Educational & Experimental Greenspace Design Optimized For Carbon Sequestration

BREE 495: Engineering Design 3
Final Design Report

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Abstract

Reducing greenhouse gas emissions from anthropogenic activity has become the focal concern of many countries' and institutions' climate action plans. Several approaches to solve or mitigate global warming are being researched from a wide variety of angles including infrastructure and technology-heavy solutions such as direct carbon capture. However, nature-based approaches to carbon sequestration have been less recognized. Thus, this project seeks to design a greenspace for the McGill University, Macdonald Campus (Québec, Canada) that can leverage the potential of terrestrial carbon sequestration processes to improve carbon sinks on campus and contribute to McGill University's 2040 carbon neutrality goal. Simultaneously, the site will serve as an educational and experimental resource for the testing and implementation of terrestrial carbon sequestration approaches. Several plant species and genuses were researched and reviewed for their carbon sequestration potential and suitability for the greenspace design. Engineered soil additives are also considered for their carbon sequestration capabilities, as well as the potential benefits offered to the plants by means of nutrient regulation and water absorption. Multiple carbon measurement and monitoring methods were explored to track and validate the performance of the greenspace. The various solutions were assessed, and the first design iteration of the greenspace was produced. The project was then further developed, and feedback was incorporated to produce the final greenspace design. Relevant standards, regulations, considerations, and risk assessment for the final design are discussed. Lastly, future developments of the project are outlined.

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List of Tables

List of Figures

Appendices

1. Introduction

As the effects of climate change increase in frequency and intensity, it is imperative to lower net carbon emissions in all existing and future anthropogenic and non-anthropogenic systems. The IPCC's 6th Assessment Report (2022) delivers a demanding and urgent call to action to reduce greenhouse gas emissions by nearly 50% by 2030. Globally, many countries, cities, companies and institutions have committed to reaching carbon neutrality by 2040, including McGill University. In 2020, the institution's net greenhouse gas emissions totaled 42,000 tons of CO_2e (McGill Office of Sustainability, 2021). The mission ahead is to lower that figure down to zero in the next 18 years. The path to carbon neutrality is often considered solely through the lens of carbon emission reduction and transitioning to less carbon-intensive alternatives; however, carbon removal and sequestration are often overlooked or unaccounted for in carbon neutrality plans yet constitute an opportune avenue to limit global warming to below 1.5℃.

There are various methods by which carbon sequestration, removal, and capture can be achieved. Resource intensive means such as direct air capture and carbon capture utilisation and storage have not yet been widely adopted due to the high cost currently associated with the technology. In contrast, terrestrial carbon sequestration is low-cost and naturally occurring in Earth's ecosystems as plants intake carbon dioxide from the atmosphere and photosynthesize. Approximately 25% of the world's carbon emissions is sequestered by forests globally and serve as significant carbon sinks (Natural Resources Canada, 2022). The integration of ecosystems and naturally occurring processes to facilitate urban sustainability is a growing area of innovation.

Specifically, greenspaces and green roofs have become popular sustainability initiatives in major metropolitan cities such as Toronto, Chicago, and Singapore. Greenspaces and green roofs not only reintroduce nature and park-like spaces into urban and suburban environments, but they are also widely adopted for their environmental benefits, which include heat island reduction, stormwater mitigation, and improved air quality (Shafique et al., 2018). However, the potential for carbon sequestration in greenspaces is not explored.

Thus, the goal of the greenspace design is to bridge the gap between terrestrial carbon sequestration and traditional greenspace design to expand carbon sequestration potential and accelerate the trajectory to achieving carbon neutrality at McGill University. The vision and objective of the project is to develop a greenspace on the Macdonald Campus of McGill

University to serve as a carbon sink, but also serve educational and experimental purposes. The greenspace will repurpose an unused plot of land on campus and be designed to sequester more than 2 t-C ha^{-1} yr^{-1}, which is currently the amount being sequestered by McGill's existing greenspaces, namely the Morgan Arboretum and Gault Nature Reserve. A recent article in the McGill Reporter quotes Jerome Conraud, the Director of Utilities and Energy Management, saying "we are looking to maximize carbon sequestration, say, at the Gault Nature Reserve or at the Morgan Arboretum" (Mcdevitt, 2021). This project proposes a plan to do exactly that. Additionally, the greenspace will be an educational space, teaching students and the public about terrestrial soil carbon. Furthermore, the greenspace will be an experimental site capable of testing different terrestrial carbon sequestration techniques. The findings from this experimental site can then be applied to McGill's existing greenspaces which, given their size, have much greater potential of making an impact.

The goal of this report is to follow and document each step of the design process of the greenspace project. A literature review of the most important aspects of the design including climate, plants, soil, and carbon measurement solutions was first carried out. Various potential solutions were then considered, proposed, discussed and decided on, including the previous design from the last academic semester. The final design is then presented including a two-dimensional model of the space, aboveground biomass, below ground biomass, and soil carbon quantification of the space, a review of relevant standards and regulations regarding the project, environmental, social, and economic considerations of the space, as well as risk management of the space and proposed future developments of the project. This is followed by some prototype solutions worked on including an *in situ* sensor design, *in situ* and *ex situ* soil carbon measurements, as well as educational considerations of the project, a website design, and stakeholder feedback solutions.

