pit	S		≤, > and >>[28]	B (5-20 d)	3-330 m^3/B	90-9,900 tonne/y	12.5-30%	≥5:1	N/R	$27/tonne biochar)	OPERATION/DESCRIPTION -A pit or trench is dug in the ground (~70 cm deep) -Biomass is piled in the pit or trench, ignited and then covered with earth. -Alternatively, a layer of coal can first be established at the bottom of the pit or trench; when this starts to show ash and stops flaming, another layer of wood is added, which smothers the coal underneath. The wood is laid parallel (so that it packs in low and tight) and in a limited depth layer (so that it cooks evenly). Sometimes a lid (e.g. corrugated aluminum sheet) is laid across and the edges are sealed, for instance using loose dirt and stamping it down to make a good closure. -When charred, the material is quenched to stop the cooking/burning -Impermanent (is not meant to be durable): made up of soil and sod KEY BENEFITS -Extremely simple to build and to operate -Low capital cost -A number of pits or trenches can be done sequentially (not limited by equipment) -Can accommodate big sized material (e.g. branches, or even trees) CHALLENGES -Labor intensive (must be continually tended) -Skill intensive -Severe atmospheric pollution is possible (particles, VOCs) -Low yield -Heat is wasted (not harnessed) OTHER NOTES -Albeit somewhat primitive, the advantages of large-scale biochar production in trenches might outweigh the temporary smoke problems and these could be mitigated by figuring out a way to recirculate the syngas (Nordin, 2019, pers. comment)

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[22] Over and above biochar (e.g. energy, wood vinegar, tar)

[23] Slow Pyrolysis (S); Fast pyrolysis (F)

[24] Woodchip-size or smaller (≤); Bigger than woodchip-size (>); Bigger than log-size (>>)

[25] Batch (B) or Continuous (C)

[26] None or Rudimentary (N/R); Fair (F); Advanced (A)

[27] Assuming that any unit would be operated 720 hours per year (6 hours per day, 5 days a week, 24 weeks per year) for Low tech/pop-up and mobile units, and operating 1,920 hours per year (8 hours per day. 5 days a week, 48 weeks per year) for stationary units. Assuming a bulk density of 250 kg/m^3 where required.

[28] Can accommodate long biomass material (e.g. branches, or even trees)

	Mounds							2-42%				OPERATION/DESCRIPTION -No container, just a vertical-sided stack - Impermanent (is not meant to be durable) KEY BENEFITS -Can accommodate big sized material (e.g. branches, or even trees) CHALLENGES -Labor intensive (must be continually tended) -Skill intensive -Severe atmospheric pollution is possible (particles, VOCs) -Low yield -Heat is wasted (not harnessed)
	Top-lit updraft (TLUD) mound video								3.33:1			OPERATION/DESCRIPTION -No container, just a vertical-sided stack - Impermanent (is not meant to be durable) KEY BENEFITS -Very little smoke is produced when burning from the top down -Can accommodate big sized material (e.g. branches, or even trees) CHALLENGES -Labor intensive (must be continually tended; need for careful stacking, igniting, quenching and constant supervision) -Skill intensive -Not as efficient as other techniques/units in terms of yield (produces a lot of ash) -Heat is wasted (not harnessed) Other notes -Biocharproject.org sells champion *Biochar* TLUD stoves in Australia
Brick kilns	Brazilian Beehive				B (2-30 d)	8-50 m³/B	240-1,500 tonne/y	12.5-33%			$150-1500	OPERATION/DESCRIPTION -beehive of hemispherical shape brick structure -stationary: made up of brick and mortar KEY BENEFITS -low capital cost -good yields are possible CHALLENGES -severe atmospheric pollution is possible (particles, VOCs)
	Argentine Half Orange				B (13-14 d)							
Concrete kilns	Misouri				B (80 h)	80 tonne/B	9,600 tonne/y	33%			$15,000	OPERATION/DESCRIPTION -stationary: made up of concrete, with steel and bricks ADDITIONNAL END-PRODUCTS -tar KEY BENEFITS -good predictable yield -improved airflow regulation -atmospheric pollution can be mitigated to a degree CHALLENGES -atmospheric pollution is not completely eliminated
Metal kilns	Flame Cap Kiln (Oregon, stackable) design											From Wilson and Associates (Kelpie Wilson)
	Ring-of-Fire (Oregon, detachable) design										https://www.allotment-garden.org/composts-fertilisers/bi	From Wilson and Associates (Kelpie Wilson)

											ochar-terra-preta/how-to-make-biochar-at-home/	
	Mark V				B (23-42 h)	30-400 kg/B	3.6-48 tonne/y	20-31%			$2000-5000	OPERATION/DESCRIPTION -portable: made up of steel
	CDhimney				B (52-84 h)	4-14 m^3/B	120-420 tonne/y	0.3-0.4 m^3 biochar/m^3 feedstock				OPERATION/DESCRIPTION -portable: made up of sheet metal and iron beams
Drum reactors	Vertical (D-Lab, ARTI, Kinyanjui)				B (0.5-24 h)	12-15 kg/B	1.44-1.8 tonne/y	3-30%			$13-61/tonne biochar	OPERATION/DESCRIPTION -portable: made up of mild steel KEY BENEFITS -good yields -portable -shorter processing time -less skill and labor required CHALLENGES -severe atmospheric pollution is possible (particles, VOCs)
	Horizontal (KEFRI)				B (6-12 h)	200 L/B	6 tonne/y	24-30%			$13-17/tonne biochar	
	Large Drum, Mark V, TPI, Black Rock Forest, Ring, New Hampshire				B (1-4 d)	2-7 m^3	60-210 tonne/y	20-30%			$60-1000	
Low-tech retorts	Adam (Improved Charcoal Production System; ICPS)				B (1-13 h)	3m^3/B	90 tonne/y	30-42%			€300	OPERATION/DESCRIPTION -stationary or portable options: made up of brick or earth blocks KEY BENEFITS -good predictable yields, improved airflow regulation, atmospheric pollution can be mitigated to a degree, Mobile or stationary -indirectly heated by burning pyrolysis gas outside of kiln CHALLENGES -atmospheric pollution is not completely eliminated
	JMU Horizontal Drum, Meko Kiln					113 L/B	3.39 tonne/yr	19-24%			$800	OPERATION/DESCRIPTION -stationary or portable options: made up of concrete block, fire brick, steel plate, drum & pipe KEY BENEFITS -good predictable yields, improved airflow regulation, atmospheric pollution can be mitigated to a degree, Mobile or stationary -indirectly heated by burning pyrolysis gas outside of kiln CHALLENGES -atmospheric pollution is not completely eliminated
	TLUD/retort hybrids images (in a kiln)			≤ and >								
	Casamance, Kasi-Sira, Bus Kiln				B (5-8 d)	60-130 m^3/B	1,800-3,900 tonne/y	15-100 kg/m^3 feedstock			$200	OPERATION/DESCRIPTION -impermanent (not meant to be durable): made up of soil, sod, sheet metal/drum KEY BENEFITS -simple to build and to operate
Top Fed Open Draft (TFOD)												

such as cones and pyramids (metal & pit) and rings												
Biocharlie	Biochar Log											OPERATION/DESCRIPTION -The BioCharlie goes into your fireplace like a log, but transforms kindling wood and other biomass into biochar while it burns.
Cone Kilns	Kon-Tiki Kiln images Fingers Lakes Biochar's Kon-Tiki Kiln Ithaka Institute's Kon-Tiki Kiln		650°-700°C								$995	OPERATION/DESCRIPTION -An open-topped conical kiln -Air is drawn in over the hot outer wall of the kiln and swirls above the fuel bed creating a vortex that ensures good mixing of pyrolysis and combustion air, resulting in very low emissions of the Kon-Tiki kiln. KEY BENEFITS -Very low emissions
	Japanese cone Kiln											
Continuous multiple-hearth kiln												
TPI* transportable metal kilns												
	Fraser Common Farm Coop Kiln Design – Single Barrel Retort											OPERATION/DESCRIPTION Single 55 gallon steel drum held horizontally over the ground on a metal stand. A perforated steel pipe routes from a hole in the top-back of the drum along the bottom of the drum and releases the gases that fuel the fire. There is space under the drum where an initial wood fire can be built in order to initiate the pyrolysis process. Cinder blocks are used to surround the whole drum to minimize heat loss.
	Fraser Common Farm Coop Kiln Design – Double Barrel Retort											OPERATION/DESCRIPTION -the double barrel design consists of a smaller barrel filled with the feedstock placed inside a larger barrel. The inner barrel creates an environment with minimal oxygen but is not entirely airtight and allows gasses to escape from the bottom into the space between the two barrels. The outer barrel has air holes around the bottom and a chimney on top to create an up-draft. The space between the two barrels is loaded with kindling and set on fire, and a lid with a chimney is placed on top. Oxygen will flow from the holes in the bottom of the outer barrel towards the chimney and the fire will move downwards burning the kindling. The gases that are released from the inner barrel will burn and further fuel the pyrolysis process as well as limit air pollution.
	Twin Oaks? Forge											
Stephen Joseph, Cornell University	Twin Trough Pyrolyser											
Zakus Farm -Ibex Valley, Yukon	In pipes		450ºC	≤								OPERATION/DESCRIPTION 1- Putting a sealed pipe of woodchips into the fire box of a wood-fired heating boiler
				≤								OPERATION/DESCRIPTION 2- Piston feeder, rather than screw feeders as tried before
More resources												http://www.biochar.info/biochar.biochar-production-methods.cfml http://biocharlog.blogspot.com/2010/05/rocket-retort-rocks.html https://newenglandbiochar.com/services/ https://biochar-international.org/biochar-production-technologies/ https://biochar-international.org/open-source-biochar-technologies/ https://www.biochar-international.org/wp-content/uploads/2018/04/company_list_2013.pdf https://energypedia.info/wiki/Charcoal_Production

												https://www.biocoal.org/ http://www.biopterre.com/wp-content/uploads/2018/07/Biopterre_Technote_Biochar-Juin2018.pdf http://biochar-us.org/manufacturers-retailers
Mobile Units												
Air Burners -Palm City, FL	PGFireBox 100kW 500kW 1MW	S		> and >>[29]		8-20 tons/h	5,224-13,060 t/y			A		OPERATION/DESCRIPTION -Air Curtain Burners (also called Air Curtain Incinerators, FireBoxes, Trench Burners, etc.) were designed principally as a pollution control device for open burning. The primary objective of an air curtain machine is to reduce the particulate matter (PM), or smoke, which results from burning clean wood waste. Using a technology called "air curtain," the smoke particles are trapped and reburned, reducing them to an acceptable limit per U.S. EPA guidelines. -Designed for the high temperature burning of forest slash, land clearing debris, green waste, storm debris, and other waste streams in compliance with the requirements of USEPA 40CFR60. -Can produce biochar if operated accordingly (starving coals from oxygen, and quenching them). -The PGFireBox reduces wood and vegetative waste to a reusable carbon ash and biochar; both products are highly valued in the agricultural market. -Fully automated controls with internet interface for remote operation and troubleshooting. KEY BENEFITS -The PGFireBox is a portable system that can be disassembled and relocated in a couple of weeks to a couple of months. All these PGFireBox designs are comprised of modular units and can be easily located and easily relocated. -The PGFireBox can accept all types of vegetative waste, including decayed or diseased trees, and root balls. No other system has operating costs as low as the PGFireBox. because none of the waste material needs to be preprocessed, it is delivered to the site and goes straight in the FireBox, no grinding no chipping. -Additionally it burns naturally so no secondary fuel source is needed, it's the same as open burning except the emissions are controlled by the air curtain technology. ADDITIONNAL END-PRODUCTS -It generates power. These generators can run recycling machines, recycled materials sorting stations, or be used to charge a battery storage bank that is used to recharge electric vehicles. -The PGFireBox is currently available in three sizes: PGF100 (100kW), PGF500 (500kW) and the PGF1000 (1MW). -A portion of the 'waste' heat in the exhaust from the Firebox is captured and directed to a heat exchanger to produce hot water (300° F [150° C] or less), which in turn supplies an Organic Rankine Cycle (ORC) power generating unit. -The system is typically connected to the local electrical grid in a 'Net Metering' arrangement like rooftop solar (depending on local regulations) where either some or all of the energy is consumed on site and any excess energy produced is sold back to the utility.
	Firebox Series 300 Series (e.g. 327) 200 Series 100 Series				C	6-10 tons/h	3918-6530 t/y					OPERATION/DESCRIPTION -*idem* PGFirebox KEY BENEFITS -The FireBox can by either dragged onto the trailer with a winch or lifted on to the trailer. Like all our FireBoxes, this unit can be dragged around the site on its skid base.
	Roll-Off Firebox S116R S119R					2-5 tons/h						OPERATION/DESCRIPTION -*idem* PGFirebox KEY BENEFITS -*idem* PGFirebox + -The Roll-Off FireBox is adapted to the standard cable hoist or hook-lift truck transportation system. Unlike our other FireBoxes, these units have a steel floor designed to support the roll-off system.
	BurnBoss					10-20 yd^3/h						OPERATION/DESCRIPTION -*idem* PGFirebox

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[29] Can accommodate long biomass material (e.g. branches, or even trees)

												KEY BENEFITS -*idem* PGFirebox + The patented BurnBoss is our first trailerable unit. This unit is self-contained and fully assembled, supported by a rugged steel frame. Tandem axles with custom designed torsion modules provide a safe and comfortable ride while towing. This unit can be towed with a standard heavy-duty pickup truck.
	TrenchBurner T300					8 tons / h						OPERATION/DESCRIPTION -The basic principles of air pollution control and cost effective waste elimination are the same for this product as our FireBox line – with one major difference: there is no thermal ceramic burn chamber. The Trench Burner, as the name implies, uses a trench dug into the ground as the burn chamber. The air curtain is provided by a manifold that extends from the trailer. The Trench Burner is a trailerable system that incorporates all the machinery in a fully assembled trailer, making it easy to tow. KEY BENEFITS -The Trench Burner is best used in short-term land clearing operations.
Amaron Energy -Salt Lake City, Utah	R&D unit video (stationary to mobile) video (mobile unit demo)	F			C			½ ton/d with stationary prototype, 20 ton/d on mobile unit				OPERATION/DESCRIPTION -rotary kiln design -15 foot long, 24 inch diameter tube. -This rotating metal tube is heated from the outside with gas burners to temperatures of 400 to 600 degrees Celsius. The tube is in constant motion and this allows the feedstock (woodchips) to be rapidly heated. The extreme heating of such small particles in a low oxygen environment quickly transforms the wood into three potentially high-value products biochar, bio-oil and syngas. KEY BENEFITS -Low power requirements compared to many other fast pyrolysis technologie
Agri-therm - Ontario		F				5-10t/d	600-1,200 t/y	1.5t-4.5/d	1.3:1-2.2:1			OPERATION/DESCRIPTION -Uses a fluidized bed -Was a spin-off of the Institute for Chemicals and Fuels from Alternative Resources (IFCAR, University of Western Ontario) -Bought out by a Chinese company -Capacity to process only agricultural waste? KEY BENEFITS -Inexpensive -Easy to Operate -Easy to Maintain -Single Person Operation ADDITIONNAL END-PRODUCTS -Bio-oil (3t/day) -Electricity
Applied Gaia, -Australia	Big Roo Mark 2 Infield Batch Pyrolyser Construction guide Description				B (8 h)	1-4 m^3	1-120 t/y				$1m^3$: AUD $16,000 $4m^3$: AUD $17,500	OPERATION/DESCRIPTION -Fill cage with straw or green waste -Back oven over cage and lower -Ignite top and feedstock -Blower provides air -No smoke -Drive oven off cage -2-4 h for straw; 8h for wood
Beston (Hennan) Machinery Co.												

-China												
Biochar Now -Loveland, Colorado	image	S		shredded	B							KEY BENEFITS -scalable and moveable (kiln-based): multiple kilns can be grouped, and moved around with a loader -custom-designed -the kiln's unique multi-zone combustion, airflow, negative pressure and recipe-driven control system allow each kiln to independently produce consistent, high quality biochar -after the conversion is complete, the kiln is picked up by a wheel loader with a custom gripper and transported to the crushing-screening-bagging workstation. After it's emptied, it moves to the filling station for a new shredded wood before returning to the firing line. CHALLENGES -although it does not need to be chipped, woody feedstock needs to be shredded OTHER NOTES -Patent-pending -Joint venture with Northern Biomass Consulting (Canada, Talby Mckay) for a plant in Nanaimo (2017) and with 6-8 facilities planned for across the country and a view to eventually expand globally
Biogreen©, subsidiary of ETIA Group -France	Spirajoule® BIOGREEN CM600 Mobile containerised pyrolysis unit images video (BGR CM600 "mobile" unit) video (PYROGREEN 600 'mobile' unit)	S or F[30]	250-900°C[31]	≤	C	≤ 16 ton/d	≤ 1,920 t/y	≤ 4.8 ton/d	3.33 :1			OPERATION/DESCRIPTION -same as fixed, but transportable (!!) ADDITIONNAL END-PRODUCTS -bio-oil (8 tons/day –50 barrels) -syngas (10 MJ/m^3, up to 450 kW (9 MWh/day) KEY BENEFITS -same as fixed + -compact and ready to use -No installation, building or civil works -Small, plug&play solution for processing your feedstock on site.
Biomass Controls -Connecticut	Biogenic refinery video											OPERATION/DESCRIPTION -Biomass Controls helps bring the vision of the Circular Sanitation Economy to reality with human-centered innovations that harness the potential of waste streams by generating energy, reusable water and biochar. KEY BENEFITS -The Biogenic Refinery is a thermal treatment solution using patented technology that provides treatment products such as pathogen free biochar, heat and electricity. -Thousands of hours of operational data have been collected from biogenic refineries operating on three continents, in temperatures as low as -20˚C. -The Biogenic Refinery is transportable, designed to operate off-grid and can handle input products with moisture contents as high as 35%. OTHER NOTES- -Supported by the Bill and Melinda Gates foundation -Has a project in Alaska for transformation of sludge (fecal waste) into biochar
Canadian Agrichar	CHAR+™ image											OPERATION/DESCRIPTION -Canadian AgriChar uses its own patented (transportable) pyrolysis system
Carbon Compost Co UK	Exeter Kiln/Retort video video (operation) More of a "small""?		300-350°C[32]	≤ and >	B (8 h)	1.7m^3 /B	51 tonne/y	~170kg/B for good, well packe				DESCRIPTION/OPERATION -Wood is placed in the inner chamber and the inner door is shut. A wood fire is started under the inner chamber. The water vapour and the volatile gases come out of the inner chamber and pass through the wood fire where they are burnt. -External energy (combustion in fire box) is required to start the process KEY BENEFITS

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[30] Residence time (speed of pyrolysis) can be set up within the range of 5-20 mins, depending on the treatment purpose.
[31] Temperature (HTT) can be adjusted according to requested process (torrefaction, pyrolysis, gasification).
[32] Kept below 500°C not to damage the equipment material.