2. Literature Review

A thorough literature review was conducted as the preliminary step of design development. Since the greenspace is intended to be designed outdoors for the Macdonald Campus, researching climate and soil data for Sainte-Anne-de-Bellevue was first carried out to have a better understanding of the weather conditions that needs to be considered in the design. Historical weather data and a good understanding of the types of soils on campus would then allow proper research and decisions on the plants to be added to the design. In tandem, soil treatments, conditioners, and additives will be researched, as well as carbon monitoring systems and devices. Once a comprehensive literature review of the necessary topics was conducted, the next step of the design process could be carried out.

2.1. Macdonald Campus

Several different sites were initially considered for the greenspace design as numerous cities have undertaken initiatives to either reduce their environmental footprints, increase green infrastructure, or pledge to be carbon neutral all together. A few examples include TransformTO, the City of Toronto's initiative to be net zero by 2040, Vancouver's Greenest City Action Plan to improve the city's sustainability, the NYC Green Infrastructure Plan to promote green infrastructure in the city, and Montréal's carbon-neutrality commitment by 2050. Ultimately, Montréal, and specifically Macdonald Campus, was decided on for the design site. The principal reason behind the selection is the Macdonald Campus is where the Bioresource Engineering Department is based and thus, data can be collected and tested as needed for the project. It was also decided the greenspace could be used as a more educational site for biological carbon sequestration, as well as allow researchers to carry out experiments regarding the same topic. Therefore, being based near an environmental research campus such as Macdonald Campus would fulfill mutually beneficial needs. Having decades of previous environmental research carried out on campus also has accumulated a wealth of data useful for project research and planning. This principally includes the Sainte-Anne-de-Bellevue climate station nearby which can provide recorded weather data for analysis from past decades as well as soil data maintained by the Canadian Soil Information Service (CanSIS), both of which are managed and maintained by Environment Canada.

2.1.1. Climate

Several weather stations are spread out across the Montréal Island with two smaller stations in Sainte-Anne-de-Bellevue and a larger weather station in nearby Dorval at the Pierre-Elliott Trudeau International Airport. Data from both the closer Sainte-Anne station and the Dorval station were researched and considered when designing the greenspace as the smaller station is adjacent to Macdonald Campus and the larger airport station maintains higher quality records stretching back further in time.

Climate normals for Pierre Elliott Trudeau International Airport in Dorval document a wide variety of average temperatures across the year as expected in **Figure 1**. Peak summer temperatures reach a daily average of around 21°C with highs above 25°C and lows of 16°C. Winter average temperatures are around -10°C, with lows reaching -15°C and highs around -5°C. Precipitation is relatively much more consistent across the year with lows in February of around 66mm per month and highs in November reaching just under 100mm for the month. This corresponds well to the Köppen climate classification on the Montréal Area being a warm-summer humid continental climate zone. Thus, requiring consideration of plants adapted to cold winters and high levels of rainfall in addition to drainage considerations of the soil in the greenspace. If too much pavement is added to the space, water will not drain fast enough.

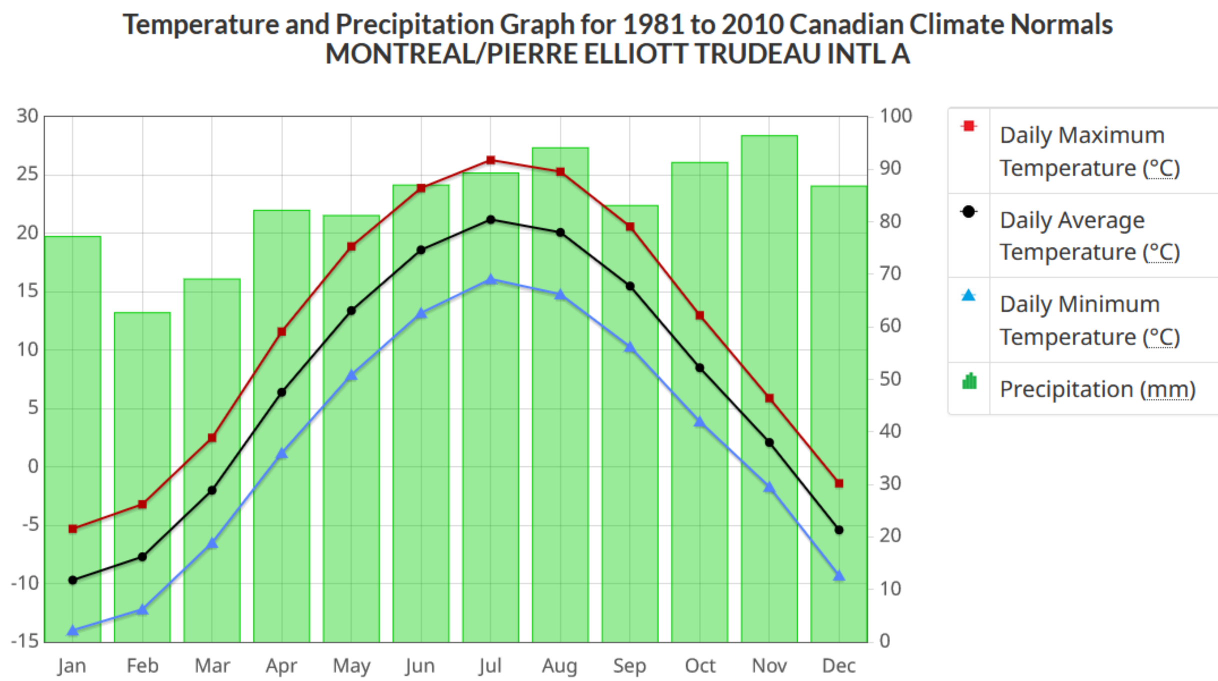

Figure 1. *Climate normals for Pierre Elliott Trudeau International Airport from 1981 to 2010 on Montréal Island (Environment Canada, 2022).*

After considering the average temperatures and precipitation of the site throughout the year, it is important to consider the site storm frequency and intensity. **Figure 2** depicts the Rainfall Intensity-Duration-Frequency curves for the Sainte-Anne-de-Bellevue weather station from 1963-2017. While any given greenspace is mostly plants and soil and thus drainage need not be a primary concern, large trees and large plots of grasses in addition to concrete paths may have an impact on the rainfall, especially for higher return periods. It is typical for engineering projects such as these to be designed with a 24 hour-25 year storm to strike a balance of accounting for large weather events and economic considerations (Martel et al., 2021).

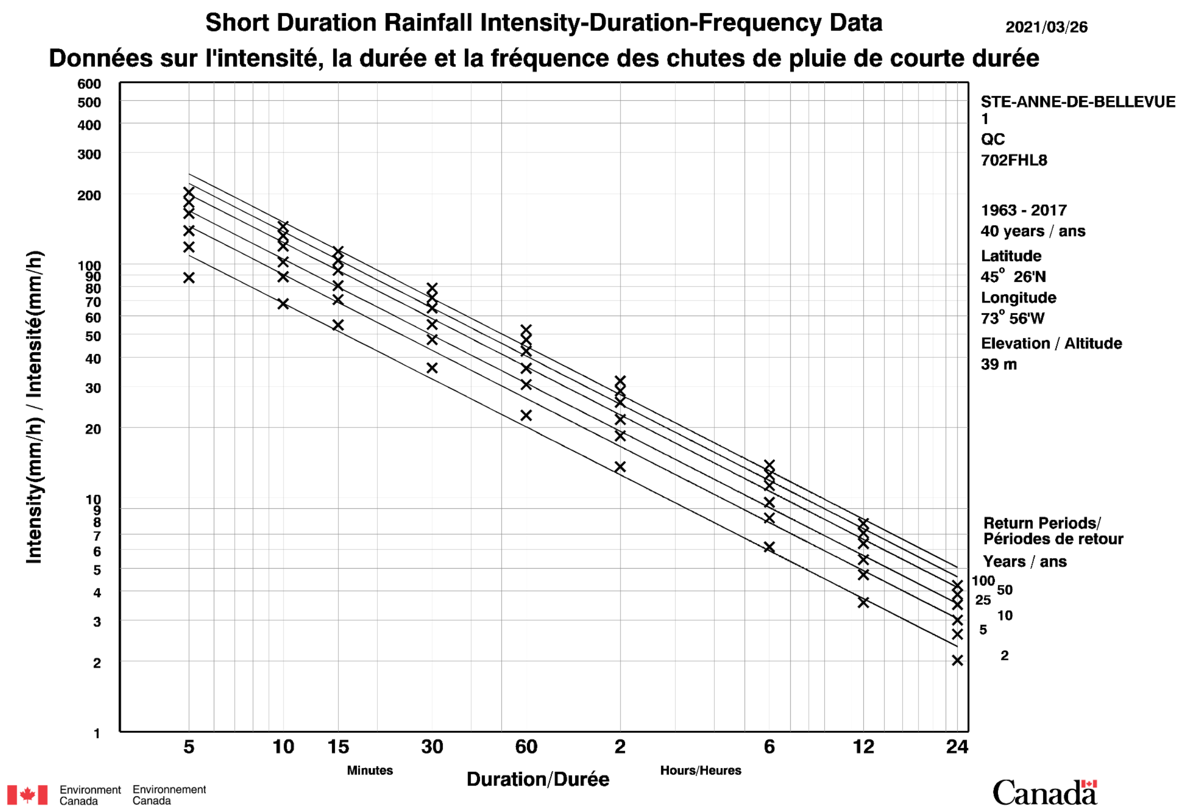

Figure 2. *Short Duration Rainfall Intensity-Duration-Frequency Data curves for the Sainte-Anne-de-Bellevue weather station (Environment Canada, 2022).*

2.1.2. Soil

Soil inherently carries several properties which can dramatically alter the plants that are able to grow in it, and with such a wide variety of soil compositions and properties just in Canada, it was deemed imperative to firmly understand the soil types on the west end of Montréal island and more specifically Macdonald Campus. While not highly detailed, the federal Canadian Soil Information Service (CanSIS) maintains an interactive map of the soil orders of Canada which specified the soil on the west end of the island as being Gleysolic. Characterized by its lack of oxygen due to chronic water saturation, the Canadian Society of Soil Science comments on these types of soils being predominantly clay-based with little ability for water to move through it (Canadian Society of Soil Science, 2022). This water saturation and lack of oxygen leads to anaerobic conditions in the soil which promotes a poor soil microbiome.