								d hardwoods.				-Fully transportable – trailer mounted (optional). -Easy access - retort and firebox doors at both ends. -Easy to operate – no special skills required.
Carbon Gold Biochar Kilns -Bristol, England	SuperChar 100 Mk II image video & Super Char 100 Mk I image		450-500°C	≤ and >[33]	B (3-10 h)[34]	1.5m^3/B	45 tonne/y	up to 100-120kg/B				OPERATION/DESCRIPTION -Available commercially (not open-sourced) -It does produce some steam and smoke and so it is advisable to locate it away from buildings and people. The kiln does need electricity to run however it is supplied with a suitable generator. -Uses 3 electric fans and a generator (provided with the kiln) -After a batch the kiln needs to be left over night to cool prior to unloading. -transportable on a trailer (although a fork lift is needed to lift the kiln)/– easy to transport in the back of a pick up and can also be moved by a tractor with a forklift. KEY BENEFITS -The kiln runs with a two stage cycle. The first stage is the drying of the feedstock whilst the second is the charring of the feedstock. The kiln acts as a steam drier during the first stage. -can process feedstock that is wet (up to 60% moisture content): uses the excess heat generated in the charring chamber to dry feedstock in the other chamber, alternatively -The kiln body (4ft high and 5ft in diameter) has an internal combustor; -re-circulates and burns off harmful greenhouse gases (methane and nitrous oxide) resulting in lower emissions from your biochar production process. CHALLENGES -Produces some smoke… -feedstock needs to be added by hand -relatively complex to start up (e.g. mud seal) ADDITIONNAL END-PRODUCTS -steam
	SuperChar 500 image video		~500°C	≤ and >[35]	B (3-10 h)[36] or semi-C	6m^3/B	180 tonne/y	800kg/day: up to 800kg per burn (400 per 6m^3 chamber)				KEY BENEFITS -can be semi-continuous, with the two-chamber feature: one charring and the other one drying, alternatively -there also is an external combustor, used to dry the first chamber of the batch… -can process feedstock that is wet (up to 60% moisture content): uses the excess heat generated in the charring chamber to dry feedstock in the other chamber, alternatively -waste heat is partially used for drying, and the rest could be tackled…
Earth Systems (Bioenergy) -Australia	Char Maker Mobile Pyrolysis Plant (MPP) MPP 20 MPP 40 video (short, promotional)	F	300-550°C	> and >>[37]	B (4-6 h)	13 m^3 or 5-9 tonne/B for the MPP20[38]	600-1,080 and 1,200-2,160 tonne/y for the	Converted into ~1-2 and ~2-4 tonne		A	AUD $250K	OPERATION/DESCRIPTION -Very high fixed carbon content -High thermal energy output: Capacity for high grade heat export to industrial processes -Bolt on bio-liquids recovery plant also available for pyroligneous liquids (wood vinegar/smoke water) and bio-oil. -Cage-based KEY BENEFITS

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[33] can process feedstock that is up to 30cm length (logs)
[34] e,g, 8 hr @ 20% humidity
[35] Can process feedstock that is up to 30cm length (logs).
[36] Depending on humidity and size of feedstock; e.g. approx. 8 hrs to process a batch at 20% humidity.
[37] Log or stick sized woody biomass (no greater than 150 mm diameter (6″) and 1.8 metres (6 foot) in length: no need of chipping, but trees would need to be bucked up. The length limitation is a requirement of the current bin arrangement – larger lengths would be possible with larger bins.
[38] Depending on moisture content and biomass characteristics (in particular wood density).

	video (description) video (operation) video (testimonial, Australia) video (demonstration, farm Australia) video (testimonial, Hong Kong) images					and 30 m^3 or 10-18 tonne/B for the MPP40[39]	MPP20 and the MPP40, respectively	biochar per B for the MPP 20 and MPP40, respectively[40]				-Is in a shipping container, hence integrates simply with all standard methods of transport suitable for shipping containers. -Minimal operating costs -Unit operates itself after loading with auto-turn off at end of run –can be operated unattended. -Designed for farm and forestry machinery operation -A sophisticated control system with multi-sensory input operates the CharMaker MPP. -Once the CharMaker MPP has ignited, operator input requirements are minimal. It can be operated unattended, and will quench and shut itself down at the conclusion of the process. This allows unattended operation overnight. The CharMaker MPP can then be unloaded the following day during work hours – thereby increasing the number of batches per work day. ADDITIONNAL END-PRODUCTS -electricity: ~52GJ in 4 h (3.6 MW)
New England Biochar - Massachusetts Bob Wells, co-founder	Mobile modified Adam retort pictures video			≤ and >	B (8-10 h)	3 yards^3/B	275 tonne/y	1 cubic yard of biochar per batch	3:1			OPERATION/DESCRIPTION -Retort-based (customizable number of retorts) KEY BENEFITS -Custom-built: the larger systems that we design and build are customized to meet the needs and ideals of the individual customer as well as their available feedstocks, product final use, what co-products they want, and many other variables. -Their technology is scalable OTHER NOTES -Offer consulting first and foremost -They might recommend other technologies
Pressvess -Kingswinford, UK	BBM Mobile Retort video		300-500°C	≤ and >	B			~165kg				KEY BENEFITS -Looks simple to operate OTHER NOTES -Very small!!
	Traditiona Ring Kiln image											OPERATION/DESCRIPTION -5 ft to 8ft diameters but can be made to order to suit any requirement -Multiple chimneys
	Double chamber retort (Charcoal retort) image video							350-400kg /burn (8-10 h)				KEY BENEFITS -Offer more efficient raw material usage giving a production ratio of 4:1 opposed to 7:1 of a traditional ring kiln -Great range control (temperature more even than in a traditional ring kiln) -High carbon content biochar with less wastage
Pyrocal Pty, Ltd. -Toowoomba, Queensland, Australia formerly known as Black is Green (BIG)	Pyrocal Continous Carbonisation Technology (CCT) images video, Vietnam, BIG Char 1200k video, Vietnam, installation of a BIG Char 2200k formerly known as BIG Char CCT	S	450-700°C		C	250-1300 kg/h[41]	480-2,496 tonne/y		10:1-2.8:1, typically 4:1 on dry mass	A	USD200k to >USD2M e.g. USD500k for a BigChar 2200 unit	OPERATION/DESCRIPTION -Continuous carbonization in a vertical rotary multiple hearth carbonizer (a variation on the Nichols-Herreshoff rotary hearth furnace, first patented by R.D. Pike in 1921; up-gas). -During the process, the biomass travels through the different sections of the rotary hearth. The volatile matter released from the process is partially combusted to provide required heat for maintaining the reaction. The system is designed to produce heat, char and gas, usually the produced gas is burned instantly to be utilized for heat and power production -Mechanical moving bed arrangement, which provides maximum flexibility for a wide range of feedstocks, including light fluffy materials, clumping materials, chips and materials with a very diverse size range. -Direct heat transfer to the incoming biomass. This means there are no heat transfer surfaces in the system to foul or corrode.

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[39] Again, depending on moisture content and biomass characteristics.

[40] Again, depending on moisture content and biomass characteristics.

[41] Typically 1000 kg/h

	Images of the BIG Char (on IBI website, old) Images of the BIG Char (on Pacific Biochar website) Video (how the BIG Char demonstration/research unit at AITF works –min 5:45-9:45											-Moderate and controllable temperatures in each stage of the hearth and thermal oxidiser which allow optimisation of char quality and emissions control for a given feedstock. -Controlled two stage oxidation of the released volatile matter, allowing efficient control of air pollutants. -Continuous co-mingling of flammable volatile gases with a controlled airflow, to eliminate flammable gas explosion risks (no hazardous zone design requirements). -Fully autothermal operation (i.e. after startup there is no need for other fuel sources to operate). -Rapid start-up. Typically, cold to full throughput in 40-60 minutes. The materials of construction allow heating from cold to full operating temperature without damage. -Expressing the costs in terms of return on investment, the equipment payback periods can be as little as 9 months or as long as 7 years. -During operation, the plant draws 5-15 kW of electricity. KEY BENEFITS -Modular -All models can be: --Configured as fixed, relocatable or mobile plants (esp. smaller models). --Grouped to provide higher throughputs and/or processing redundancy. -This proven Australian technology has been implemented on a commercial scale since 2014 with installations in eight countries. -The entire system is controlled by a PLC programmed to specific installation requirements. ADDITIONNAL END-PRODUCTS -Thermal energy (830-4330) OTHER NOTES -A demonstration/research unit was/is on-site on a trailer at Alberta Innovates-Technology Futures (AITF) -The unit is mounted on a truck and is 4 metres long by 2.4 metres wide and 3.5 metres high (excluding the collapsible exhaust flue).
Pyrolitech -Australia	video											OPERATION/DESCRIPTION -portable retort
Ragnar Original Innovation (ROI) -Chester, NH *Acquired in October 2019* by Tigercat -Brantford, ON -video (promotional for Envirosaver™ 350 and 400)	Envirosaver™ 350 -images -video (NOVUS wood group, Houston Texas) -video (loading dirty pallet debris) -video (loading small trees in winter conditions)	S	>1,370 °C[42]	> and >>[43]	C	15-20+ ton/ h	10,800-14,400 ton/y		~14:1on weight basis	A	USD650k(!!!)	OPERATION/DESCRIPTION -Single step: feedstock is put into the chamber, and biochar exists -Over chamber air curtain for eliminating smoke and particulate release -Available as a stationary unit with optional electric drive -Transportable on common lowboy trailer -Option: dump (when the combustion chamber is raised to the dump position, char falls below the grate and non-combustibles (stones/metal) are suspended above and are dumped out together after the slide gate in the back of the combustion chamber is lifted and the combustion chamber is raised to the dump position. KEY BENEFITS -Impression that they are very professional + operate internationally -Very simple (compared to other units of the same type/scale, and proven, but very low yield -Extremely low operating costs, simple and easy single person operation -High (volume) capacity (throughput), esp. for a mobile unit -Live stream video monitoring of pyrolysis chamber so operator has full visibility for ease of feeding -Track mounted and self-propelled (no need of tractor or other) -Track mounted for easy trailer loading -Continuous automatic biochar removal for maximum throughput. ADDITIONNAL END-PRODUCTS -Biochar: fixed-C content of between 75-85%, pH 7-10, specific surface area 360 m^2 /g. Moisture in biochar can be controlled for different needs between 10 to 70% -no bio-oil and gas

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[42] Carbonizer sustains consistent and very high temperatures throughout operation.

[43] Very large debris (e.g. trees) need be processed, but no need for pre-grinding, shredding or chipping (actually not so good with fine debris (e.g. chipped wood)).

												-lots of energy (Lots of energy leaves the system as heat) OTHER NOTES -Relatively low yield…
	Envirosaver™ 400 images		>1,370 °C[44] +[45]	≤ and > and >>[46]	C	15-20+ tons/h	*Idem* 1) - 3) Envirosaver™ 350		*Idem* Envirosaver™ 350	A		*Idem* ES 350 + -It is a trailer on its own (only needs the lorry): wheeled chassis provides for quick and easy relocating. -Both the combustion chamber and hopper are equipped with a live floor system to feed at an adjustable rate and convey material through to complete combustion. -The Hopper/Feeder system provides continual metering of fine or processed materials not suited for batch feeding in to the combustion chamber.
	Carbonator™ 500 images		>1,370 °C[47]	>	C	15-20+ tons/h	*Idem* Envirosaver™ 350		*Idem* Envirosaver™ 350	A		*Idem* ES 350 + -Option to recover heat energy / heat exchanger for water or oil, Organic Rankine Cycle (ORC) electric generating module -water injection nozzles for instant quenching of char (this could be a challenge; perhaps using a tank, generator and pump…). -Track mounted to allow for direct re-introduction of high quality biochar to forest or agricultural land where conversion is taking place.
Zachus Farm -Ibex Valley, Yukon	Three-way BioChar Machine			≤		40kg/16h	1.8 tonne/y					OPERATION/DESCRIPTION -Piston feeder and auger for output. -Only focused on biochar (not syngas/tar and heat tar) ADDITIONNAL END-PRODUCTS -16 hours to produce 40 kg
Stationary Units												
Airex -Bécancour, Qc (Laprade Industrial Park) Sylvain Bertrand, CEO	CarbonFX			≤				15000 tonne/y[48]				OPERATION/DESCRIPTION -includes a whole production chain -processes sawdust and barks from fir, spruce and maple species -Airex Energy's business model is to export its CarbonFX systems worldwide. KEY BENEFITS -biochar product is CFIA-certified
	Pilot torrefaction unit							250 kg/h				OTHER NOTES -will be implemented at an AbitibiBowater plant in Témiscamingue, in collaboration with FP Innovations and Cyclofor
Alterna Biocarbon -Prince George (Isle Pierre), BC								4,000-5,000 tonne/y				OPERATION/DESCRIPTION -Van Aardt Process
Ambient Energy (AE) LLC -Washington, USA	M3RP (Machine – Reuse, Recover, Recycle Process),											OPERATION/DESCRIPTION -Pyrolysis and depolymerization ADDITIONNAL END-PRODUCTS -Gas -Oil

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[44] Carbonizer sustains consistent and very high temperatures throughout operation.

[45] Moreover, the moving floor allows for metered pre-heated under–fire air to be introduced into the combustion chamber for rapid pyrolysis.

[46] No need for pre-grinding or chipping: large debris (unprocessed trees, stumps, brush) can be placed directly into the systems primary combustion chamber, converting entire woodpiles in one pass into a high value soil additive. The live floor allows for processing of fine debris such as ground, chipped wood or bark with sawdust.

[47] Carbonizer sustains consistent and very high temperatures throughout operation.

[48] Production goal

Anaergia -Ontario												OPERATION/DESCRIPTION -Nutrients and digestate management KEY BENEFITS -Based on proprietary AMR technology
Avello® Bioenergy -Iowa, USA	FRAC® process	F		≤	C	6 kg/h						OPERATION/DESCRIPTION -6” fluidized bed reactor KEY BENEFITS -Their process includes proprietary technology licensed from Iowa State University ADDITIONNAL END-PRODUCTS -Oil OTHER NOTES -Website is up, but last news are from 2012…
BC Biocarbon -Prince Georges/McBride, BC	video		500-800°C	≤		1000kg/hr						Jos Hoetjes Phil Marsh, Chief Technology Officer Simon Beller, Chief Financial Officer
Beston (Hanan) Machninery Co -China	BST-03					300 kg/h	576 tonne/y					
	BST-05					500 kg/h	960 tonne/y					
	BST-12					1200 kg/h	2,304 tonne/y					
	BST-20					2000 kg/h	3,840 tonne/y					
	BST-30					3000 kg/h	5,760 tonne/y					
Biochar Boréalis - Mashteuiatsh, Qc			300-500°C						3:1			OPERATION/DESCRIPTION -Processes/gives value to woodchip -Uses a French pyrolysis technology called Biogreen, produced by ETIA -UQAC is presently looking at the possibility of developing a specific protocol that would be recognized by the government and allow carbon credits to be issued for the production and use of biochar. OTHER NOTES -Partnership between the MRC du Domaine-du-Roy and Pekuakamiulnuatsh Takuhikan (the Innu community of Mahsteuiatsh)
Biochar Energy Systems (BES) Russell Burnett	Open-source transportable Pyrolysis system image principle		400-600°C	≤		350-1000 kg/h	480-672 tonne/y	50-65 kg/h[49]	~5-6.6:1			KEY BENEFITS -Can process feedstock ≤ 15 mm ADDITIONNAL END-PRODUCTS -Wet syngas, typically 130 kg/h -Heat ~450MW OTHER NOTES -Possibly out of business
Biochar Solutions Inc. (BSI) -Cannondale, Colorado	B-1000 Thermal Conversion System			≤	C							OPERATION/DESCRIPTION -Pyrolysis, two-staged KEY BENEFITS -In the first stage of the process, the material is carbonized in a controlled aerobic (O_2 limited) environment at a temperature between 500-700 °C for less than one minute. -In the second stage, material is held in a hot gas environment for up to fourteen minutes at a temperature between 300-550 °C before the material is removed from the process through an auger system.

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[49] For hardwood at 500°C

Bioforcetech Corportation -Redwood City, CA	BFT P-FIVE					300-500 lb/h						OPERATION/DESCRIPTION -once the startup operation is complete, the P-FIVE pyrolysis machine runs automatically 24/7, ensuring a constant production of biochar without the presence of any operator. The process can be monitored anywhere with our online, easy to use software. KEY BENEFITS -An energy recovery system (pyrolysis reactor) makes the process sustainable and efficient. -Low NOx emissions: the P-FIVE Pyrolysis machine has been designed to achieve the maximum production of gaseous material. The gas is immediately burnt into a special flameless reactor. Burning the produced syngas without flame, allows a lower combustion temperature, resulting into low NOx emissions. OTHER NOTES -The P-FIVE pyrolysis machine was designed for biosolids treatment, but this reactor is also able to treat a wide range of materials or mix. The P-FIVE pyrolysis can process biosolids, manure, green waste, green waste/biosolids mix, food waste and most organic waste.
Biogreen©, subsidiary of ETIA Group -France	Spirajoule® images video (explanation of process and showing the equipment) video (Set up of a Plastic to Electricity Pyrolysis Plant –4 days!) video (BGR CM ''mobile'' unit by Norris Thermal Technologies in USA)	S or F[50]	250-900°C [51]	≤	C	≤2.5 m^3/h[52] [53]	≤190 tonne/y		4:1-3:1		€80-2000k depending on the capacity of the system	OPERATION/DESCRIPTION -Can perform torrefaction, pyrolysis and gasification –all forms of thermochemical conversion -The external energy that powers Biogreen is electricity. -Biogreen pyrolysis process is based on electrically heated screw conveyor (Spirajoule®), designed for advanced thermal treatment in temperatures up to 800°C. Processed product temperature is precisely controlled basing on the temperature settings. The electrical heating will stop when the pyrolysis reaction is self-sustaining but will be able to control the temperature to optimize the composition of products. The system is highly automated and digitally controlled this keeps the maintenance work low. The dwell time of material inside Biogreen® reactor is regulated by screw rotation speed. Thermal conversion is performed in oxygen-free (pyrolysis) atmosphere in unique construction of equipment, which guarantees a constant quality of product obtained from the treatment. -The product temperature is precisely controlled based on the heating screw temperature setting while the residence time (dwell time) is regulated by screw rotation speed setting. This unique construction of pyrolyser guarantees process flexibility and constant quality in all forms of treatment applied in Biogreen. KEY BENEFITS -Modular -Based on a patented heating screw conveyor: Spirajoule® -Fully modular, containerized equipment: comes in containers (''intermodal containers/''seacans''); some can be ''mobile'', but others will be fixed. -Equipment simplicity provides high reliability, little maintenance, and low operating costs. -Industrial pyrolysis operating for over a decade over 5 continents: first unit commissioned in 2003 + more than 30 machines operating on different feedstock worldwide -Full and reliable control of treatment conditions –complete PLC display of all operating data -Worldwide availability -Versatile/flexible: variety of sizes and configurations -Biochar produced is certified in France ADDITIONNAL END-PRODUCTS -Syngas (high LHV, up to 16 MJ/Nm^3 -Oil compounds OTHER NOTES -Norris Thermal Technologies is the the representant for the USA market
Biomacon Gmbh	Decarbo Energy Systems		950-1050° C	≤	C	20-300 kg/h	175.2-2.628 tonne/y	3.5-56.2 kg/h	5.5:1	A		OPERATION/DESCRIPTION -The pyrolysis unit is a screw feed system available in different sizes. The system utilizes electricity for ignition of the process. When the process is running no additional energy is needed.

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[50] Residence time (speed of pyrolysis) can be setup within the range of 5-20 mins, depending on the treatment purpose.

[51] Temperature (HTT) can be adjusted according to requested process (torrefaction, pyrolysis, gasification).

[52] Higher throughput can be obtained with parallel units.

[53] Different models have different throughputs.

-Rehburg (Bremen), Germany -Thomas Hoffman, eng.	[Heating power 15-400 kW] In 3 categories: Home: 40-63kW Farm: 40-160kW Industry: 250-400kW											-The syngas is burnt in the chamber/a water-based heat exchanger captures the heat (80% of the total)/that heat can be used for heating buildings. I imagine the heat could be used to generate power too. KEY BENEFITS -Exhaust gases are re-circulated combined with a low-NOx burner with electronic control, allowing for extremely low amounts of NOx. The overall emissions from the process is low because of the long residence time in the afterburning chamber for the gases. ADDITIONNAL END-PRODUCTS -Heat (15-400 kW) OTHER NOTES -It is possible for pyrolysis system to be integrated a co-firing system with already existing steam boilers. -They are working on pyrolysis of dried wastewater sludge -They advertise their device as a 'carbon negative boiler' -Built according to the European standard EN 303-5 "Solid fuel fired boilers, manual and automatically fired furnaces, nominal heat output up to 500 kW"
Biomass Tech & Equip Pty	Kansai Kiln		450-900ºC [54]	≤	C	300-1000 kg/h	576-1920 tonne/y		4:1-2.5:1, Depending on feedstock			OPERATION/DESCRIPTION -The Kansai kiln uses a screw feeder that sits inside a trough. -The pyrolysis gases are combusted above the trough and the heat is reflected down onto the moving biomass. KEY BENEFITS -Can process feedstock < 10mm
Biomass Technology Group (BTG) -Enschede, The Netherlands	Empyro project	F				1-5 ton/h	1,920-9,600 ton/y					OPERATION/DESCRIPTION -Rotating cone reactor -Biomass particles at room temperature and hot sand particles are introduced near the bottom of the cone where the solids are mixed and transported upwards by the rotating action of the cone. -Initial work of the University of Twente has been the starting point in 1993 for BTG ADDITIONNAL END-PRODUCTS -Bio-oil (1.2 t/h, main product)
Carbofex Oy Oy -Finland												
Carbonex -France	video		800-1000ºC									
Carbon Terra - Augsburg, Germany	Schottdorf-Meiler	S	700ºC	≤		6 t/d	1,440 t/y	2 t/d	3:1		€388k + €58k for a feeding system and feedstock storage	OPERATION/DESCRIPTION -Schottdorf kiln -Several Schottdorf kilns built one functioning unit. -The general system set up includes a pyrolysis reactor, a gas burner, a steam turbine and a power generator. -The flue gas is rising through the reactor the biomass will work as a filter and clean the gases. -The plant can be operating during long periods of time. It does in general needs to be shut down 2-4 times per year. And the restarting of the process needs between 6-9 days including cool down and maintains work KEY BENEFITS -The process is sold in modules containing 4, 8 or 16 kilns and a down fire combustion chamber. This gives scalable options able to provide systems for small applications or large industrial systems ADDITIONNAL END-PRODUCTS -Gas: delivers 300 kW thermal energy through the gas. One module exciting of four reactors can produce up to 1,2 MW electricity using a steam cycle when using sufficient feedstock
Carbon Zero -France												OPERATION/DESCRIPTION -Horizontal bed kiln

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[54] Desired temp in the chamber is 900ºC.

Char Technolgies -London, ON	video (showing the pyrolysis plant)		high									OPERATION/DESCRIPTION -High temperature pyrolysis (HTP) -Acquired Altech Group in 2018 KEY BENEFITS -Products: --SulfaCHAR (can be used to removed hydrogen sulfide from gas streams, or used as sulfate-rich biochar for agricultural amendment) --CleanFyre (coal of renewable source)
CHZ Technologies -Ohio (subsidiary of Aliquippa Holdings, LLC)	Thermolyzer™ Model 4 Model 37 Model 75 Model 150		low		C	4-150 ton/d	960-36,000 ton/y					OPERATION/DESCRIPTION -Low heat pyrolysis + continuous gasification -Each reactor come delivered as skid mounted modules, greatly shortening construction time. -In most situations local workers (overseen by our field engineers) can complete much of the plant assembly, since many components are modular in design. Designed this way plants can be fully operational in an amazingly short period of time. KEY BENEFITS -Modular: quick to design and build -Scalable: can start at a wide range of scales, and can grow -Flexible: can use different types of feedstock + plants can be modified to accommodate different feedstocks -thermogas™ is used to fuel the reactor's gas turbine. - the gasifier reactor can convert all forms of carbon waste to energy, with no minimum feedstock size (e.g. tires, biomass, waste oil) ADDITIONNAL END-PRODUCTS -thermogas™ (a 100% replacement for natural gas -is even suitable for turbine operation) -biofuel substitutes for ethanol and diesel fuel OTHER NOTES -Every facility is custom-designed the client's exact needs.
Ensyn -Delaware, USA (Chevron is an important shareholder) -also has a plant in Renfrew, ON	image collaborates with UOP in the "Envergeen Technologies" joint venture –a Honeywell company	F[55]	520°C			3,500 kg/h	6,720 tonne/y					OPERATION/DESCRIPTION -Technology: fluid bed/riser -Rapid Thermal Processing or RTP™, converts non-food biomass from the forest and agricultural sectors to liquids through fast pyrolysis. -Uses a tornado of hot sand to rapidly heat the biomass, and then rapidly quench it KEY BENEFITS -Proven track record for continuous commercial operations for > 25 years -Ensyn Corporation claims to be a producer of advanced, drop-in cellulosic biofuels that can replace petroleum products. ADDITIONNAL END-PRODUCTS -Bio-oil (main product)
FEECO International -WI, USA												
Fortum/Valmet (formerly Metso; in collaboration with Preem) -Finland		F	500°C									OPERATION/DESCRIPTION -Built a pyrolysis-oil plant connected to the Joensuu power plant in Finland. KEY BENEFITS -Employs hot sand from a fluidized-bed boiler for heating the pyrolysis feedstock -The concept allows also integration of fast pyrolysis to existing industrial or district heating CHP plants ADDITIONNAL END-PRODUCTS -Bio-oil (50,000 tonnes/yr, main product): Fortum Otso

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[55] 1-2 sec residence time

Genesis Industries -California	General video		500-550ºC	≤		300-350 kg/h	576-672 tonne/d	100-120 kg/h	~3:1			OPERATION/DESCRIPTION -2-staged: pre-dryer + pyrolyser -Excess pyrolysis gases can be used to power a micro-turbine or furnace/boiler. KEY BENEFITS -Unit designed to process a variety of feedstocks: Designed to handle a variety of feedstock from cereal straw to feedlot and timber-based wastes. -Modular design for future expandability. -Very few wearing parts ADDITIONNAL END-PRODUCTS -Syngas -Wood vinegar (liquid/condensate)
	Model CR-2 video					200 kg/h	384 tonne/y	50 kg/h	4:1			
	Model CR-3					1000 kg/h	1920 tonne/y	250 kg/h	4:1			
Green Fuel Nordic Oy -Finland												
Groupe Bordet -Germany	Carboépuré®					500-10,000 t/y	500-10,000 t/y		6:1			
Biopower Industries -Lithuania	Biomass Gasifier Model GTJ-450			≤		4-5 t/d	960-1200 t/y		20 :1			ADDITIONNAL END-PRODUCTS -power (200 kW_e) and thermal energy (300 kW_t)
Innovative Reduction Strategies Inc. (IRSI) -Edmonton, Alberta *Chris Olson, Owner/Operator	Ulysses	S			C							ADDITIONNAL END-PRODUCTS -thermal energy KEY BENEFITS -modular OTHER NOTES -Chris completed the Alternative Energy Program at the Northern Alberta Institute of Technology (NAIT).
KiOR (joint venture between Khosla Ventures (KV) and BIOeCON -Columbus	BFCC Refinery	F[56]		≤								ADDITIONNAL END-PRODUCTS -bio-oil (30-92 gallons per bone dry ton (BDT) of biomass) KEY BENEFITS -Woodchips are first "processed and conditioned" for conversion into oil: the use of additives to the biomass to make it more susceptible for conversion prior to a subsequent conversion process
Leggett Group -Namur, Qc (Formerly owned by Advanced Biorefinery Inc.)	ABRI-Tech Video (portable demonstration/research unit) Video (how the demonstration/research unit works –min 0:00-5:45)	F		≤	B			≤ 1 tonne/d[57] And 50 tonne/d[58]				OPERATION/DESCRIPTION -Use of steel shot as our heat carrier in the pyrolysis unit (formerly used sand) -Given the importance of a properly prepared feedstock for attractive yields, ABRI-Tech does not allow itself to sell the pyrolysis unit without the biomass dryer. -They have a transportable ‘’demonstration/research’’ unit -A number of such units have been sold and are operating atm (2013) KEY BENEFITS -Modular -Auger retort style -Hot steel shot heat transfer: moving hot steel shot around a loop via two screw conveyors (augers). At one point, the loop (the reactor) biomass is added and is rapidly heated by the steel shot.

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[56] Catalytic Fast Pyrolysis process.
[57] Experimental unit.
[58] Full scale unit.

												ADDITIONNAL END-PRODUCTS -Volatile gases are combusted -Production of bio-oil (44-66%) -Production of ashes as well
Northern Biomass Consulting -Parksville, BC (or Prince George?) Talby Mckay												OTHER NOTES -Offer consulting first and foremost -Plans to build a biochar processing plant in Nanaimo, B.C. (2017) -Branched off from family company offering grinding services in Northern Alberta -Offers training and management services to grinding companies, fibre recovery processes to mills, and biomass consulting to pellet producers across Western Canada. -In partnership with Biochar Now (CO)
Polytechnik Biomass Energy -France												
Phoenix Energy -San Francisco, CA	PHX-1000 image							1 ton/d				OPERATION/DESCRIPTION -The technology is often referred as a gasifier and not pyrolysis -Designs and builds small scale (.5 to 2 MW) gasification powerplants fueled by biomass -The system is continuous and automated. The standard set up starts with a grinder for shredding the feedstock. -The grinder also separates metals from the feed. The biofuel exits the grinder and enters a storage hopper. A conveyor belt transports the feedstock to the pyrolysis reactor. The product gas is going through a series of scrubbers and filters. The filter system is made of sawdust and wood chips. The filter material can be utilized as feedstock after being used. The listed maintains work is weekly changing of the filter, monthly change of the biochar separation grate and annual top end rebuild KEY BENEFITS -Business model: building small, profitable plants -seamlessly integrated with the electrical grid: this means that when you produce more power than you need, you can sell your excess power to the local utility -The syngas is used to fuel a specially modified natural gas genset to produce electricity and heat. -tight footprint: 50'-25'; the complete installation of a PHX-1000 requires approximately 3/4 – 1 acre. -modular, and self-contained -quick pay-back: depending on renewable energy incentives in your area and your particular power needs, payback in 4 to 5 years. ADDITIONNAL END-PRODUCTS -Syngas (500 kW); The standard set up is utilizing the gas for electric generation utilizing natural gas generator sets from Caterpillar, the regular set up is 1 MW of electric but can be scaled up if needed. OTHER NOTES -The Indian-made Ankur gasifiers that Phoenix uses have a long track record.
Pro-Natura -France	CarboChar											
PYREG GmbH - Carbon Technology Solutions -Germany video	P500 BIOMASS® P1,500 BIOMASS	S	500-700°C	≤		1,000-2,500 t/y		≤ 680 t/y			€300k + €58k for feeder and storage USD $400,000	OPERATION/DESCRIPTION -the PYREG process is a continuous method and uses the principle of dried carbonization. -the input material (at least 65% dry matter content) is not incinerated, but first degassed at a temperature of 500-700 °C and then, by admission of a well-defined air stream, carbonized. -the material passes through the PYREG reactor, hauled by conveyor screws. -as this process enables users to precisely adjust treatment parameters like temperature control, carbonization time and admission of primary air, the optimum quality of the final product can be achieved. KEY BENEFITS -The pyrolysis system is compact and highly automated and utilizes a compact design able to be set up in a container -the process allows the precise control of the parameters, so that carbon products can be produced in various quality grades and nutrients can be recycled gently

												-the process produces little thermal NOx: as the combustible gas generated in the PYREG reactors is completely burned by the FLOX® method (flameless oxidation) at a temperature of 1,000 °C inside a separate combustion chamber, thermal NOx is significantly avoided. -the formation of problematic substances like oils or tar is suppressed as well, because the carbonization gas is not cooled, but oxidized in the combustion chamber. -inside an optional flue gas cleaning system, harmful acid gases are absorbed by means of alkaline flue gas scrubber, whereas volatile components like mercury are retained by charcoal filters. -autothermal, which means that only some external starting energy is required. -modular scaling possible if required. ADDITIONNAL END-PRODUCTS -in addition, up to 150 kWth or 600 kWth of excess heat energy can be used, for instance for drying humid biomass, for heating or power generation. OTHER NOTES -We have been designing and manufacturing carbonization plants in certified quality in series production for almost 10 years. -The system is set up to run 24 hours for 12 days followed by two days of cool down and cleaning.
Pyrocal Pty, Ltd. -Toowoomba, Queensland, Australia	Pyrocal Continous Carbonisation Technology (CCT) *Idem* as mobile unit	*Idem* as mobile unit	*Idem* as mobile unit	*Idem* as mobile unit	*Idem* as mobile unit	*Idem* as mobile unit	*Idem* as mobile unit	*Idem* as mobile unit	*Idem* as mobile unit		*Idem* as mobile unit	*Idem* as mobile unit
Rainbow Bee Eater -Australia	ECHO2			≤	C				100-250 kg/h			ADDITIONNAL END-PRODUCTS -Syngas -Energy
Susteen Technologies -Calgary (distributor)	Biobattery image video (principle) video (demonstration, esp. bio-oil end-product)			≤	C							KEY BENEFITS -Can provide energy (bio-oil) -Uses Thermo-Catalytic Reforming (TCR®) technology – a system that combines an advanced form of pyrolysis with a second-stage process: *First charring stage at intermediate temperatures: 400-500°C (thermal decomposition, extracts volatile organic compounds) *Second charring stage at high temperature: 600-750°C (catalytic reforming + brought into contact with the volatiles again). Through catalytic functions the organic compounds are cracked to quality fuel gases and oils. The steam reforming of water and carbon increases the yields of a hydrogen rich syngas. -Bio-oil produced with this novel technology has higher-value properties compared to conventional pyrolysis: Liquid compounds are condensed and the product syngas is cleaned for particlesand aerosols in a relatively simple product treatment stage. ADDITIONNAL END-PRODUCTS -Syngas -Bio-based oil
ThermoChem Recovery International (TRI) Baltimore, MD			400°-1000° C			> 500 tons/d						OPERATION/DESCRIPTION -The reactors are indirectly heated (using an advanced proprietary heat exchanger), they utilize some of the deepest fluidized beds in the world (30+ feet), and they are fluidized with steam giving them incredibly stable operational characteristics. -Uses indirect heating and a variety of inert fluidizing gases including steam, nitrogen, and carbon dioxide. KEY BENEFITS -The stability and precision of TRI thermal conversion reactors is unparalleled in the commercial scale pyrolysis & gasification industry. -The reactors are so isothermal and well mixed that gas composition can be controlled, even when reforming carbon sources as heterogeneous as landfill waste and this applies to every carbon feedstock that has ever been tested.

												OTHER NOTES -TRI is a national leader in the development and implementation of commercial scale (500 ton/day and larger) thermal conversion reactors utilizing indirect heating and deep fluidized beds. This experience translates to improved performance and conversion efficiencies for pyrolysis projects.
Xylo-Carbone -St-Tite, Québec Simon Langlois, copropriétaire						30,000 m^3/y	7,500 tonne/y	6,000 tonne/y	1.25:1			KEY BENEFITS -Launched in January 2018 -Processes low-quality roundwood

4. ANALYSIS

Any pyrolysis equipment has its share of advantages and shortcomings. The overall value of equipment can be derived from the analysis of the whole breadth of these advantages and shortcomings in the specific context they are to be used (use case). A most effective way to identify optimal equipment is to iteratively compare sub-groups, narrowing down the options at every step. The following is a first iteration in that process, where equipment is compared at the higher level to identify a broad category of equipment that has highest chances of satisfying the use case requirements.

4.1 Evaluation grid

In view of proceeding with a first screening and narrow down the options to those that have highest probability of meeting the use case requirements, the relative value of the 3 categories (Low tech/pop-up, mobile, stationary) was calculated based on their fit to preferred equipment features (Table 3).

For every equipment feature, each category was attributed a score of 1, 2, or 3 (low, medium, high). Where fit to the criterium could significantly vary amongst units of a particular category, a score range was attributed rather than a finite number. For instance, some 'mobile units' can handle material that is contaminated with rocks and soil and of varying size and character (forego chipping), while others cannot.

A ponderation factor was further applied so as to take into account the importance of the feature in the Yukon context. The ponderation factors ranged from 0.1 to 1, with tenth increments. For instance, a ponderation factor of 1 was applied to such features as 'Does not produce smoke' and 'Capacity to forego transportation of the material over long distances', given the importance of those features in the context of slash management in Yukon. Contrastingly, 'Bio-oil can be harvested' was attributed a ponderation factor of 0.1, considering the relatively lower importance of that feature in the context.

The ponderated scores were then summed up by sub-type of features (technical, financial, socio-economic), and overall. Finally, the scores were compared

Table 3. Comparative analysis of pyrolysis equipment in the context of slash management in Yukon, based on preferred equipment features.