A soil survey conducted by Macdonald college in 1954 depicted in **Appendix 1** found the Macdonald soils to have low drainage with a predominantly clay-loam to clay texture profile (Lajoie & Baril, 1954). The soil was described with few scattered stones and not subject to erosion though eroded material may be deposited from nearby eroded soil (Lajoie & Baril, 1954). Sparse and small areas were found to have a sandy soil texture (Lajoie & Baril, 1954). The area was described as being suitable for some agriculture and dairy farming with suitable artificial drainage installed (Lajoie & Baril, 1954).

Given that clay soils are often described as having poor natural drainage properties and the soil survey corroborates this on Macdonald Campus, water drainage of the greenspace must be considered. The high precipitation levels observed at the Pierre Elliott Trudeau International Airport weather station combined with the poorly drained clay soils of the area may necessitate drainage installations. While artificial drainage has high environmental and economic costs in addition to disturbing the soil carbon content and microbiome, it should be considered if the plot is deemed inadequate for natural drainage.

Finally, the plant species decided must also consider the soil characteristics of the campus; plants chosen must be able to tolerate clay soils with relatively high water retention and possibly less aerobic environments in the soil then other more well-draining soils. These considerations can be taken by either carefully selecting non-native plant species which are able to tolerate soil and weather conditions such as these or by utilizing primarily native species to the west end of Montréal island.

2.2. Plant Species

The next literature review conducted was regarding various plant species as they are a central component to the design of a greenspace. Several different plant types were reviewed against a list of criteria which included their carbon sequestration potential, adaptability to climate change, lifespan, and growth rate. Highly considered was the growth rate and thus, the carbon sequestration potential over time of any given species. While some plants grow rapidly and immediately sequester relatively large amounts of carbon (e.g., shrubs), this method of carbon capture is short-term and depletes over time. In contrast, larger and slower-growing plants, such as trees, initially sequester very little carbon, but over time increase their carbon content exponentially, as depicted in **Figure 3** (Zhang et al., 2022). Therefore, a variety of slow-growing and fast-growing plants, as well as large and small plants were researched to achieve a relatively stable increase of carbon sequestration over time.

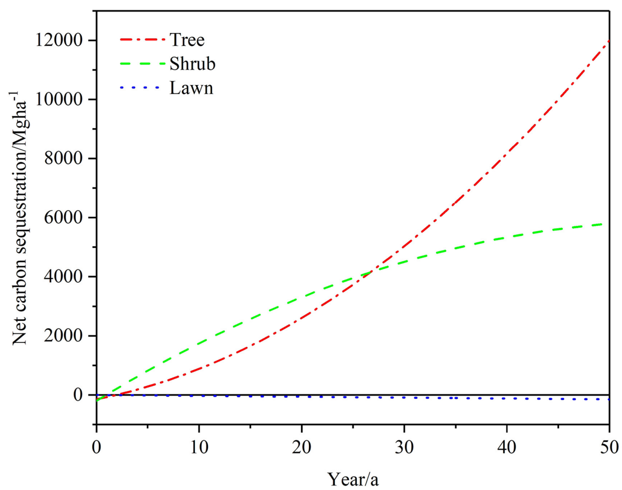

***Figure 3**. Compared net average carbon sequestered over a 50-year period between trees, shrubs, and lawn grass (Zhang et al., 2022).*

2.2.1. Trees

Four distinct tree species were considered in the design for a combination of their carbon sequestration potential, lifespan, growth rate, and adaptability to climate change. Trees were generally considered highly favourable for the design due to their longer lifespans, larger biomass content, and relatively high carbon sequestration potential when compared to other plant genuses. The longer lifespans and inherent slow growth of these plants, however, can delay significant carbon sequestration for up to two decades (Zhang et al., 2022). To address this issue, other families of plants were also considered.

2.2.1.1. Poplar (*P. x bernardii*)

Amongst all the plant species researched, hybrid poplar are some of the most well-documented and researched in the realm of carbon sequestration. Specifically, the *P. deltoides* x *P. tremuloides* hybrid poplar, often designated by the name *P. x bernardii* Boivin

(Demeritt, 1986), was found to sequester an average of 27.43 t-C ha^{-1} yr^{-1}, which is significantly higher than most tree species (Udawatta & Jose, 2011; Winans et al., 2015). Poplar trees on average grow four metres in height per year and reach maturity at around six years. Furthermore, the tree itself is able to be used for its wood products including pulp and ethanol production (Balatinecz & Kretschmann, 2001). These trees prefer more rural or suburban growing conditions with full sunlight; frequent watering is necessary combined with well-draining and slightly acidic soil (Berhongaray et al., 2013).