Features	**Ponderation**	**Low tech/ pop-up**	**Mobile units**	**Stationary units**
Technical Factors				

Does not produce smoke	1	1 1	2-3 2-3	3 3
Capable of performing slow pyrolysis	0.9	3 2.7	2-3 1.8-2.7	1-3 0.9-2.7
Capable of performing pyrolysis at 450-550°C	0.9	1-3 0.9-2.7	1-3 0.9-2.7	1-3 0.9-2.7
Effectively excludes oxygen	0.5	1-2 0.5-1	1-3 0.5-1.5	3 1.5
Features at least a fair level of process control	1	1 1	2-3 2-3	3 3
Can handle feedstock size ≥ or >> woodchips	0.7	1-2 0.7-1.4	1-3 0.7-2.1	1-2 0.7-1.4
Has a throughput capacity that is aligned with the needs	0.5	1 0.5	2-3 1-1.5	3 1.5
Overall yield of biochar is in the higher range	0.3	3 0.9	1-2 0.3-0.6	3 0.9
Risk of potential issues with (local) procurement and replacement of parts is low	1	1 1	2-3 2-3	1 1
Syngas can be captured and used	0.8	1 0.8	2-3 1.6-2.4	3 2.4
Bio-oil can be harvested	0.1	1 0.1	1-2 0.1-0.2	3 0.3
Does not cause issues with localised mercury emissions	0.6	3 1.8	3 1.8	1 0.6
Sub-total		11.9-14.9	14.7-24.5	16.7-21
Financial Aspects				
Capacity to forego transportation of the material over long distances	1	3 3	3 3	1 1
CAPEX is limited	0.5	3 1.5	2 1	1 0.5
Cost for O&M is low	0.8	1 0.8	2 1.6	3 2.4
Capital risk is low (value for rent/resale is high)	1	2 2	3 3	1 1
Scalability	0.9	1-2 0.9-1.8	3 2.7	1-2 0.9-1.8
Sub-total		8.2-9.1	11.3	5.8-5.7
Socio-Economic Factors				
Higher impact on Yukon economy	1	3 3	2-3 2-3	1 1
Higher impact on rural development	1	3 3	2 2	1 1
Siting and permitting is easy	0.2	2 0.4	3 0.6	1 0.2
It is easily/quickly commissioned	0.2	2 0.4	3 0.6	1 0.2
Expertise needed for commissioning currently exists in Yukon	0.6	1 0.6	3 1.8	1 0.6
The equipment is safe to operate	1	1 1	2-3 2-3	3 3
Sub-total		8.4	9-11	5
GRAND TOTAL		26.5-32.4	34.8-46.8	28.5-32.7

4.2 Identification of optimum scale category

The analysis found that the ‘Mobile units’ category had significantly higher probability of responding to the use case (slash pile management in Yukon). While there was some overlap between the categories when solely considering Technical Factors, the upper range of ‘Mobile units’’ still scored highest. ‘Mobile units’ were decidedly superior for the Financial and Socio-Economic factors, with no overlap between the categories. Overall, the superiority of ‘Mobile units’ was significant, with no overlap over any other category. It should be noted that variability among ‘Mobile units’ is generally higher than with other categories, with larger span of value ranges. Important differentiating factors are presented in Table 4.

Moreover, some factors were neutral (no influence), e.g.

- Equipment exist in any category that can perform slow pyrolysis, or that can perform pyrolysis at 450-550°C.

Yet some factors are challenges, when comparing ‘Mobile units’ to other categories, e.g.:

- Some mobile units have lower potential for quality control than stationary plants, the latter typically being operated through a software while it is not always the case with the former;
- All other scales potentially have higher biochar yields;
- Mobile units have significantly higher capital cost than Low tech/pop-up units;
- Stationary units typically have a better potential for incidental by-products to be harvested (e.g. energy).

Table 4. Advantages of ‘’Mobile Units’’ over other categories.

Factor, and situation re. ‘Mobile Units’	**Advantages of ‘Mobile Units’**		
	over Low tech/ pop-up	over Stationary Units’	
Technical Factors			
Does not produce smoke			
*Mobile units exist that produce very little to no smoke	x		-Low tech/pop-up equipment are known to have a higher probability of releasing smoke; in fact, they typically release significant quantities of smoke –including particulates/air-borne pollutants and CH_4 (Figure 5, p. 93).
Features at least a fair level of process control			
*Mobile units typically at least have multiple monitoring devices and some form of adjustment levers; moreover, some of them are operated through a software	x		-All Low tech/pop-up equipment have very low process control capacity. None have any formal mean of control, albeit some of them can accommodate or are equipped with, for instance, a temperature sensor. It is up to the operator to adjust the process if readings are not satisfactory, and the operator does not have much control.

			-Low process control leads to poor consistency of the end-product, and incomplete/ineffective pyrolysis, with for instance increased contaminant issues. For instance, De la Rosa (2019) observed that traditional kilns produced wood-based biochars with twice the concentration of PAHs, compared to more advanced kilns.
Can handle feedstock size ≥ or >> woodchips			
*Mobile units exist that can handle raw, big sized material without any need for comminution, or only gross bucking up.	x		-Some Low tech/pop-up units exist that don't require pre-processing or comminution, but most do.
		x	-Stationary units typically require comminution.
Has a throughput capacity of that is aligned with the needs			
*The results of this study show that throughput capacity of mobile units varies tremendously, with typical values 500-5000 tonne/y; that being said, some units can process upwards of 10,000 tonnes per year. *Considering the possibility of redundancy with max 3 units, mobile equipment exist that could process the projected needs (20,000 tonne/y).	x		-The throughput capacity of Low tech/pop-up units tends to be very low as compared to other categories; the results of this study show that it can vary tremendously (1.44-9,900 tonne/y), with typical values 100-1000 tonnes/y. -As an indication, IBI (2019) asserted that Low tech/pop-up units typically could process 0.05-1 tonne/h. Using the same assumption as used in this study (720 hours per year), this is 36-720 tonne/y. -Eeven when assuming the higher range of throughput capacity (720 tonne/y), a redundancy of 29 units would be required –which appears unrealistic.
		x	-The results of this study show that throughput capacity of stationary units can vary substantially, with some units being able to process 10s of thousands of feedstock per year. -As an indication, IBI (2019) asserted that stationary units exist that can process up to 4 tonnes/h. Using the same assumptions used in this study, this is up to 7,680 tonnes/y. -Considering possibility of redundancy with max 3 units, stationary units exist that could process the projected needs (20,000 tonnes/yr).
Risk or potential issues with (local) procurement of parts is low			
*Mobile units exist that are reliable and that have been proven in remote conditions, with low potential for issues with acquisition of (local) material and equipment (e.g. replacement parts).	x		-Low tech/pop-up units tend to be less reliable; some are even impermanent by design. They often are unproven technologies, and have many potential points of failure, which could prove burdensome. -For instance, Zakus farm had to contend with numerous trial and errors in the development of a Low tech/pop-up unit.
		x	-Stationary units tend to have lots of moving parts, which are as much of potential points of failure; these could prove very expensive and complex to replace. -Modular plants might have lower risk with acquisition of local material/equipment as compared to built-on-site plants; their overall reliability also is higher, due to the fact that the overall functioning is not affected by a problem in one unit/module.
Syngas can be captured and used			
*Mobile units exist that capture and use syngas to help sustain the process temperature.	x		-Low tech/pop-up units typically do not capture and use syngas, which is a significant loss of opportunity in terms of energy efficiency. In the less advanced systems, syngas is not even captured and flared, making for a safety issue.
Financial Aspects			

Capacity to forego transportation of the material over long distances			
*Mobile units allow for decentralized systems: they keep transportation needs at a bare minimum for feedstock and biochar end-product by moving the pyrolysis plant rather than the material. This minimizes transportation costs, fossil fuel usage and GHG emissions. As well, the produced biochar can be used onsite, e.g. in the cleared agricultural field.		x	-Transporting material to and from a centralized system would be tremendously expensive, with commensurate usage of fossil fuels, and release GHGs. -As aptly described by Sheridan (2019): ''a system in which a single large centralized biochar production facility receives feedstock from geographically dispersed farms may suffer excessively from material handling and transport costs when compared to systems built around smaller on-farm or portable equipment (Sheridan, 2019).''
CAPEX is limited			
*The results of this study show that unit cost for mobile units could be in the range of $300,000-$600,000.		x	-Stationary units have very high capital cost. As described by Austin (2010): 'the capital costs of building production facilities are high and often unattainable.' -A modular stationary plant (i.e. built from modules) can be cheaper but can possibly be even more expensive than a built-on-site plant.
Costs for O&M are low			
	x		-Low-tech/pop-up units tend to be labor intensive and finicky (like 'black magic'); operation and maintenance could prove very expensive, much more so than mobile units for a same quantity of feedstock processed.
Value for rent/resale is high (capital risk is low)			
*Mobile units leave the resale option available, minimizing capital risk. For instance, a mobile unit would be easy to ship somewhere else, should it no longer be needed in Yukon *Moreover, rental options exist for 'mobile units'.	x		-Low tech/pop-up units could hardly be sold/rented/leased.
		x	-Stationary equipment could be very expensive and difficult to dismantle, sell, and ship somewhere else should it no longer be needed in Yukon. -A modular stationary plant could be less complex and expensive to dismantle and ship than a built-on-site plant.
Scalability			
	x		-The possibility of scaling up Low tech/pop-up units to the needs (20,000 tonne/year) appears unrealistic (e.g. > 29 units); that being said, Low tech/pop-up units still are easy to add up to one another.
		x	-A modular stationary plant would have the advantage that production capacity can grow simply by adding more kilns/modules –in opposition to a built-on-site plant,
Socio-Economic Factors			
Higher impact on Yukon economy (i.e. O&M ≥ CAPEX)			
*The balance between capital expenditures and operational costs is optimal, with a promise to spur economic development while limiting the export of investment money outside the Territory.		x	-A stationary unit is typically hugely capital intensive, and all this investment money would be exported outside the Territory.
Higher impact on rural development			

*A mobile unit would likely create at least two sustainable jobs locally, outside of the Capital.		x	-Although a ‘stationary unit’ could bring the creation of a number of sustainable jobs (possibly 3-10), they would most likely be concentrated in the Capital, and equipment can be hugely capital-intensive.
Siting and permitting is easy			
*Mobile units do not need siting permission as it is transportable.		x	-Siting and permitting of a stationary plant prove very complex, and expensive.
It is easily /quickly commissioned			
*A mobile unit could in all likelihood be commissioned in 1-2 years.	x		Low tech/pop-up units could prove more complex to commission –with much trial and errors, which might incur supplementary delays.
		x	-Stationary units would be much more complex to commission, perhaps taking 5-10 years. -A modular stationary plant could have less technically challenging commissioning than a built-on-site plant.
The equipment is safe to operate			
	x		-Low tech/pop-up equipment typically offer marginal protection of the workers against risks related to heat, gases, and volatile matters (e.g. dust).

Other categories could be better suited for other use cases. For instance, Low tech/pop-up units could be best suitable for microentrepreneurs utilizing thinly-distributed feedstock. They could also be advantageous for small-scale production of value-added biochar (e.g. high phosphorus content biochar made from bonemeal). IBI (2019) mentioned that ’[traditional kilns] are unsuitable for the production of larger amounts of biochar to be used in agriculture.’ The environmental impact of such unit (e.g. energy efficiency and release of smoke, GHGs and toxicants) also is questionable. That being said, improving the design of simple Low tech/pop-up units such as earthen kilns could eventually lead to retort-like features (Nordin, 2019, pers. Comment). For instance, usage of a mobile air curtain blower over an earthen (pit/trench) kiln could significantly improve its overall value. This might deserve further investigation, considering the outstanding simplicity and very low price tag of earthen kilns, as well as the ease of scaling up to tackle large quantities of material.

Stationary units, on the other side, perhaps would be better suitable where a stable supply of biomass is available within an economically transportable distance.

5. DISCUSSION/RECOMMENDATIONS

The identification of an optimum pyrolysis equipment is an iterative process and will require a few more steps. This study established that 'Mobile units' have significantly higher probability of responding to the use case than any other category of pyrolysis equipment. The following recommendations are meant to further clarify the context, build the case for usage of pyrolysis and biochar in Yukon, and narrow down the options among the 'Mobile units' category, with ultimate goal of identifying an optimal unit. A preliminary list of experts is included in Table 9 (Appendix 1.I, p. 106), to which specific mandates perhaps could be attributed.

5.1 Clarifying the context

5.1.1 Defining the regulatory environment and desired certification needs

In order to better inform any further step, a thorough review of the permits, licenses, standards and certifications that are required and those that are recommended for operation of a pyrolysis equipment and use of biochar as an agricultural soil amendment in Yukon should be conducted. This should be analysed and compared to that needed for alternative slash management practices (e.g. burning, chipping and mulching or integrating into soil). For instance, standards possibly exist (CSA Group, ISO, USEPA) for measuring smoke emissions and measuring recovery of incidental energy, as well as certification programs testifying the fit to established criteria, and legal requirements (e.g. USEPA 40 CFR 60; ISO 21501-4:2018). In the same way, the standard requirements and options for measuring carbon sequestration and obtaining carbon credits should be determined. The procedures to obtain CFIA certification in order to be allowed to use biochar as an agricultural soil amendment should also be further investigated, and set in motion if need be.

5.1.2 Investigating the feasibility of chipping slash pile material

As mentioned in point 3.1.1.3, the feasibility of chipping slash material should thoroughly be investigated, especially in regards to the presence of rocks and soils, including technical and financial aspects.

5.1.3 Further investigate equipment features' relative value

Some equipment features that might help in narrowing down the options would require further investigation, as it is unclear at this point whether one feature would be preferable over another. These include the following:

Continuous vs. batch process?

Continuous feed systems have higher energy efficiency and lower pollution emissions (e.g. less smoke), higher yield, are less labour intense, offer more control over the pyrolysis conditions, and produce more consistent biochar. They also can have higher throughput capacity. But also typically are more complex and expensive, and have more moving parts (potential points of failure). They are also said to be less able to handle low quality and inhomogeneous feedstock that batch system (Gustafsson 2013). Semi-batch processes also exist[59]. Any evaluation of the value of continuous vs. batch processes should take into consideration the likely time shifts of workers operating the pyrolysis equipment (8 hours/day?), which could potentially quell the advantages of continuous processes.

<u>Should it be able to harness waste heat?</u>
Pyrolysis releases a lot of energy in the form of low-grade heat (temperature lower than that 450-550°C required to sustain the process). Capturing waste heat would enhance the overall efficiency. It potentially could also enhance the bottom line by reducing the energy input. Waste energy can be used to dry the subsequent feedstock; alternatively, it can be used to produce electricity (see point 3.1.2.7). The capacity to harness and use heat depends on the design and operation of the equipment. ''Where possible heat energy should be extracted for local use, for example; space heating, drying produce, or greenhouse heating (Sheridan, O., 2019).'' However, capturing heat can incur a technological burden. The value of such feature should be calculated taking into account overall economics and environmental impacts.

<u>Retort vs. kiln?</u>
Retorts are typically more energy efficient: once gasification occurs, the retort reheats itself using the wood's natural gases as fuel. Temperature is more evenly distributed throughout, with more constant biochar production. As well, retorts are generally simpler to operate and have less moving parts than kilns. They generally have the capacity to process logs and bigger pieces, and have higher yield (~4:1 as opposed to 7:1 for traditional ring kiln). Moreover, retorts typically reduce harmful emissions by 75% compared to kilns, and the carbon content of biochar produced by a retort is higher than when produced by a kiln (IBI, 2019). However, retorts require more handling of the feedstock.

5.1.4 Identifying potential advisers

A preliminary list of contacts is included in Table 9 (Appendix 1.I, p. 106). This list should further be developed, with established pyrolysis/biochar experts that could potentially help with the ultimate goal of this project: identification of an optimum pyrolysis equipment for management of slash and usage of biochar end-product as agricultural soil enhancement in the Yukon context. Pyrolist (2019) has a listing of service providers.

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[59] Jonsson, 2016: 'A semi-batch process is running the same process as a batch reactor but has several reactors connected with each other. The connection gives the option to use the surplus of heat from the process to start up the other batches. This causes the method to be more energy efficient and also have a higher production rate compared with a simple batch process.'

5.2 Build the case for use of pyrolysis and biochar in Yukon

5.2.1 Look into and perhaps rectify perceptions

Perceptions might exist that could limit practitioners in embracing the use of pyrolysis to manage slash piles and use of biochar to enhance soil productivity in Yukon. These should be explored, and perhaps rectified. For instance, burning might be entrenched in mentalities here as much as elsewhere (Lucas, 2019b). As mentioned by IBI (2019), 'overcoming public misperceptions that conflate pyrolysis with incineration or combustion is one obstacle to establishing a biochar project. Proposing a biomass pyrolysis plant can also elicit objections due to many of today's bioenergy enterprises' reliance on clear cutting and other unsustainable practices.' As pyrolysis is relatively new in Yukon, presentation of this process should be done up front, for instance through education and positive communication initiatives, which might do a lot in preventing misconceptions and having to fight them further down the line. To change, people need to be shown what advantage they can gain (e.g. harmonious cohabitation, enhancement of soil productivity, carbon credits). Evaluating the risk related to feedstock and supply chain could also do a lot to defuse any fears from potential investors (e.g. Ecostrat, 2019; CSA Group is in the process of transforming the standards to a National Standard of Canada).

5.2.2 Bolster knowledge re. use of biochar end-product

Substantial knowledge gaps exist that require further research to ensure safe, beneficial and efficient use of biochar as an agricultural soil amendment in Yukon. In particular, the validity of the claim that biochar can improve agricultural soils productivity in Yukon conditions entirely remains to be demonstrated scientifically, despite numerous anecdotal evidences. A solid body of literature exists showing that it does in a variety of conditions, including conditions similar to those of Yukon, but past Yukon research has mostly led to inconclusive results (e.g. Drury, 2014). Moreover, practical knowledge on biochar use is thin. For instance, it has been posited that a 10-30 tonne/ha application rate would be appropriate in Yukon –based on research conducted elsewhere (Dr. Mingchu Zhang), but nothing shows that it effectively is the case in Yukon, and some experimental results point towards the need for a higher application rate (e.g. Drury, 2014). Other authors suggest to add as much biochar as is needed to increase SOM to at least 6% (Pensulo, 2012). Nevertheless, effectivity of biochar for usage other than agriculture has been demonstrated in Yukon (e.g. mine remediation at 22.8 tonne/ha; Nordin, 2015). As mentioned by Sheridan (2019) for the Yukon context, 'existing knowledge can […] be used to plan applied research programs to determine if and how benefits can be delivered in specific locations and use cases.' Some recommendations from past studies conducted in Yukon are reproduced here:

> Drury, 2014: 'It is recommended that further study is needed on the implications of adding biochar to soils, it is highly advised that producers contemplating its use conduct small scale trials within their operations in order to assess its value for them and their crops. It is also the recommendation of this study that research and monitoring take place to understand the long term implications of biochar addition. Biochar is a non--

> reversible amendment and its long term effects are poorly understood. For biochar to be considered further for agricultural usage in our region, continued research should be undertaken to try and better understand these dynamics.'
>
> Nordin, 2015: 'Further research should consider varying the application rates of the soil amendments [e.g. biochar, compost, leonardite, humic acid] to achieve the most economical blend possible for the given mine-affected soil problem. The research has the potential to enhance the mine closure and reclamation process using local materials and expertise. Following are recommendations for [subsequent] growing season: (1) Monitoring should be carried out routinely from mid-June to mid-September; (2) standard watering protocols should be continued; (3) the monitoring protocols used in 2014 should be continued.'
>
> Nordin, 2019, pers. comment: Our observations suggested that best results for soil amendment might come from a mixture of biochar and organic or inorganic fertilizer. Further research in these areas would be useful. For instance, the field tests used for our projects with CCI a few years ago could be revived. As well, growth chamber experiments could be useful, perhaps using biochars created under varying pyrolysis methods. Getting in the queue for the growth chamber could be a first step.

As well, any further research should reflect the variability in agricultural soils conditions encountered in Yukon, with thorough definition of soil properties (e.g. texture, native SOM, nutrients). Any biochar research in Yukon should also seek for a much more detailed understanding of the material at hand: without thorough analysis of the biochar properties (e.g. H:C ratio, PAHs), it is impossible to make sense of the agronomic results –whatever they are. Large-scale application techniques suitable to the Yukon context need also be explored. For instance, Major (2010) suggested using a conventional manure spreader, with provisions to prevent volatilization.

5.2.3 Seeking support

In order to back up further public investments, perhaps letters of intent from prospective slash pile managers and biochar users could be solicited.

Moreover, public support programs should be looked up and perhaps solicited, especially as it relates to climate change mitigation and adaptation. For instance, the following programs might be suitable:
Natural Resources Canada
- Sustainable Development Technology Canada (SDTC) – SD Tech Fund™'
- Indigenous Forestry Initiative (IFI) Program
- Investments in Forest Industry Transformation (IFIT) Program

Agriculture and Agri-Food Canada
- Agricultural Clean Technology Program

CIRNA

- Community Economic Development Program’

National Research Council of Canada

- Industrial Research Assistance Program (IRAP)

First Nation economic development bodies could also be solicited, for instance Dakwakada Capital Investments, Kluane Community Limited Partnership, Kluane Dana Shäw Corporation, Chu Níikwän Development Corporation, and Da Daghay Development Corporation.

5.3 Narrow down the options

Now that it has been established that ‘Mobile units’ have the highest probability of responding to the use case requirements, the following steps should be implemented to further narrow-down the options, with ultimate goal of identifying the optimal equipment. In parallel, further research could eventually lead to the enhancement of earthen kilns.

5.3.1 Identify all relevant ‘mobile unit’ options

This study turned up close to 20 options for ‘mobile units’. An all-encompassing review of ‘mobile units’ options should be conducted, in view of turning up any equipment that has not already been rendered. Any option from anywhere around the world should be considered. This step perhaps could be supported by the database developed by SESM (2016; >1000 entries).

5.3.2 Second screening iteration

In view of further narrowing down the options, the relative value of all units rendered by an all-encompassing review of ‘mobile units’ should be calculated on a case-by-case basis using publicly available information, for instance company websites and trade-industry publications. The evaluation criteria should include those used in this study (e.g. does not produce smoke, CAPEX is limited), plus others that have not entirely been considered in this study –typically because they did not help in discerning category-based trends or because not enough information was available publicly. An analytical grid similar to that of this study could be used, with ponderation reflecting the importance of the factor in the context of the specific use case. The comparison of units’ value should take into consideration the fact that publicly-available information will not be complete for all units. Supplementary evaluation criteria could include the following:

Yukon proof: proven capable of operating in cold conditions

The already short operating season for any outdoor unit (6 months) might include sub-zero temperatures and snow, and the equipment should be able to sustain such conditions.

Is certified for low smoke and other pollutants emissions

Considering the importance of addressing potential harmonious cohabitation issues, the adoption of pyrolysis as the preferred slash management practice in Yukon would benefit from using equipment that is certified as releasing lowest smoke and other pollutants (e.g. NOx).

Is energy efficient

For instance, the equipment might benefit from responding to the EBC (2019) energy efficiency requirements. A good start is the reduction of energy waste, for instance through good heat conservation and transfer in the chamber. An evaluation should be made of any energy that is required to sustain the pyrolysis unit, such as electricity for any engine that move the material along (e.g. augers) and engine and heat required to pre-dry the biomass.

Has a sustainable design/based on the Hannover principles

Pyrolysis generally has a great potential to transform 'waste' into a valuable product (biochar). Optimal pyrolysis equipment should take into account the full short and long-term consequences of its usage. For instance, it should aspire to the integration of its material, spiritual and ecological facets rather than separating them.

Has the least moving parts possible

Any moving part is a potential point of failure. The number of moving parts is related to durability and reliability. Reducing the number of moving parts might decrease the risk of issues with procurement and replacement of parts.

Skills required to operate and maintain the equipment are in line with local capacity/has a balanced complexity

Complexity of a system depends on the design and is not related to the size of the equipment. There is a lot of leeway between raw/low-tech mobile units and complicated/fancy ones. For instance, a small unit can be very complex to operate, or not at all; in the same way, a large unit can be complex to operate, but have technology to help. For each unit, the skills required to operate and maintain the unit should be evaluated and compared against the local skills available and possibility of capacity building.

Is well developed

An equipment that is developed at least at full scale, if not already at commercial scale would have lesser inherent risk than an equipment that is proven only at lab or pilot scale, a fortiori only on paper.

Is still being improved

Continuous improvement shows commitment from the vendor.

Has a strong track record

Evaluation/appreciation and references from current and past users/customers could prove tremendously helpful in appreciating the value of a pyrolysis equipment.

The vendor is open, professional, and capable of giving the information needed
The capacity of the vendor to sell their product is a good first indicator. Some companies have a strong presence online that is not reflected in the real world.

The vendor has a strong track record
The reputation and history of the vendor should be thoroughly considered. Testimonials from current or past clients might prove very useful. As mentioned in point 0, a 'menagerie of pyrolysis wizardry' and 'pie-in-the-sky companies' exist out there, and professional judgement must be exercised in analysing the value of a company.

The vendor is active in Canada
Experience in dealing in Canada or at least open to making business and offering post sale services might prove tremendously useful. Current business in Canada could also prove greatly advantageous if only for experience with custom clearance, the local taxation system, and cultural norms.

The vendor or its representative is located within relative proximity
Proximity of the vendor might make commissioning easier, with shorter equipment transportation requirements, and possibly some savings on transport of the equipment and custom clearance charges. Proximity of the vendor or its representative might also make it easier for a technician to come on-site for troubleshooting and repair. For instance, a vendor/representative located in western/northern Canada or at least in North America might be preferred to one located in Asia or Australia.

Offers a good cost/benefit ratio
The benefit of specific features (e.g. capable of harnessing energy) should be balanced against overall cost so as to derive an overall cost/benefit ratio. Overall, the equipment should be as profitable as possible for everyone.

5.3.3 Third screening

Equipment that scored highest in the second screening iteration should be further scrutinized with collection of information beyond that which is available publicly. For instance, vendors could be contacted to request most up-to-date information. A detailed questionnaire could be distributed, followed with targeted interviews. The number of equipment that receive such scrutiny should be limited (e.g. ≤ 15) to limit the efforts required to contact vendors. The relative value of each unit should again be calculated using this more complete set of information, and compared.

5.3.4 Discussion, visits, and final recommendation

Those equipment that scored highest in the third screening iteration should be discussed by a team of experts, with ultimate goal of identifying an optimum equipment. Visits to vendors and of operating equipment[60] could greatly enhance this discussion. The number of equipment that receive such scrutiny should be limited (e.g. ≤ 5). Final recommendation should be made collaboratively. The team could include, for instance:

- Ag Branch representative(s)
- Forestry Branch representative(s)
- Funding partner(s) representative(s)
- Yukon pyrolysis/biochar pioneer(s)
- Pyrolysis/biochar consultant(s), from Yukon and beyond (see point 5.1.4, and Table 9, Appendix 1.I, p. 106).
- Representative(s) of affected communities

5.4 Building the local capacity

The operation and maintenance of any pyrolysis equipment will require the expertise of a number of Technical Operators. At any moment, at least two Operators should be onsite for safety purpose. Backup/redundancy Operators will also be necessary. Example of baseline capacity include welding, millwright, fabrication, electrical, mechanics, tractor/excavator and fork lift operations. As any initiative, local hire from affected communities is preferable. Education/empowerment of potential workers should start early in the process so as to have sufficient resources once needed.

6. CONCLUSIONS

In Yukon, uncontrolled open burning of slash piles is often performed, resulting in resource wastage and substantial air pollution. A comprehensive risk-management approach was proposed, where avoidance measures should take priority over remediation; alternative reduction measures were also presented. Pyrolysis is proposed as the remediation measure, where wood is ''cooked'' and carbon is sequestered in recalcitrant forms in biochar that can be used to enhance agricultural soils productivity. Using pyrolysis to remediate slash piles generated by land clearing has the potential to generate a win-win-win scenario: harmonious cohabitation, reduction of the carbon footprint, and profitability of agriculture. A main condition for this scenario to occur is that pyrolysis equipment implemented/imported be suited to the specific use case, with a defined set of desirable projected biochar end-

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[60] For instance:

- Biochar & Bioenergy 2019 conference. June 30-July 3, Colorado State University in Fort Collins, CO. Co-sponsored by the US Biochar Initiative and Bioenergy Alliance Network of the Rockies.
- IBI Study Tour, 2019. September 4-6, Finland.
- IBI Biochar World Congress, 2019. November 10-14, Korea University in Seoul, North Korea.
- ReGen Europe. January 29-30. Nantes, France.
- Forest Biomass and the Bioeconomy: Using Forest Residues for Profit, Carbon Sequestration and Soil Restoration. April 25, 2020. Washington, WA.

product properties for usage as agricultural soil productivity enhancement, and equipment that is capable of delivering this while being adapted to the management of slash piles. This project explored a variety of scales and types of equipment and analysed them through the lens of their fit to the use case requirements.

This project demonstrated that pyrolysis units that are mobile have significantly higher probability of being suitable. The main advantage over Low tech/pop-up equipment is that mobile units offer a much better control over pyrolysis conditions, rendering consistent and predictable biochars responding to specific desired properties. The main advantage of mobile units over stationary units is that it limits the cost involved with transportation of feedstock (slash) and product (biochar). The throughput capacity of mobile units also is easily scalable and adaptable to the current slash production (20,000 tonne/y) and prospective needs. That being said, other types of equipment could be more suitable for other use cases. For instance, a Low tech/pop-up unit could eventually be more advantageous for small-scale production of a value-added biochar such as phosphorus-rich biochar from bonemeal.

Further recommendations include the narrowing down of mobile unit options. A variety of mobile unit suppliers and equipment have been turned up by this project, and other options possibly still also exist out there, which would deserve further consideration. The suitability of mobile equipment options should be analysed on a case-by-case basis using incrementally refined criteria towards the identification of an optimal option. For instance, the proximity and track record of the vendor should thoroughly be examined. This project gathered interest from a large set of stakeholders, and further steps should continue involving the community.

Over and above remediating the smoke and green-house gas risks brought about by slash piles and providing agricultural benefits through biochar application, carbon credits could be generated that could eventually become a supplementary revenue stream in a carbon market; a possibility of generating energy for a revenue also exists, and should be explored in a case-by-case cost/benefit evaluation.

The development of a pyrolysis file in Yukon also has the potential to help tackle issues other than slash piles management. Pyrolysis could for instance be used to manage other combustible materials such as construction & demolition waste and pallets, woodmills sawdust, and water sanitation sludge. It could also be considered in the management of risk imparted by beetle killed timber. Over and above usage as an agricultural soil amendment, biochar has also been demonstrated to be effective in mine reclamation efforts and in soilless commercial horticulture (e.g. greenhouses, greenroofs, cannabis production, forest seedlings production). Moreover, the Yukon experience with slash management, pyrolysis and biochar has the potential to contribute valuable information to practitioners evolving where the context shares environmental, socio-economic or cultural elements such as in NWT and northern BC.

REFERENCES

Ahmed, A. et al., 2016. Biochar influences on agricultural soils, crop production, and the environment: a review. 24(4): 495-502.

Alberta Innovates/Technology Future (AITF), 2015. Biochar CFIA Registration. 2 p.

Atkinson C.J. et al., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant and Soil. 337(1). pp. 1-18.

Austin, A., 2010. Beyond the Hype. Biomass magazine. September 2010.

Australia Government, 2019. Carbon Farmers of Australia. Trading Platform.

Backer, R. et al., 2018. Getting to the root of the matter: Water-soluble and volatile components in thermally-treated biosolids and biochar differentially regulate maize (Zea mays) seedling growth. Plos One. 13 (11). e0206924.

Backer, R., 2016. Biochar Soil Amendments in Southwestern Québec, Canada: An Investigation of Impact on Crop Yields, Interaction with N Fertilizer and Characterization of the Biochar Volatilome. Thesis. McGill University. 160 p.

Ball, M. et al., 2013. Yukon agriculture state of the industry report. Yukon Government, Energy, Mines and Resources, Agriculture Branch. Whitehorse, YT. 46 p.

Barrow, C.J., 2012. Biochar: potential for countering land degradation and for improving agriculture. Applied Geography. 34. pp. 21-28.

Basso, A.S. et al., 2013. Assessing potential of biochar for increasing water-holding capacity of sandy soils. Glowbal Change Biology Bioenergy. 5(2). pp 132-143.

Bastos, A.C. et al., 2014. Potential risk of biochar-amended soil to aquatic systems: an evaluation based on aquatic bioassays. Ecotoxicology. 23. pp. 1784-1793.

British Columbia Government (BC Gov), 2019. Open Burning Smoke Control Regulation (OBSCR). Environmental Management Act. July 08, 2019.

Beesley, L. et al., 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environmental pollution. 159. pp. 3269-3282.

BioEnergy Lists, 2019a. Making Biochar: biochar, simplified.

BioEnergy Lists, 2019b. Larger scale pyrolyzers: combined heat and char systems, combined power and char systems, pyrolysis systems.

Brown, R., 2012. Biochar production technology. Biochar for Environmental Management; science and Technology. Chapter 8. pp. 159-178.

Brown, T.R. et al., 2011. Estimating profitability of two biochar production scenarios: slow pyrolysis vs fast pyrolysis. Biofuels, Bioproducts & Biorefining. 5(1). pp. 54-68.

Bruun, E.W. et al., 2014. Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. Soil Use and Management. 30. pp. 109-118.

Bruun, E.W. et al., 2012. Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. Soil Biology and Biochemistry. 46. pp 73-79.

Bruun, E.W. et al., 2011. Influence of fast pyrolysis temperature on biochar labile fraction and short-term carbon loss in a loamy soil. Biomass and Bioenergy. 35(3): 1182-1189.

Buss, W. et al., 2016. Strategies for producing biochars with minimum PAH contamination. Journal of Analytical and Applied Pyrolysis. 19. pp. 24-30.

Buss, W. and Mašek, O., 2014. Mobile organic compounds in biochar–a potential source of contamination–phytotoxic effects on cress seed (Lepidium sativum) germination. Journal of environmental management. 137. pp. 111-119.

Cai, Y. et al., 2015. Biochar effects on soil fertility and nutrient cycling. Biochar; Production, Characterisation, and Applications. Chapter 9. pp. 246-271.

CBC, 2019. Visitors flock to Yukon village to see bioenergy system in action. Byers, Alexandra. March 30, 2019.

CBC, 2018. Yukon logger bets on biomass to cut costs and waste. April 04, 2018.

Carbon Tracker, 2018. EU Carbon prices could double by 2021 and quadruple by 2030. Press Release. 26 April 2018.

Chan, K. et al., 2008. Agronomic values of greenwaste biochar as a soil amendment. Soil Research. 45. pp. 629-634.

Cheng, C.H. and Lehman, J.C., 2009. Ageing of black carbon along a temperature gradient. Chemosphere. 75(8). pp. 1021-1027.

Cheng, C.H. et al., 2008. Natural oxidation of black carbon in soils: changes in molecular form and surface charge along a climosequence. Chemosphere. 72(6). pp. 1598-1610.

Clough, T.J. and Condron, L.M., 2010. Biochar and the nitrogen cycle: introduction. Journal of Environmental Quality. 39. pp. 1218-1223.

Cole, D.P., 2012. High-resolution mass spectrometric characterization of molecules on biochar from pyrolysis and gasification of switchgrass. Energy & Fuels. 26 (6). pp. 3803-3809.

De la Rosa, J.M. et al., 2019. Effect of pyrolysis conditions on the total contents of polycyclic aromatic hydrocarbons in biochars produced from organic residues: Assessment of their hazard potential. Science of the Total Environment. 667. pp. 578-585.

DeLuca, T.H., 2015. Biochar effects on soil nutrient transformations. Biochar for environmental management: Science, technology and implementation. pp. 421-454.

Deenik, J.L. et al., 2010. Charcoal volatile matter content influences plant growth and soil nitrogen transformations. Soil Science Society of America Journal. 74. pp. 1259–1270.

Dennis, J., 2011. Biochar Manual for small farms in BC. UBC. 27 p.

Ding, Y. et al., 2016. Biochar to improve soil fertility: a review. Agronomy for Sustainable Development. 36(2). p. 36.

Ding, Y. et al., 2010. Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water, Air, & Soil Pollution. 213. pp. 47-55.

Drury, T., 2014. Final report Yukon Biochar Project: Increasing self sufficiency in Yukon's agricultural sector through the use of biochar. Prepared for Canadian Agricultural Adaptation Program Council. 57 p.

Dutta, T. et al., 2017. Polycyclic aromatic hydrocarbons and volatile organic compounds in biochar and biochar-amended soil: a review. Global Change Biology Bioenergy. 9(6): 990-1004.

Duteau, M., 2016. Yukon Biomass Energy: a literature review; forestry, supply chain, harvest, and sustainability. Presentation Document for the Yukon Biomass Forum, Kwanlin Dün Cultural Centre, Whitehorse YT, March 15-16, 2016. Final version April 02, 2016.

ECOERA, 2019. Carbon Emission Removal Service.

Ecostrat, 2019. The standards for biomass supply chain risk; de-risking capital market investment in biomass.

Enders, A. et al., 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresource Technology. 114. pp. 644-653.

European Biochar Foundation (EBF), 2019. Guidelines for Sustainable Production of Biochar. Version 8E of 1st January 2019 (original version 2012). Arbaz, Switzerland.

Gao, S. and DeLuca, T.H., 2016. Influence of biochar on soil nutrient transformations, nutrient leaching, and crop yield. Advances in plants and agriclulture research. 4(5): 1-16.