2.2.1.2. Pine (*Pinus strobus*)

Pinus strobus, also known as the Eastern White Pine, is a relatively medium-sized tree that requires very little maintenance and is tolerant to various weather conditions, preferring cooler temperatures and higher latitudes. While sensitive to heavily urbanised environments they often thrive in rural and suburban ecosystems, specifically with high sun and acidic soils, though it is tolerant of slightly alkaline soils (Betts, 1954). In terms of carbon sequestration, pine trees were found to sequester on average 7.92 t-C ha^{-1} yr^{-1} when measured via tree biomass converted to sequestered carbon (Bernal et al., 2018; Leverett et al., 2021; Udawatta & Jose, 2011; USDA, 2015). Over the average 150-year lifespan of *P. strobus*, large amounts of carbon can be sequestered above ground for relatively long periods of time.

2.2.1.3. Oak (*Quercus bicolor*)

Quercus bicolor is a relatively large oak tree found growing naturally on the river beds of the St. Lawrence River and prefers moist soil and high sunlight. This species is very adaptable to various growing conditions and is tolerant of relatively compact soils, different levels of sunlight, and little to no fertilisation or irrigation. However, these trees are more adapted to suburban and rural environments, not being very tolerant of highly urban surroundings (Rogers, 1990). *Q. bicolor* has been recorded to sequester around 3.77 t-C ha^{-1} yr^{-1} on average, though this can vary heavily (Bernal et al., 2018; Vesterdal et al., 2007; Wotherspoon et al., 2014). Given some oak trees have been observed with life spans over 600 years old (Rogers, 1990), these are a slow growing and long living species that in the short-term will sequester very little amounts of carbon, but over time will be very impactful environmentally. This long lifespan combined with a highly complex and deep root system makes it an appealing choice to include in a green space focused on carbon sequestration.

2.2.1.4. Beech (*Fagus sylvatica*)

Beech trees are traditionally very large with heights recorded as high as 50 ft, trunks with diameters reaching 3 ft, and recorded ages of up to 200 years. *Fagus sylvatica* is a species of deciduous beech that is native to western and central Europe with a preferred climate very similar to that of the greater Montréal area including full sun and temperatures averaging 25-35℃ in the summer. With a preference for loamy, moist, well-drained, and acidic soils, this species is ideal for Macdonald Campus and the banks of the St. Lawrence River (Prislan et al., 2019). *F. sylvatica* has been studied for several years regarding its carbon sequestration potential and has been recorded to sequester on average 8.15 t-C ha^{-1} yr^{-1} (Gratani et al., 2018; Nijnik et al., 2013). Combining its biomass, complex root system, age, and size this species is one of the most highly regarded in terms of its carbon sequestration potential.

2.2.2. Grasses

The current vegetation present on the Macdonald Campus is predominantly lawn grass. In addition to lawn grass, two other grass species were considered given the high carbon sequestration potential of grasslands in the Canadian prairies (Wang et al., 2014). Unlike forest ecosystems where carbon is mainly sequestered in the biomass of trees, grasslands primarily sequester carbon underground, forming a stable and resilient carbon sink (Dass et al., 2018).

2.2.2.1. Switchgrass (*Panicum virgatum*)

Switchgrass, also known as *Panicum virgatum*, is a C4 perennial grass species that grows during the warm season. *P. virgatum* is native to North America and found in prairies, open woods, and marches, and can grow in lowlands and floodplains, as well as in uplands (Vogel & Burson, 2004). Switchgrass grows 0.5-3 m tall and is broadly adapted and long-lived (Vogel & Burson, 2004). Switchgrass is known for its high productivity and fast growth and is suitable for cultivation on marginal land with low nutrient requirements (Jarecki et al., 2020). As a high biomass-yielding crop, switchgrass is used in pastures and for bioenergy production. *P.virgatum* is a species that has an extensive and deep root system, with a below to aboveground biomass ratio of approximately 2:1 (Monti et al., 2012). With respect to carbon sequestration, switchgrass can sequester around 2.76 t-C ha^{-1} yr^{-1} (Bernal et al., 2018; Collins et al., 2020; Liebig et al., 2008). In addition to its carbon sequestration potential, switchgrass is useful for reducing erosion and water pollution (Collins et al., 2010), making it a beneficial multipurpose species.

2.2.2.2. Miscanthus

Miscanthus, also commonly known as silvergrass, is similar to switchgrass in that it is also a C4, perennial, warm season grass. Miscanthus is native to Asia, but grows across North America, particularly in the Great Lakes region encompassing Ohio, Michigan, Illinois and Ontario (USDA, n.d.). North American miscanthus is between 3-10 ft tall and like switchgrass, around 50% of its biomass is made up by its root system (USDA, n.d.). The miscanthus hybrid *Miscanthus x giganteus* is a common crop cultivated in Ontario for its biomass and bioenergy production potential (Christian et al., 2008). The crop is also low maintenance, drought tolerant, and well-adapted for warmer climates (Graham et al., 2019). *Miscanthus x giganteus* is recorded to sequester around 1.50 t-C ha^{-1} yr^{-1} (Felten & Emmerling, 2012; McCalmont et al., 2015; Nakajima et al., 2018,), making it one of the grasses with the highest carbon sequestration potential.