Garcia-Perez M. et al., 2010. Methods for Producing Biochar and Advanced Biofuels in Washington State. Part 1: Literature Review of Pyrolysis Reactors. First Project Report. Department of Biological Systems Engineering and the Center for Sustaining Agriculture and Natural Resources, Washington State University, Pullman, WA, 137 pp

Garcia-Perez, M. and Metcalf, J., 2008. The formation of polyaromatic hydrocarbons and dioxins during pyrolysis: a review of the literature with descriptions of biomass composition, fast pyrolysis technologies and thermochemical reactions. Washington State University. 63 p.

Ghidotti M. et al., 2017a. Profiles of volatile organic compounds in biochar: insights into process conditions and quality assessment. ACS Sustainable Chemistry & Engineering. 5 (1). 510–517.

Ghidotti, M. et al., 2017b. Source and Biological Response of Biochar Organic Compounds Released into Water; Relationships with Bio-Oil Composition and Carbonization Degree. Environmental Science & Technology. 51(11). Pp. 6580-6589.

Gignac, J., 2019. Independent renewable energy producers can now sell to Yukon utilities. Yukon News. February 05, 2019.

Glaser, B. and Birk, J.J., 2012. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Indio). Geochimica et Cosmochimica Acta. 82. pp. 39-51.

Glaser, B., 2006. Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. Philosophical Transactions of the Royal Society B. 362(1478). pp. 187-196.

Glaser, B. et al., 2001. The 'Terra Preta' phenomenon: a model for sustainable agriculture in the humid tropics. Naturwissenschaften. 88(1): 37-41.

Glodowska, M., 2014. Biochar as a potential inoculant carrier for plant-beneficial bacteria. Thesis. McGill University. 101 p.

Gonzaga, M.I.S. et al., 2017. Pyrolysis methods impact biosolids-derived biochar composition, maize growth and nutrition. Soil and Tillage Research. 165 (Supplement C). pp. 59-65.

Government of Canada/Gouvernement du Canada (GC), 2019. Canada's Changing Climate Report. Canada in a Changing Climate: Advancing our Knowledge for Action. Environment and Climate Change Canada.

GC, 2018. Guide to Submitting Applications for Registration under the Fertilizers Act. Canadian Food Inspection Agency (CFIA). 38 p.

GC, 1985. Fertilizers Act and Regulations. R.S.C., 1985, c. F-10 and C.R.C., c. 666.

Gul, S. et al., 2015. Physico-chemical properties and microbial responses in biochar-amended soils: mechanisms and future directions. Agriculture, Ecosystems & Environment. 206. pp. 46-59.

Gustafsson, M., 2013. Pyrolysis for heat production-Biochar the primary byproduct. Master's Thesis, University of Gavle.

Hale, S.E. et al., 2012. Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. Environmentl Science & Technology. 46(5). pp. 2830-2838.

Hubbe, A. et al., 2007. Evidence of plaggen soils in European North Russia (Arkhangelsk region). Journal of Plant Nutrition and Soil Science. 170 (3). pp. 329-334.

International Biochar Initiative (IBI), 2019. Website.

IBI, 2015a. State of the Biochar Industry: Company list.

IBI, 2015b. Definition and Product Testing Guidelines for Biochar That Is Used in Soil (IBI Biochar Standards). Version 2.1. (version 2.0 published in 2014). 60 p.

IBI, 2013. IBI Biochar Certification Program.

IBI, 2012. IBI White Paper Implications and Risks of Potential Dioxin Presence in Biochar. By Kelpie Wilson and Debra Reed. 11 p.

International Panel on Climate Change (IPCC), 2018. Special Report on Global Warming of 1.5ºC. Incheon, South Korea. October 18, 2018.

IPCC, 2014. Fifth Assessment Report.

Ippolito, J.A. et al., 2015. Biochar elemental composition and factors influencing nutrient retention. Biochar for Environmental Management: science, technology and implementation: 139-163.

Isbister, K., 2017. Literature Review: Windrow Woodchips as a Soil Amendment for Newly Cleared Agricultural Land in Yukon. Flora Teknika. Whitehorse, YT. 29 p.

Jeffery, S., et al., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture Ecosystems & Environment. 144(1). pp. 175-187.

Johnson, J., 2011. Agricultural waste disposal best practices guide. Regional District of Okanagan-Smilkameen. Penticton, BC. 36 p.

Jonsson, E., 2016. Slow pyrolysis in Brista: an evaluation of heat and biochar production in Sweden. Thesis. KTH Royal Institute of Technology. Sweden. 55 p.

Joseph, S. et al., 2015. Feeding biochar to cows: An innovative solution for improving soil fertility and farm productivity. Pedosphere. 25(5). pp. 666-679.

Joseph, S. et al., 2010. An investigation into the reactions of biochar in soil. Soil Research. 48(7). pp. 501-515.

Karppinen, E.M. et al., 2019. The Charosphere Promotes Mineralization of 13 C-Phenanthrene by Psychrotrophic Microorganisms in Greenland Soils. Journal of Environmental Quality. March 08 2019.

Karppinen, E.M., 2018. Biochar as a soil amendment to enhance petroleum hydrocarbon degradation in northern landfarms. Thesis. University of Saskatchewan. 174 p.

Kammann, C, et al., 2016. Combining biochar and organic amendments. Biochar in European Soils and Agriculture. Chapter 6. Routledge, London. pp. 136-164.

Keiluweit, M. et al., 2012. Solvent-extractable polycyclic aromatic hydrocarbons in biochar: influence of pyrolysis temperature and feedstock. Environmental Science & Technology. 46. pp. 9333– 9341.

Keiluweit, M. et al., 2010. Dynamic molecular structure of plant biomass-derived black carbon (biochar). Environmental Science & Technology. 44(4). pp. 1247-1253.

Knowles et al., 2011. Biochar for the mitigation of nitrate leaching from soil amended with biosolids. Science of the Total Environment. 409 (17). pp. 3206-3210.

Kochanek, J. et al., 2016. Karrikins Identified in Biochars Indicate Post-Fire Chemical Cues Can Influence Community Diversity and Plant Development. PLOS ONE. 11(8). e0161234 10.1371

Krug, E. C. and Hollinger, S. E., 2003. Identification of factors that aid carbon sequestration in Illinois agricultural systems. ISWS Contract Report CR 2003-02.

Laird, D. A. et al., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma. 158 (3-4). pp. 443-449.

Lang, T. et al., 2005. Retention of organic elements during solid fuel pyrolysis with emphasis on the peculiar behavior of nitrogen. Energy & Fuels. 19(4): 1631-1643.

Larney, F.J. and Angers, D.A., 2012. The role of organic amendments in soil reclamation: A review. Canadian Journal of Soil Science 92(1). pp. 19-38.

Lehmann, J. and Joseph, S., 2015. Biochar for Environmental Management: Science and Technology. Second edition (first edition published 2009). London, Sterling, VA. 416p.

Lehmann, J. et al., 2006. Biochar sequestration in terrestrial ecosystems–a review. Mitigation and Adaptation Strategies for Global Change. Mitigation and Adaptation Strategies for Global Change. 11(2). pp. 403-427.

Lucas, J., 2019a. High Level Overview: Development of Agricultural Land Clearing Practices that Reduce GHG Emissions and Build Soil Capacity in the Yukon & NWT. Second edition. Agriculture Branch, Yukon Government. 3 p.

Lucas, J., 2019b. Burning of cleared land trees (agriculture situation) – situation and discussion. Agriculture Branch, Yukon Government. 8 p.

Luo, Y. et al., 2011. Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biology & Biochemistry. 43(11). pp. 2304-2314.

Major, J., 2010. Guidelines on practical aspects of biochar application to field soil in various soil management systems. International Biochar Initiative (IBI). Version 1.0, 9. November 2010. 23 p.

McDonough, W. et al., 2003. The Hannover principles: Design for sustainability. W. McDonough Architects.

Morales, M.M. et al., 2013. Sorption and desorption of phosphate on biochar and biochar–soil mixtures. Soil Use and Management. 29. pp. 306-314.

Matheus, P. and Omtzigt, T., 2012. Yukon revegetation manual practical approaches and methods. Beta form. Mining and Petroleum Environment Research Group (MPERG). Yukon College. Whitehorse, YT. 176 p.

McClellan, A.T. et al., 2007. Effects of flashed carbonized© macadamia nutshell charcoal on plant growth and soil chemical properties. 80 (100). 120.

McLagan, D.S., et al., 2018. Identifying and evaluating urban mercury emission sources through passive sampler-based mapping of atmospheric concentrations. Environmental Research Letters. 13 (7).

Mia, S. et al., 2014. Biochar application rate affects biological nitrogen fixation in red clover conditional on potassium availability. Agriculture, Ecosystems & Environment. 191. pp. 83-91.

Novak, J.M., et al., 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science. (3). pp. 195-206.

Nordin, K., 2015. Use of Biochar in Yukon Mine Revegetation / Reclamation Field Studies 2013-2014. Laberge Environmental Services.

Pacific Northwest Biochar Initiative (PNWBI), 2015. Referral List: Producers, suppliers, researchers, agencies and nonprofits that are working with or familiar with biochar. Version 21. Last updated March 09, 2015.

Peake, L.R. et al. (2014). Quantifying the influence of biochar on the physical and hydrological properties of dissimilar soils. Geoderma. 235. pp. 182-190.

Pensulo, C., 2012. The Potential of Biochar to Enhance Environmental Sustainability in Sweden. Master's Thesis. Uppsala University, Sweden.

Pyrolist, 2019. The pyrolysis industry's online marketplace.

Rajkovich S. et al., 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biology and Fertility of Soils. 48. pp. 271-284.

Roberts, K.G. et al., 2009. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environmental science & technology. 44. Pp. 827-833.

Rombolà, A.G. et al, 2015. Relationships between chemical characteristics and phytotoxicity of biochar from poultry litter pyrolysis. Journal of agricultural and food chemistry. 63. pp. 6660-6667.

Scheub, U., 2016. Terra preta: How the world's most fertile soil can help reverse climate change and reduce world hunger. Greystone Books Ltd.

Scudder, G.G.E., 1997. Environment of the Yukon. Vancouver: University of British Columbia. 45 p.

Sheridan, O., 2019. Pyrolysis of woody biomass to produce biochar and energy co-products – A review. 15 p.

Singh, B.P. and A.L. Cowie, 2014. Long-term influence of biochar on native organic carbon mineralisation in a low-carbon clayey soil. Scientific reports. 4: 3687.

Singh B. et al, 2010. Characterisation and evaluation of biochars for their application as a soil amendment. Soil Research. 48. pp. 516-525.

Sixth Element Sustainable Management (SESM), 2016. The Pyrolysis 1000. Prepared by Gerald Kutney.

Spokas, K.A. et al., 2012. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. Journal of Environmental Quality. 41(4). pp. 973-989.

Spokas, K.A. et al., 2011. Qualitative analysis of volatile organic compounds on biochar. Chemosphere. 85 (5). pp. 869-882.

Sun, J. et al., 2017. Effects of pyrolysis temperature and residence time on physicochemical properties of different biochar types. Acta Agriculturae Scandinavica, Section B—Soil & Plant Science. 67(1). pp. 12-22.

United States Biochar Initiative (USBI), 2019. Manufacturers & Retailers List.

Van Zwieten L. et al., 2010. A glasshouse study on the interaction of low mineral ash biochar with nitrogen in a sandy soil. Soil Research. 48. Pp. 569-576.

Wang, G.-J. et al., 2016. Effects of Biochar and Compost on Mung Bean Growth and Soil Properties in a Semi-arid Area of Northeast China. International Journal of Agriculture & Biology. 18(5).

Wang, Z. et al., 2013. Characterization and influence of biochars on nitrous oxide emission from agricultural soil. Environmental Pollution. 174. pp. 289-296.

Weidemann, E. et al., 2018. Influence of pyrolysis temperature and production unit on formation of selected PAHs, oxy-PAHs, N-PACs, PCDDs, and PCDFs in biochar—a screening study. Environmental Science and Pollution Research. 25(4). Pp. 3933-3940.

Wornat M.J. et al., 1995. Structural and compositional transformations of biomass chars during combustion. Combustion and Flame. 100. pp. 131-143.

WSP et al., 2014. Étude sur la production et la commercialisation du biocharbon et ses dérivés. Rapport présenté à la Filière forestière des Premières Nations du Québec, 151 p. et annexes.

Yang, Y. et al. (2015). A field experiment on enhancement of crop yield by rice straw and corn stalk-derived biochar in Northern China. Sustainability. 7(10). pp. 13713-13725.

Yao, Q. et al., 2017. Three years of biochar amendment alters soil physiochemical properties and fungal community composition in a black soil of northeast China. Soil Biology and Biochemistry. 110. pp. 56-67.

Yao, Y. et al., 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere. 89 (11). pp. 1467-1471.

Yukon College (YC), 2014. Continuous Feed Biochar Machine. Cold Climate Innovation (CCI).

YC, 2012. Three-Purpose Biochar Machine. Yukon Research Centre (YRC), Technology Innovation.

Yukon Government (YG), 2019a. Climate Change and Yukon. Climate Change Secretariat. webpage.

YG, 2019b. Yukon Soils and Geography. Energy, Mines, and Resources; Agriculture Branch. webpage.

YG, 2019c. Get your soil tested. Energy, Mines, and Resources; Agriculture Branch. webpage.

YG, 2018a. Greenhouse gas emissions in Yukon. Yukon Environment. Climate Change Secretariat. 4 p.

YG, 2018b. Renewable Energy and Energy Efficiency Update January 2016 – June 2018. Energy, Mines, and Resources; Agriculture Branch. Whitehorse, YT. 18 p.

YG, 2018c. Yukon Agriculture State of the Industry Report: 2013 to 2017. Energy, Mines, and Resources; Agriculture Branch. Whitehorse, YT. 52 p.

YG, 2016. Yukon Biomass Energy Strategy. Yukon Government. Whitehorse, YT. 19 p.

YG, 2014. Air Emission Regulations: application for an air emissions permit for burning/incinerating.

YG, 2006. Yukon agriculture policy – agriculture land development guidelines. Yukon Government, Department of Energy Mines and Resources, Agriculture Branch. Whitehorse, YT. 2 p.

Zhang, Q.-Z. et al., 2014. Effects of biochar on soil microbial biomass after four years of consecutive application in the north China plain. Plos One. 9 (7).

Zhao, B. et al., 2018. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. Journal of cleaner production. 174. pp. 977-987.

Zhao, S.X. et al., 2017. Effect of temperature on the structural and physicochemical properties of biochar with apple tree branches as feedstock material. Energies. 10 (9). 1293.

Zheng, H. et al., 2013. Characteristics and nutrient values of biochars produced from giant reed at different temperatures. Bioresource Technology. 130. pp. 463-471.

Zimmerman, A. R. et al., 2011. Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. Soil Biology & Biochemistry. 43(6). pp. 1169-1179.

APPENDIX

A. Pictures and Images

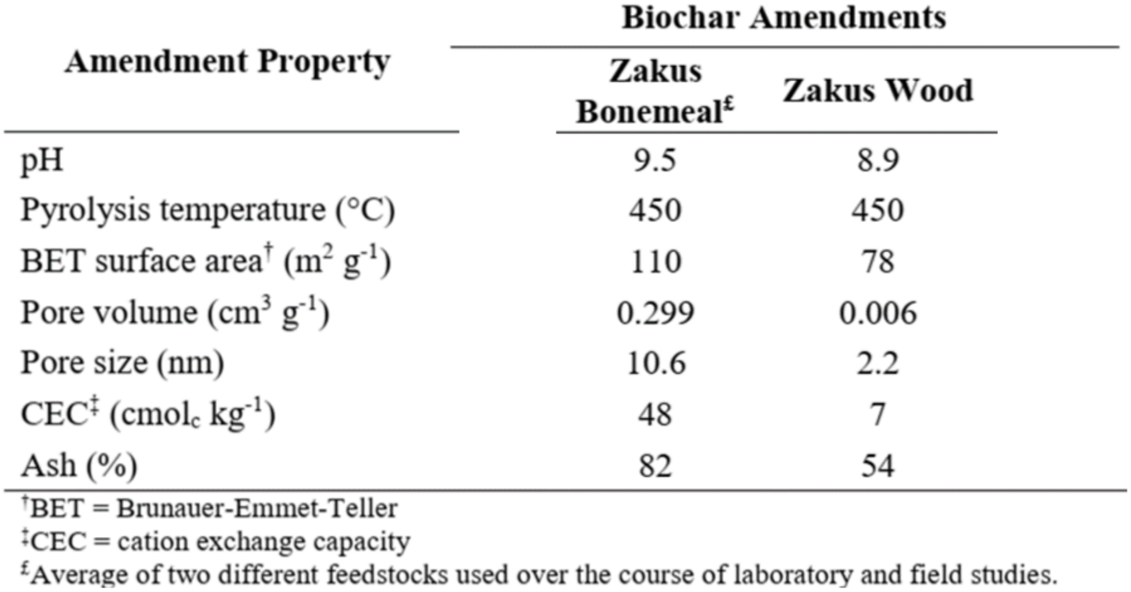
Figure 3. Open burning of slash, Yukon –Fall 2018 (Lucas, 2019b).

Figure 4. Open burning of slash (close-up), Yukon –Fall 2018 (Lucas, 2019b).

Figure 5. Operation of a Low tech/pop-up unit, releasing smoke (Garcia-Perez, 2010).

B. Properties of biochars used by Karppinen (2018)

Table 5. Characterisation of biochars used in laboratory and field studies (adapted from Karppinen, 2018).

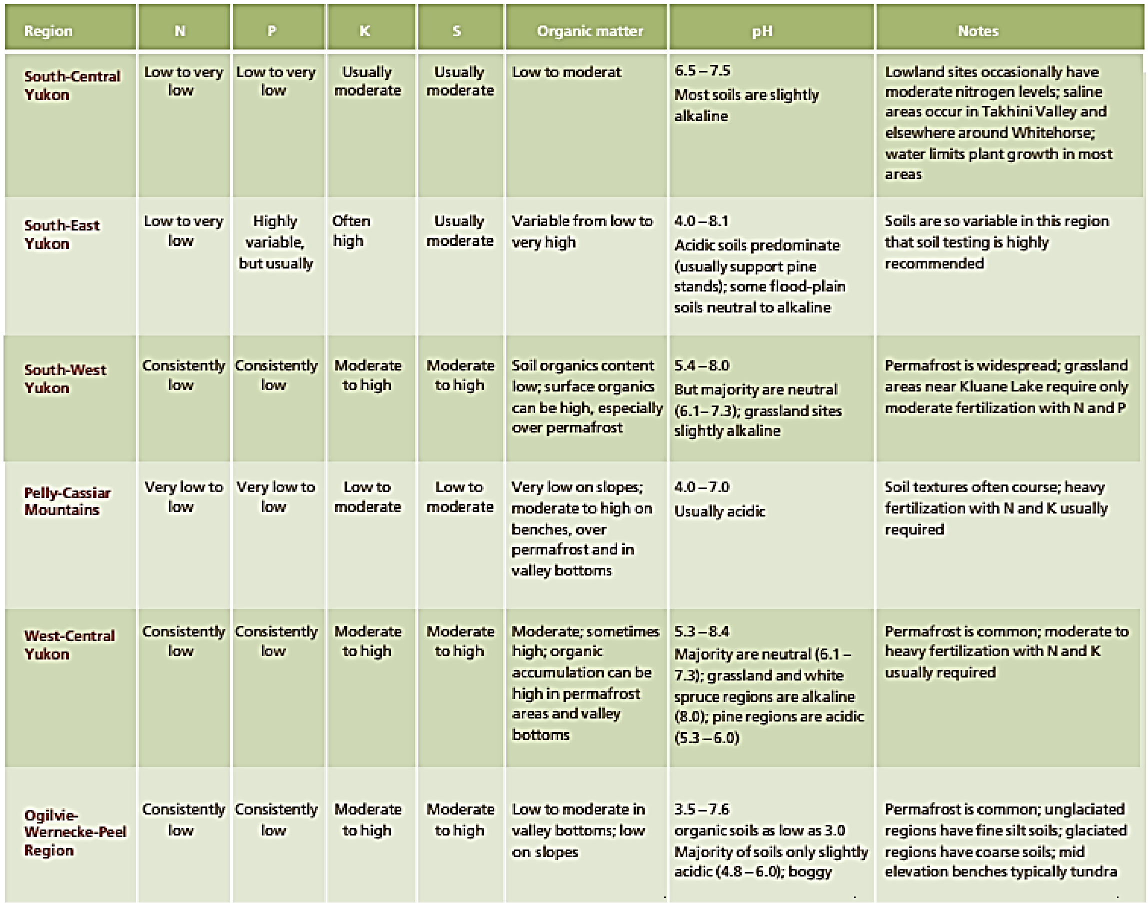


Amendment Property	Biochar Amendments	
	Zakus Bonemeal£	Zakus Wood
pH	9.5	8.9
Pyrolysis temperature (°C)	450	450
BET surface area† ($m^2\ g^{-1}$)	110	78
Pore volume ($cm^3\ g^{-1}$)	0.299	0.006
Pore size (nm)	10.6	2.2
CEC‡ ($cmol_c\ kg^{-1}$)	48	7
Ash (%)	82	54

†BET = Brunauer-Emmet-Teller
‡CEC = cation exchange capacity
£Average of two different feedstocks used over the course of laboratory and field studies.

C. Regional soil condition trends in Yukon

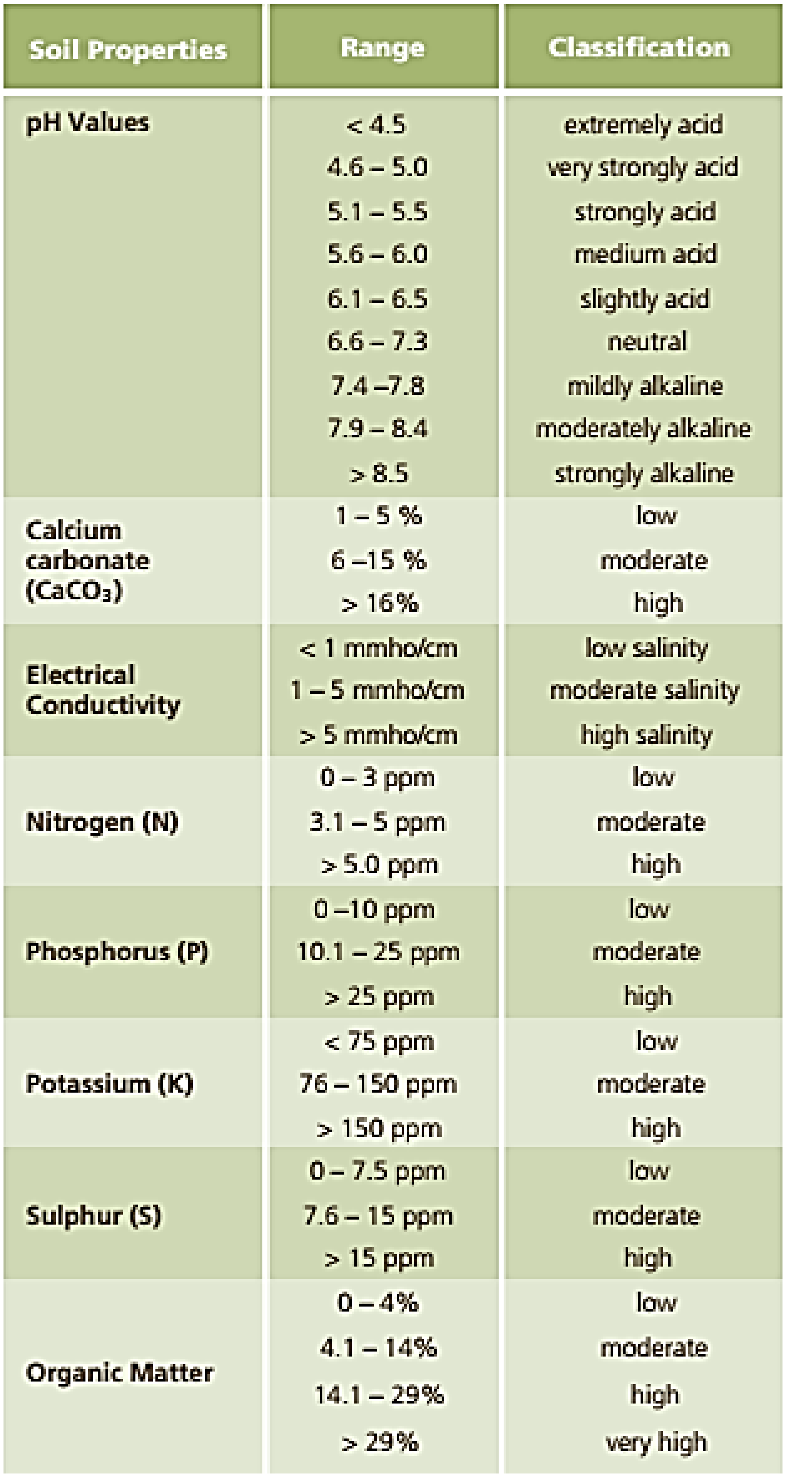
Table 6. Regional trends in soil conditions and nutrient status across Yukon (adapted from Matheus and Omtzigt, 2012).



Region	N	P	K	S	Organic matter	pH	Notes
South-Central Yukon	Low to very low	Low to very low	Usually moderate	Usually moderate	Low to moderat	6.5 – 7.5 Most soils are slightly alkaline	Lowland sites occasionally have moderate nitrogen levels; saline areas occur in Takhini Valley and elsewhere around Whitehorse; water limits plant growth in most areas
South-East Yukon	Low to very low	Highly variable, but usually	Often high	Usually moderate	Variable from low to very high	4.0 – 8.1 Acidic soils predominate (usually support pine stands); some flood-plain soils neutral to alkaline	Soils are so variable in this region that soil testing is highly recommended
South-West Yukon	Consistently low	Consistently low	Moderate to high	Moderate to high	Soil organics content low; surface organics can be high, especially over permafrost	5.4 – 8.0 But majority are neutral (6.1 – 7.3); grassland sites slightly alkaline	Permafrost is widespread; grassland areas near Kluane Lake require only moderate fertilization with N and P
Pelly-Cassiar Mountains	Very low to low	Very low to low	Low to moderate	Low to moderate	Very low on slopes; moderate to high on benches, over permafrost and in valley bottoms	4.0 – 7.0 Usually acidic	Soil textures often course; heavy fertilization with N and K usually required
West-Central Yukon	Consistently low	Consistently low	Moderate to high	Moderate to high	Moderate; sometimes high; organic accumulation can be high in permafrost areas and valley bottoms	5.3 – 8.4 Majority are neutral (6.1 – 7.3); grassland and white spruce regions are alkaline (8.0); pine regions are acidic (5.3 – 6.0)	Permafrost is common; moderate to heavy fertilization with N and K usually required
Ogilvie-Wernecke-Peel Region	Consistently low	Consistently low	Moderate to high	Moderate to high	Low to moderate in valley bottoms; low on slopes	3.5 – 7.6 organic soils as low as 3.0 Majority of soils only slightly acidic (4.8 – 6.0); boggy	Permafrost is common; unglaciated regions have fine silt soils; glaciated regions have coarse soils; mid elevation benches typically tundra

D. Criteria for evaluating soil properties and nutrient status

Table 7. Criteria for evaluating soil properties –including nutrient status, based on data from soil testing (adapted from Matheus and Omtzigt, 2012).



Soil Properties	Range	Classification
pH Values	< 4.5	extremely acid
	4.6 – 5.0	very strongly acid
	5.1 – 5.5	strongly acid
	5.6 – 6.0	medium acid
	6.1 – 6.5	slightly acid
	6.6 – 7.3	neutral
	7.4 –7.8	mildly alkaline
	7.9 – 8.4	moderately alkaline
	> 8.5	strongly alkaline
Calcium carbonate ($CaCO_3$)	1 – 5 %	low
	6 –15 %	moderate
	> 16%	high
Electrical Conductivity	< 1 mmho/cm	low salinity
	1 – 5 mmho/cm	moderate salinity
	> 5 mmho/cm	high salinity
Nitrogen (N)	0 – 3 ppm	low
	3.1 – 5 ppm	moderate
	> 5.0 ppm	high
Phosphorus (P)	0 –10 ppm	low
	10.1 – 25 ppm	moderate
	> 25 ppm	high
Potassium (K)	< 75 ppm	low
	76 – 150 ppm	moderate
	> 150 ppm	high
Sulphur (S)	0 – 7.5 ppm	low
	7.6 – 15 ppm	moderate
	> 15 ppm	high
Organic Matter	0 – 4%	low
	4.1 – 14%	moderate
	14.1 – 29%	high
	> 29%	very high

E. IBI (2015b) biochar quality standards

Test Category A: Basic Utility Properties (Required for All Biochars)			
Parameter	**Criteria[1]**	**Unit**	**Test Method[2]**
Moisture	Declaration	% of total mass, dry basis	ASTM D1762-84 Standard Test Method for Chemical Analysis of Wood Charcoal (specify measurement date with respect to time from production)
Organic Carbon (C_{org})	10% Minimum Class 1: ≥60% Class 2: ≥30% and <60% Class 3: ≥10% and <30%	% of total mass, dry basis	Total C and H analysis by dry combustion-IR detection. Inorganic C analysis by determination of CO_2-C content with 1N HCl, as outlined in ASTM D4373 Standard Test Method for Rapid Determination of Carbonate Content of Soils. Organic C calculated as Total C – Inorganic C. See Appendix 7 for H:C_{org} discussion.
H:C_{org}	0.7 Maximum	Molar ratio	
Total Ash	Declaration	% of total mass, dry basis	ASTM D1762-84 Standard Test Method for Chemical Analysis of Wood Charcoal
Total Nitrogen	Declaration	% of total mass, dry basis	Dry combustion-IR detection following the same procedure for total C and H above.
pH	Declaration	pH	pH analysis procedures as outlined in section 04.11 of TMECC (2001) using modified dilution of 1:20 biochar:deionized H_2O (w:v) and equilibration at 90 minutes on the shaker, according to Rajkovich et al. (2011). See Appendix 5 for further information.
Electrical Conductivity	Declaration	dS/m	EC analysis procedures as outlined in section 04.10 of TMECC (2001) using modified dilution of 1:20 biochar:deionized H_2O (w:v) and equilibration at 90 minutes on the shaker, according to Rajkovich et al. (2011). See Appendix 5 for further information.
Liming (if pH is above 7)	Declaration	% $CaCO_3$	AOAC 955.01 potentiometric titration on "as received" (i.e., wet) samples. Use dry weight to calculate % $CaCO_3$ and report "per dry sample weight".
Particle size distribution	Declaration	% <0.5 mm; % 0.5-1 mm; % 1-2 mm; % 2-4 mm; % 4-8 mm; % 8-16 mm; % 16-25 mm; % 25-50 mm; % >50 mm	Progressive dry sieving with 50 mm, 25 mm, 16 mm, 8mm, 4mm, 2 mm, 1 mm, and 0.5 mm sieves.

Test Category B: Toxicant Assessment (Required for All Biochars)

Parameter	Range of Maximum Allowed Thresholds		Test Method[4, 5, 6]
Germination Inhibition Assay	Pass/Fail		OECD methodology (1984) using three test species, as described by Van Zwieten et al. (2010). See Appendix 5 for further information.
Polycyclic Aromatic Hydrocarbons (PAHs), total (sum of 16 US EPA PAHs)[7]	6 – 300	mg/kg[8] dry wt	US EPA 8270 (2007) using Soxhlet extraction (US EPA 3540) and 100% toluene as the extracting solvent
Dioxins/Furans (PCDD/Fs)[9]	17	ng/kg WHO-TEQ[10] dry wt	US EPA 8290 (2007)
Polychlorinated Biphenyls (PCBs)[11]	0.2 – 1	mg/kg dry wt	US EPA 8082 (2007) or US EPA 8275 (1996)
Arsenic	13 – 100	mg/kg dry wt	TMECC (2001)
Cadmium	1.4 – 39	mg/kg dry wt	TMECC (2001)
Chromium	93 – 1200	mg/kg dry wt	TMECC (2001)
Cobalt	34 – 100	mg/kg dry wt	TMECC (2001)
Copper	143 – 6000	mg/kg dry wt	TMECC (2001)
Lead	121 – 300	mg/kg dry wt	TMECC (2001)
Mercury	1 – 17	mg/kg dry wt	US EPA 7471 (2007)
Molybdenum	5 – 75	mg/kg dry wt	TMECC (2001)
Nickel	47 – 420	mg/kg dry wt	TMECC (2001)
Selenium	2 – 200	mg/kg dry wt	TMECC (2001)
Zinc	416 – 7400	mg/kg dry wt	TMECC (2001)
Boron	Declaration	mg/kg dry wt	TMECC (2001)
Chlorine	Declaration	mg/kg dry wt	TMECC (2001)
Sodium	Declaration	mg/kg dry wt	TMECC (2001)

Test Category C: Advanced Analysis and Soil Enhancement Properties (Optional for All Biochars)

Parameter	Criteria	Unit	Test Method[12]
Mineral N (ammonium and nitrate)	Declaration	mg/kg	2M KCl extraction followed by spectrophotometry (Rayment and Higginson 1992)
Total Phosphorus & Potassium (P&K)*	Declaration	% of total mass, dry basis	Modified dry ashing followed by ICP (Enders and Lehmann 2012)
Available P	Declaration	mg/kg	2% formic acid followed by spectrophotometry (Wang et al. 2012)
Volatile Matter	Declaration	% of total mass, dry basis	ASTM D1762-84 Standard Test Method for Chemical Analysis of Wood Charcoal
Total Surface Area	Declaration	m^2/g	ASTM D6556 Standard Test Method for Carbon Black – Total and External Surface Area by Nitrogen Adsorption. See Appendix 5 for further information.
External Surface Area	Declaration	m^2/g	

* Total K is sufficiently equivalent to available K for the purpose of this characterization

F. European biochar quality standards (EBF, 2019)

6. Biochar properties

It is not the task and purpose of the EBC certificate to provide a complete physico-chemical characterization of biochar. The costs of analyses for such a characterization would go beyond economically reasonable limits. Rather, it is crucial for the EBC certificate to guarantee compliance with all environmentally relevant limit values and to declare all product characteristics relevant to agricultural practice.
The permissible test methods as well as the analytical methods for the individual parameters are detailed in Chapter 13.

6.1 The biochar's carbon content must be higher than 50% of the dry mass (DM). Pyrolysed organic matter with a carbon content lower than 50% are classified as Pyrogenic Carbonaceous Material (PCM).

The organic carbon content of pyrolysed biomass fluctuates between 5% and 95% of the dry mass, dependent on the feedstock and process temperature used. For instance the carbon content of pyrolysed poultry manure is around 25%, while that of beech wood is around 85% and that of bone is less than 10%.
When using mineral-rich feedstocks such as animal manure, the pyrolysed products may contain more ash than carbon. Such pyrolysed matter with carbon contents below 50% are therefore not classified as biochar but as Pyrogenic Carbonaceous Material (PCM).
When PCM meet all other threshold criteria of this biochar certificate, they may be marketed as EBC certified Pyrogenic Carbonaceous Material (PCM).

6.2 The molar H/Corg ratio must be less than 0.7

The molar H/Corg ratio is an indicator of the degree of carbonisation and therefore of the biochar stability. The ratio is one of the most important characterising features of biochar. Values fluctuate depending on the biomass and process used. Values exceeding 0.7 are an indication of non pyrolytic chars or pyrolysis deficiencies (Schimmelpfennig and Glaser, 2012).

6.3 The molar O/Corg ratio must be less than 0.4

In addition to the H/Corg ratio, the O/Corg ratio is also relevant for characterising biochar and differentiating it from other carbonisation products (Schimmelpfennig and Glaser, 2012). Compared to the H/Corg ratio, direct measuring of the O content is expensive and not standardized. Therefore the calculation of the O content from C, H, N, S and ash content is accepted.

6.4 Volatile Organic Compounds (VOC)

During the pyrolysis process aromatic carbon, carbonates and a multitude of divers volatile organic compounds are formed. The later constitute a large part of the pyrolysis gas that partly condensates on biochar surfaces and pores. These condensed pyrolysis gas compounds are substantial constituents of biochar materials (Spokas et al., 2011; Yang et al., 2013), are essential for certain biochar functions and thus necessary for the

characterisation of biochar and PCM. Moreover, the VOC-content is an important indicator for the evaluation of the pyrolysis process.
Permitted test methods: Thermal-Gravimetric-Analysis (TGA)
Principle: The TGA determines the loss of weight of the volatile matter according to the temperature without oxygen.
(Not obligatory for producers of less than 50 t biochar or PCM per year)

6.5 The biochar nutrient contents with regard to nitrogen, phosphorus, potassium, magnesium and calcium must be provided.