2.2.2.3. Lawn Grass (*Poa pratensis*)

Given the ubiquity of standard lawn grass, this was used as a baseline of comparison when deciding on other plants to use in the greenspace. *Poa pratensis*, better known colloquially as Kentucky bluegrass, is one of the most common lawn grass species used but is often referred to as being carbon neutral or carbon positive (Zhang et al., 2022). These grasses typically have fairly complex root systems and thus decent terrestrial carbon levels, but this is due to their high irrigation and fertilisation levels, both of which are environmentally intensive inputs (Guertal, 2012). In addition, the maintenance often associated with turf grasses is typically fossil fuel driven in the form of lawn mowers, which contributes heavily to atmospheric carbon concentrations. While some studies performed such as Guertal (2012), Zirkle (2011), and Bandaranayake (2003) find lawn grass sequesters up to 1 t-C ha^{-1} yr^{-1}, other studies such as Zhang et al. (2022) found lawn grass to be a net carbon emitter. Thus, for calculations, lawn grass was assumed to be net carbon neutral which serves as a very suitable baseline.

2.2.3. Other Species

While conducting the literature review, two additional plant species were researched that have been associated with noteworthy carbon capture. Namely, red clover and apple trees. Both plants have properties unique from the aforementioned trees and grasses, such as fruit-bearing capabilities and visual agreeability.

2.2.3.1. Red Clover (*Trifolium pratense*)

The red clover, otherwise known as *Trifolium pratense*, is a short-lived perennial plant that grows best in areas with higher levels of precipitation. The legume *T. pratense* is associated with nitrogen-fixing bacteria and is regarded as a grassland plant species with mentionable influence on soil N availability as well as plant community production (Gillett, 2008; Van der Heijden et al., 2008). However, its role in impacting soil C has been less researched and is thus, ambiguous. A study conducted by De Deyn et al. (2010) found that under optimal circumstances the red clover was able to sequester 3.17 t-C ha^{-1} yr^{-1} and 0.35 t-C ha^{-1} yr^{-1}. Though it should be noted that this value was reduced upon termination of fertiliser use. The red clover has a relatively low tolerance to salinity and drought, and it must be adequately managed to reduce reseeding (Cover Crops Canada, n.d.). The species is native to Europe but grown for forage in Canada (Gillett, 2008).

2.2.3.2. Apple Trees

Apple trees are a member of the genus *Malus*, which is native to the temperate zone of the Northern hemisphere. Mature apple trees grow to be 4-12 m in height and prefer full sun. As for their relationship to carbon, apple trees have been reported to sequester on average around 4.2 t-C ha^{-1} yr^{-1} (Page, 2011; Scandellari et al., 2016; Wu et al., 2012). Wu et al. (2012) found that the apple trees reached peak carbon sequestration at age 18, followed by a decline until end of life. Moreover, it was discovered that the captured carbon would not offset the emissions associated with management practices before the age of maturity. However, this species does offer a unique product: fruit. With issues of climate change and population growth, food demand is expected to rise accordingly (Sharma et al., 2020). Not to mention, the fruit and flowering are aesthetically pleasing as well.

2.3. Soil

Research conducted on the amount of carbon sequestered in the soil relative to the carbon in the aboveground biomass varies by source, but Kumar et al. (2006) claims the amount of carbon sequestered in the soil is on average three times as much of that in the vegetation. Researching global carbon stocks in boreal forests, Bradshaw & Warkentin, 2015 estimated the quantities of carbon sequestered in Canadian boreal forest soil to be over three times greater than in the same forest vegetation. It is not uncommon to find literature claiming the amount of carbon naturally sequestered in soil is several times that of its biomass counterpart, and thus the soil biogeochemistry must be heavily considered when designing a greenspace for carbon sequestration. Soil health and its impacts on plant growth and carbon sequestration have been researched and will be considered in the final greenspace design. Engineered additives to soils have been researched and reviewed for their impact on the carbon sequestration potential as well as their benefits to plant growth.

2.3.1. Soil Health

Soil health is defined as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans" by the United States Department of Agriculture (USDA-NRCS, 2012). To properly define soil heath, it is important to distinguish inherent and dynamic soil health as defined by the Cornell University Soil Health Manual Series Fact Sheet Number 16-02 (Moebius-Clune et al., 2016). Inherent soil quality relates to the physical properties of the soil such as the geologic parent material and climate; these are properties that can't be changed with treatment or use and are inherent to the composition of the soil. Dynamic soil qualities by contrast are more related to soil health and vary based on soil use and management; these properties involve the soil microbiome and nutrient levels and can be significantly impacted or altered by human management.

The primary goal of soil health promotion is to foster a healthy and diverse soil microbiome. Soil health is primarily eroded by either disturbing the soil by digging, which disrupts the soil structure and releases oxygen and chemicals such as insecticides and pesticides that are detrimental to soil microbes. A healthy soil microbiome supports proper water infiltration, prevents weed growth, properly cycles nutrients, and augments carbon sequestration.

Due to these important parameters, maintaining proper soil health of the greenspace design is a high priority. As mentioned by Moebius-Clune et al. (2016), some characteristics of a healthy soil include good soil tilth, sufficient depth, high drainage, a high population of microorganisms, and no trace of toxic chemicals.

Thus, maintenance and fostering of a healthy soil microbiome must be addressed in the construction and ongoing use of the greenspace. Construction of the plot must be done in a manner to minimize soil disruption including path laying, planting, and erection of signage. Soil additives and conditioners, presented in the next section, have been extensively considered in the design to foster proper soil health and its maintenance. By addressing soil health and maintaining it throughout the lifetime of the design, higher carbon sequestration can be achieved with healthier and higher quality plants.

2.3.2. Soil Additives

Addition of natural or engineered materials to the soil is common throughout the world to achieve a wide variety of soil functions. Some of these additives are more popular than others, and some have been more researched and engineered compared to some which are more naturally occurring. Synthetic fertilizers and compost for example are commonly added to agricultural fields, much like what is seen in Québec, while some are more niche such as Biochar, which is still being researched for its industrial application, but dates back thousands of years to ancient times. Hydrogels have been identified for their unique properties but are almost always derived from petroleum which have limited their applications. Thus, bio-based hydrogels are gaining research popularity and their applications in the environment. A brief literature review of the most pertinent soil additives and conditioners was conducted to gauge their effectiveness and usefulness on a greenspace designed for carbon sequestration.

2.3.2.1. Compost

As defined by Haug (1993) in *The Practical Handbook of Compost Engineering*, the definition of compost is roughly "the biological decomposition of organic feedstocks under conditions that allow thermophilic temperatures to stabilize the product free of active seeds or pathogens which produces a soil conditioner that can beneficially be applied to soil." Due to Haug's well-rounded discussion of compost and its highly regarded nature among compost engineers, the majority of compost discussion in this report is sourced from his work.

Compost is beneficial and desirable for several reasons; it contributes to a circular economy by reducing waste and reliance on artificial fertilizers, it promotes a healthy soil microbiome in a way synthetic fertilizers can not, and valorizes otherwise useless waste. Compost can be made with a wide variety of biomass feedstocks though a good level of aeration, whether passive or active, is required. Most commonly food waste, tree leaves and branches, manure, livestock bedding, and biological industrial waste such as cardboards are used in compost production. Proper aeration, moisture content, and heat must be maintained and monitored throughout the composting process.

Compost typically progresses through three primary stages of development, all defined by the temperatures of the material; an initial mesophilic temperature is established at the beginning of the process where these organisms digest easily accessible macromolecules such as lipids and carbohydrates. After this stage, thermophilic microorganisms heat the compost dramatically for a sustained period. This high and maintained temperature, often above 60 degrees Celsius, has the effect of denaturing plant seeds, inactivating pathogens, and killing most other organisms which makes the final product safe for addition to near any soil. Finally, these high temperatures fall because most of the easily digestible nutrients have been metabolized already, and thus fungi grow rapidly to digest the more stubborn plant matter such as cellulose and lignin.

While the composting process releases carbon dioxide, it is a much more favourable process to the alternative anaerobic digestion of the organic matter that would occur in landfills otherwise. In addition, some of the nutrients in compost applied to soil inevitably volatilize and are lost to the atmosphere; while the process is imperfect, compost added to soil has undeniable benefits which drive its increasing popularity today. Compost has been shown to improve soil health and nutrient levels when added to soil which in turn fosters healthier plant growth which increases the carbon sequestered in the biomass.

2.3.2.2. Biochar

Biochar is the product of thermal decomposition of biomass into charcoal in the absence of oxygen, a process known as pyrolysis (Weber & Quicker, 2018). Thought to have originated thousands of years ago in the Amazon rainforest by natives burying charcoal in the soil (Chia et al., 2012), its addition has well-studied benefits to the plant life where it is buried. These soils to this day maintain an unusually high cation exchange capacity and pH, as well as high levels of phosphorus compared to the typical nutrient-poor soils of the unsettled rainforest (Glaser et al., 2001). Modern-day research has come to appreciate this phenomenon after having been relatively ignored for thousands of years and its modern form, termed Biochar, is being researched extensively as a soil additive to add nutrients to the soil and aid in soil nutrient regulation. While Biochar has a broad range of uses from power production to heat generation, its uniquely high carbon content has made it the target of research more recently for its potential in carbon sequestration and thus reducing greenhouse gas emissions. This most frequently takes the form of Biochar deposition in soils used to grow plants (Matovic, 2010).