The nutrient contents of different biochars are subject to major fluctuations. It has to be considered that these nutrients may only partly be available to plants. They may take decades before entering the biological life cycle. The nutrient availability of the phosphorus found in biochar is for instance only 15% in the first year, that of nitrogen a mere 1%, while that of potassium can reach 50% (Camps-Arbestain et al., 2015).
Permitted test methods: DIN EN ISO 17294 – 2 (E29), DIN EN ISO 11885
(Specify for each batch)

6.6 The following thresholds for heavy metals must be kept

The following maximum values for heavy metals correspond - for the basic quality grade - to Germany's Federal Soil Protection Act (Bundes-Bodenschutzverordnung or BBodSchV), and - for the premium quality grade - to Switzerland's Chemical Risk Reduction Act, Appendix 2.6 on recycling fertilisers. The respective thresholds refer to the biochar's total dry mass (DM):

basic: Pb < 150 g/t DM; Cd < 1,5 g/t DM; Cu < 100 g/t DM; Ni < 50 g/t DM; Hg < 1 g/t DM; Zn < 400 g/ t DM; Cr < 90 g/t DM; As < 13 g t^{-1} TM
premium: Pb < 120 g/t DM; Cd < 1 g/t DM; Cu < 100 g/t DM; Ni < 30 g/t DM; Hg < 1 g/t DM; Zn < 400 g/t DM; Cr < 80 g/t DM; As < 13 g t^{-1} TM

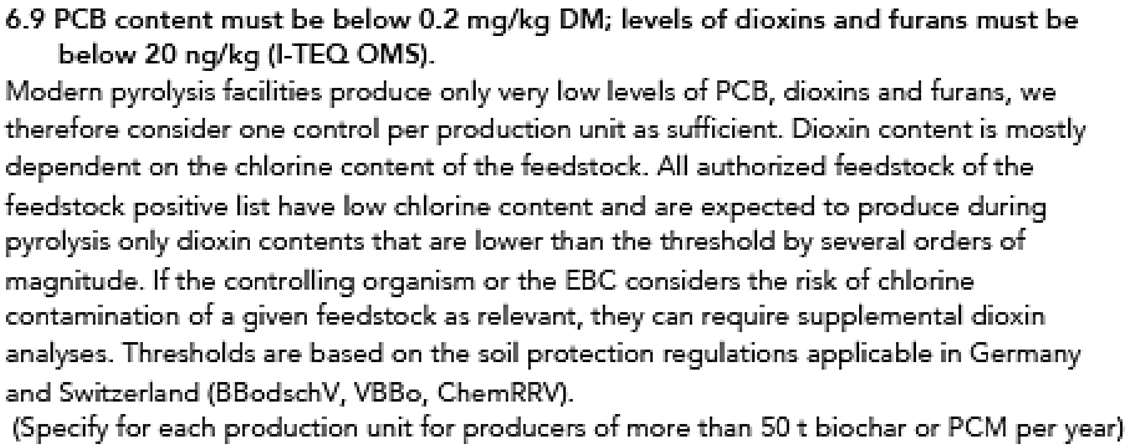
Beside some few heavy metals that are volatile at pyrolysis temperatures, the amount of heavy metals contained in the originally feedstock will remain in the final product. Therefore, most heavy metals are more concentrated in the biochar than in the original biomass. However biochar is able to very effectively bind a number of heavy metals, thereby immobilising them for a considerable long time.
As the quantities of biochar used in agriculture are relatively low compared to those of compost and manure, toxic accumulation of heavy metals could practically be ruled out.

Abrasion in connection with the use of chromium-nickel steels in the construction of pyrolysis reactors may lead, especially in the first weeks of production, to an increased nickel contamination of biochar. For biochar with a nickel load of up to 100 g / t TM, a one-off exemption may be applied for, according to which these biochars may be used for non agronomic uses or for composting, provided that the applicable limit values of the finished compost are complied with.

6.7 pH, bulk density, water content and specific surface area.
The biochar's pH value is an important criterion with regard to its specific use in substrates, soil amendments, or for binding nutrients in animal husbandry.
Details on bulk density and water content are necessary for the production of homogeneous substrate mixtures or filter ingredients requiring constant carbon contents.
The specific surface area is a measure of a biochar's quality, and a control value for the pyrolysis method used.
The water holding capacity of a given biochar is a valuable indication on it's effectiveness in increasing a soil's water holding capacity and for humidity buffering when e.g. applied to the root zone. However, its analysis is not mandatory.

6.8 The biochar's PAH content (sum of the EPA's 16 priority pollutants) must be under 12 mg/kg DM for basic grade and under 4 mg/kg DM for premium grade biochar.
As in any combustion, pyrolysis also causes polycyclic aromatic hydrocarbons (PAHs) to be released (Fagernäs et al., 2012). Their amount is dependent in particular on production conditions (Bucheli et al., 2015). Modern pyrolysis methods allow a significant reduction of the PAH pollution. High PAH levels are an indication of unsatisfactory or unsuitable production conditions.
On the other hand, biochar is able to very effectively bind PAHs and is, therefore, used as air filter for removing PAHs from exhaust gases or for immobilising PAHs in contaminated soils (Li et al., 2014). The risk of PAH contamination, when using biochar in agriculture, is hence considered to be low, even if higher thresholds would be taken into account. Although some PAHs bound in biochar may become available to plants, this takes place at an even lower level than with compost, digestate or manure due to biochars' adsorptive capacity (Gomez-Eyles et al., 2013).
Nevertheless current approval practice indicates that the PAH threshold defined in the Swiss Chemical Risk Reduction Act (ChemRRV) will also apply to biochar and that an exemption on the grounds of biochar's sorption properties is hardly feasible. Therefore, the threshold for premium grade biochar corresponds to the PAH threshold defined in the Swiss Chemical Risk Reduction Act (ChemRRV), also used as a guideline in the Compost Act (Kompostverordnung). No PAH thresholds are specified yet in the European soil protection regulations for soil conditioners and organic fertilisers. The threshold for basic grade biochar is therefore based on a value which, taking the latest research into account, implies a minimum risk for soils and users.

Please note that, due to biochar's high adsorption properties, most standard methods for testing PAHs are unsuitable for biochar. According to researches carried out by Hilber et al. (2012), an extended Toluol extraction is needed before any suitably representative test value can be determined. DIN EN 15527: 2008-09 (with toluol extraction) proved to be close to the method of Hilber et al. (2012) and is admitted too (see chapter 13).



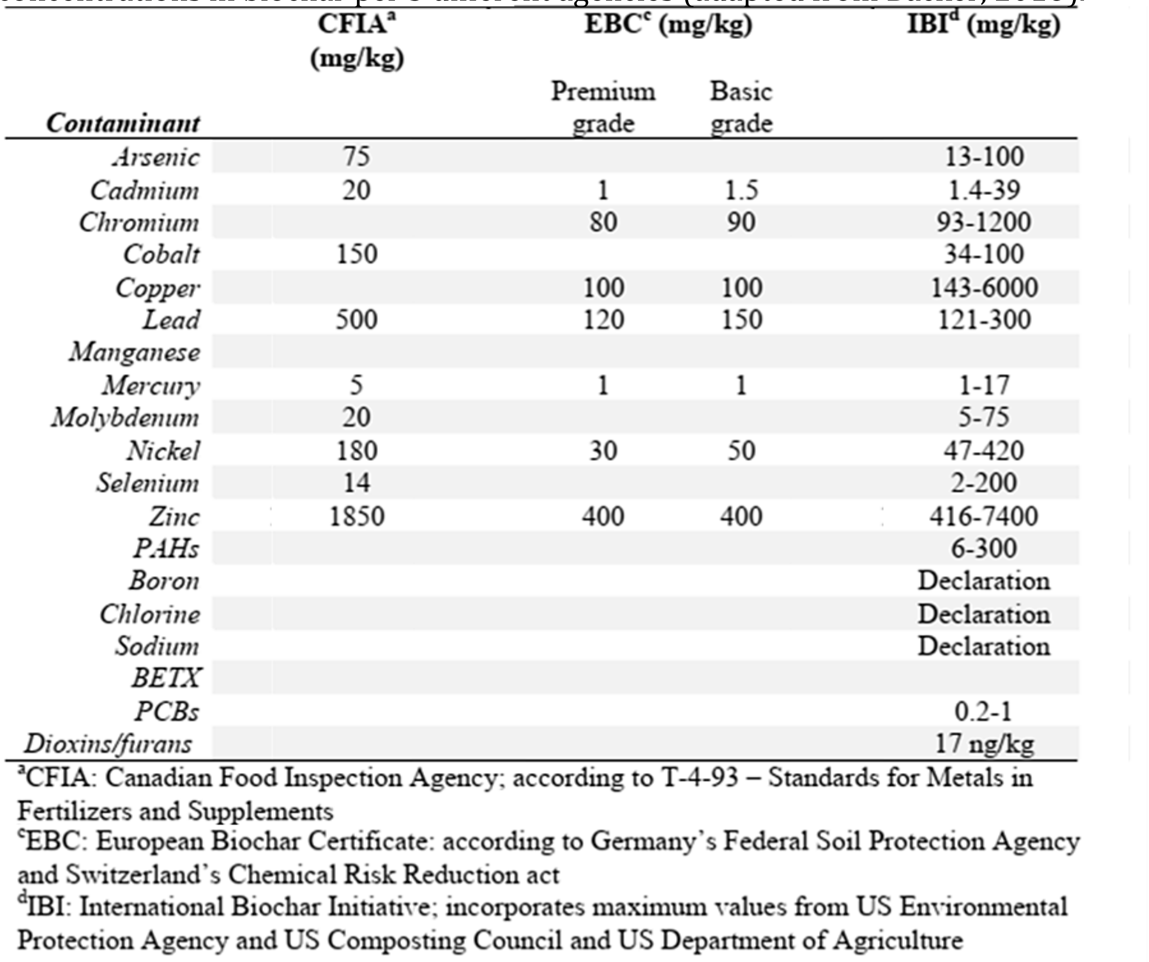
6.9 PCB content must be below 0.2 mg/kg DM; levels of dioxins and furans must be below 20 ng/kg (I-TEQ OMS).

Modern pyrolysis facilities produce only very low levels of PCB, dioxins and furans, we therefore consider one control per production unit as sufficient. Dioxin content is mostly dependent on the chlorine content of the feedstock. All authorized feedstock of the feedstock positive list have low chlorine content and are expected to produce during pyrolysis only dioxin contents that are lower than the threshold by several orders of magnitude. If the controlling organism or the EBC considers the risk of chlorine contamination of a given feedstock as relevant, they can require supplemental dioxin analyses. Thresholds are based on the soil protection regulations applicable in Germany and Switzerland (BBodschV, VBBo, ChemRRV).

(Specify for each production unit for producers of more than 50 t biochar or PCM per year)

G. Maximum thresholds for metals and other contaminants

Table 8. Comparison of maximum thresholds for acceptable metal and contaminant concentrations in biochar per 3 different agencies (adapted from Backer, 2016).



Contaminant	CFIA[a] (mg/kg)	EBC[c] (mg/kg)		IBI[d] (mg/kg)
		Premium grade	Basic grade	
Arsenic	75			13-100
Cadmium	20	1	1.5	1.4-39
Chromium		80	90	93-1200
Cobalt	150			34-100
Copper		100	100	143-6000
Lead	500	120	150	121-300
Manganese				
Mercury	5	1	1	1-17
Molybdenum	20			5-75
Nickel	180	30	50	47-420
Selenium	14			2-200
Zinc	1850	400	400	416-7400
PAHs				6-300
Boron				Declaration
Chlorine				Declaration
Sodium				Declaration
BETX				
PCBs				0.2-1
Dioxins/furans				17 ng/kg

[a]CFIA: Canadian Food Inspection Agency; according to T-4-93 – Standards for Metals in Fertilizers and Supplements

[c]EBC: European Biochar Certificate: according to Germany's Federal Soil Protection Agency and Switzerland's Chemical Risk Reduction act

[d]IBI: International Biochar Initiative; incorporates maximum values from US Environmental Protection Agency and US Composting Council and US Department of Agriculture

H. Other equipment suppliers and biochar vendors

Many companies seem to have gone out of business in the last few years –some of them very significant– for instance:

- Alterna Biocarbon (Prince George (Isle Pierre), BC)
  - Used the Van Aardt Process
- Biochar Engineering (CO)
- Biz Solutions LLC
- Carbon Brokers International (CO)
- Carbon Char Group (NJ)
- Diacarbon Energy Inc. (Merrit/Burnaby, BC)
  - Diacarbon's thermal biomass refinery (TBR) technology employed a continuous process pyrolysis to convert lower-value biomass into higher energy biofuels and products.
- Dynamotive/Dinamotive Energy Systems Corporation (Vancouver, BC)
  - Had acquired a patent from Resource Transforms Ltd. (RTI) in 2000)
  - Applied a unique bubbling fluidized bed technique, in which the biomass is rapidly heated by introducing the particles in a fluid bed of hot (usually) sand particles, and the bed is heated indirectly.
- Ecovolve (Jason Aramburu, NY)
- Infused Seed Balls (Talby Mckay, Nanaimo BC)
- Integro Earth Fuels Inc./NuCoal (NC)
- Pacific Pyrolysis
  - Pacific Pyrolysis Pty Ltd (PacPyro) had developed and commercialized a slow-pyrolysis technology that produced renewable energy and a proprietary biochar called Agrichar™.
- Prasino Group (Alberta)
- Pyrolyzer (FL)
- Pyrovac Group (Qc)
  - Designed and constructed a 3000 kg/h vacuum pyrolysis plant for the conversion of softwood bark residues into bio-oils and biochar.
  - In 2012 the plant was dismantled and moved to Oregon.
- R&A Energy Solutions (OH)
- Renewable Oil International LLC (Alabama)
- Rocket Stove (WA)
- Syngest (IA)

Other companies offer equipment that cannot process woody material (e.g. agricultural waste or animal bones only) or produce a char that is not suitable for agricultural use, for instance:

- HM3 Energy (OR)
- 3R Agrocarbon /formerly Terra Humana Ltd. (Sweden)

Yet others only offer the end-product (biochar), and not the equipment, for instance:

- AgBiochar LLC (CA)
- AirTerra (Rob Lavoie, Alberta)
- Aries Clean Energy – Aries Green (Franklin, TN)
- Biochar Supreme – Black Owl Biochar (WA)
- BioFire (Tunisia)
- Black Bear Biochar (UK)
- Blue Sky Biochar (Thousand Oaks CA, USA)

- Byron Biochar (Australia)
- CarboCulture (California)
- Carbon Cycle (Germany)
- Carbon Resources (Florida)
- CharGrow (Asheville, NC)
- CoolPlanet – CoolTerra Biochar (Greenwood Village, CO)
- Ecoera (Sweden)
- Green State Biochar (Vermont)
- Haliburton Forest and Wild Life Preserve (Ontario)
- La Carbonerie (France)
- Miller Soils – Biochar-Based Growing Solutions, e.g. Red's Premium Biochar (CO)
- NovoCarbo – NovoTerra Biochar (Germany)
- Oxford Biochar (UK)
- Pacific Biochar /*formerly* Landscape Ecology – Josiah Hunt (HI)
- Pure Life Carbon (Alberta)
- SEEK Organic Biochar (China)
- Terra Char (Columbia, MO)
- The American Biochar Company (Niles, MI)
- The American Root Company – Big Foot Biochar/Mycorrhizae (OR, USA)
- Titan Clean Energy Products (Saskatchewan)
- Wakefield Biochar (Columbia, MO)
- Zilkha Biomass Energy (AB)

I. Contact list

Table 9. Pyrolysis and Biochar specialists and consultants, inside and outside of Yukon.

Business name (Representative(s)) -Location + contacts	**Specialty**
Agrinova -Alma/Mashteuiatsh, Qc	Can tailor-make biochar, using their Biogreen pyrolyser. State of the art laboratory to fulfill the needs for R&D and biochar analysis.
Alberta Innovates Technology Futures (AITF) -Alberta	In collaboration with Canadian Wood Fiber Centre (CWFC)
Australia-New Zealand Biochar Initiative	
Biochar consulting (Lloyd Hafferty) -ON	
Biochar Farms -USA	Biochar Farms was established to provide practical, accessible, and objective information about biochar production and its application to soils.
Biochar Solutions -Canondale, CO	
Biochar for Sustainable Soils (B4SS) -International	Funded by the Global Environment Facility (GEF). The United Nations Development Programme (UNEP) is the implementing agency.
Biopterre -Qc	
Biomass Technology Group (BTG) -The Netherlands	They offer research and technology development (RTD), including contractual research.
Canadian Biomass Energy Research (CBER) Ltd (Cornelius Suchy) -Revelstoke, BC Tel.: 250-814 -7184 info@biomassenergyresearch.ca	CBER is a consulting engineering firm with a mission to promote clean, sustainable and successful biomass to energy projects in Canada.
Delaney Forestry Services (Matt Delaney) -OR	

Duteau Bioresource Contracting (Michel Duteau) YT	
Eprida -Georgia	
GECA Environnement (Suzanne Allaire) -Québec, Qc Tel. : 581-305-3374 ceo@geca-environment.com	
Finger Lakes Biochar	'Plant Waste Wisely'
Ithaka Institute (Hans-Peter Schmidt, Head of the Institute) -Based in Germany, with offices in a variety of countries, including USA	
Laberge Environmental Services (Ken Nordin) -YT	
NovoCarbo -Germany	
Natural Resources Canada/Ressources Naturelles Canada (Sebnem Madrali, research engineer; and Guy Tourigny) -Bells Corner, ON	Biomass and Fuels CanmetENERGY: Ottawa Bioenergy Systems Research Group Program Goal: Increasing utilization of biomass
New England Biochar (Bob Wells) -Massachussetts	
Northern Biomass Consulting (Talby McKay) -Prince George, BC	Also owns 'Northern Bio-Carbon Processing' and 'Infused Seed Balls'
Pacific Northwest Biochar Initiative -OR, CO, WA	
Phoenix Energy -CA	
Pyrovac	Developing, designing and constructing industrial pyrolysis plants

(Christian Roy) -Saguenay, Qc	
Ragnar Original Innovation (ROI) -Chester, NH *Acquired in October 2019* by Tigercat -Brantford, ON	They offer on-site carbonizing (leased and contracted services) through Clean Air Combust LLC, a wholly owned subsidiary of ROI Blackwood Solutions (Bloomington, IN) has a Carbonator 500 unit and offer on-site carbonizing Biocarbon Forward (Qualicum Beach, BC) also has a Carbonator and offer on-site carbonizing Prairie Creek Energy Services (AB) also has an EnviroSaver unit…
Rodale Institute -Kutztown, PA	
Sixth Element Management	
T.R. Miles Technical Consultants -Portland, OR	We assist the development, design and installation of Agricultural and Industrial Systems for Materials Handling, Air Quality and Biomass Energy.
TSS Consultants (Frederick Tornatore, Chief Technology Officer)	
Voices for Good Air -BC	Environment and Climate Change Canada has awarded Voices for Good Air (VFGA) a $100,000 **EcoAction Community Funding Program** grant for its 'Forest Waste to Biochar' initiative.
VTGreen (Subsidiary of ETIA) -France Tel: (33) 664 5301 17 Mail: contact@vtgreen.fr	Our activities include research, the development of bio-based products, support to the establishment of biomass thermochemical valorization chain. Our development activities are based on the Biogreen technology developed and patented by ETIA.
Western Forestry Conservation Association - Oregon, Washington, Idaho, Montana, Northern California and British Columbia	
University of New Zealand (Dr Jim Jones) -New Zealand	
Zakus Farm (Warren Zakus) -YT	
Other contacts mentioned at the end of WSP et al., 2014.	