Currently, Biochar is most commonly produced from undesirable crop residues such as tree bark and grasses (Matovic, 2010). In ideal scenarios today, these side products of crops are either composted or added directly back to the soil where they will decompose and release the carbon stored in biomass back to the atmosphere. Biochar hopes to adjust this cycle by decomposing this plant matter into charcoal instead where the carbon is largely sequestered and prevented from entering back into the atmosphere, and then is deposited into the soil as this is the most chemically stable solution (Matovic, 2010). This soil storage however also happens to be very beneficial for plants growing in it as the cation exchange, porosity, and water holding capacity properties of the charcoal are all hypothesised to be highly beneficial in terms of water and nutrient regulation in the soil (Weber & Quicker, 2018).

2.3.2.3. Bio-Based Hydrogels

Hydrogels are a three-dimensional network of polymer chains named after their high water holding capacity that is possible from water molecules being able to diffuse throughout the matrix and interact with the polymers (Godiya et al., 2020). While these polymer chains are often derived from petrochemicals in many of their applications today, biologically-based hydrogels are gaining increasing attention derived from sources such as corn zein and starch and their potential applications in the environment for uses such as pollutant removal and as soil additives are becoming increasingly researched (Guiherme et al., 2015).

While not directly a carbon sequestration method, bio-based hydrogels have been well-documented for their beneficial effects in soil and thus the plants grown in them. More productive and longer lasting biomass directly relates to higher rates of carbon sequestration and thus indirectly works to aid in carbon sequestration. Specifically, the chemical properties of hydrogels via their easily modifiable chemical groups either through different polymer derivatives or by chemical reactions to alter them (Peppas et al., 2020) have been documented to be beneficial for nutrient regulation in soils and their water absorption properties make water drainage and regulation much easier (Guiherme et al., 2015).

2.4. Carbon Measurement & Monitoring Systems

Implementation of carbon measurement and monitoring systems are critical to tracking and validating the performance of the greenspace and studying the carbon sequestered over time. The system will (1) provide the data necessary to conduct an informed analysis of the greenspace's outcomes, and (2) serve as the hands-on, experimental testing feature for students to learn about carbon sequestration. The data obtained from the system is a quantitative form of feedback that will guide design iterations and be an important reference for the client when scaling the project. Additionally, record of the data can initiate the standardization of carbon sequestration optimization as a core feature of future greenspace developments. To facilitate the learning and educational features of the design, the carbon measurement and monitoring system needs to be easy to learn and user-friendly for students such that their engagement will allow them to develop skills in data collection and further their understanding of modelling natural processes.

There are five carbon pools in terrestrial ecosystems, which include aboveground biomass, belowground biomass, litter, woody debris, and soil organic matter (Han et al., 2007). However, this design will focus on measuring and monitoring three of the carbon pools - aboveground biomass, belowground biomass, and soil carbon. The four main forms of terrestrial carbon measuring and monitoring are physical-based calculation, *in situ* measurements, *ex situ* measurements, and remote sensing.

2.4.1. Physical-Based Calculations

Physical-based calculations are a method used to estimate the carbon content of aboveground biomass. There are variations with respect to the measurements needed for the calculation, but at the minimum, the height and diameter of the plant is required (Vashum & Jayakumar, 2012). Then, the biomass of the plant is calculated using species-specific allometric equations. The value of the coefficients in the equation differs based on the species, and are obtained from literature and databases such as the World Agroforestry Centre (Dong et al., 2019). Lastly, the carbon content is assumed to be a standard 50% of the biomass calculated (Vashum & Jayakumar, 2012). To estimate soil organic carbon, **Eq. 1** can be used, where *SOC* is soil organic carbon of the full soil profile (Mg ha^{-1}), n is the total number of horizons of the full soil profile, BD_i is the bulk density of horizon i, TH_i is thickness of horizon i (cm), CR_i is the stoniness volume percentage of horizon i (% vol.), and C_i is the percent carbon in horizon i (Bautista et al., 2016).

$$SOC = \sum_{i=1}^{n}((BD_i \times (TH_i \times 0.01) \times (1 - \frac{CR_i}{100})) \times C_i) \times 100 \quad \textbf{(1)}$$

2.4.2. *In Situ* Measurements

In the context of this project, *in situ* measurements refers to real-time sensing methods using equipment such as probes and CO_2 flux measurement devices. There are two primary methods for measuring CO_2 flux at the soil surface: the chamber-based method and infrared spectroscopy. The chamber-based method, which is further categorised based on the use of an open-chamber or closed-chamber, is most commonly used (Angell et al., 2001). Specifically in the closed-chamber method, a small amount of air is circulated from the chamber to an infrared gas analyzer, and then sent back to the chamber where the increase in concentration of CO_2 inside the chamber, $\frac{dC_c}{dt}$ (μmol mol^{-1} s^{-1}), as shown in **Eq. 2**, is measured (Madsen et al., 2009). Then, using **Eq. 2**, where P is pressure (Pa), V is the system volume (m^3), R is the universal gas constant (8.314 Pa m^3 K^{-1} mol^{-1}), T is the absolute temperature (K), and S is the area covered by the chamber (m^2), CO_2 flux, F_c (μmol m^{-2} s^{-1}) is calculated (Madsen et al., 2009). Products on the market, such as the joint LI-COR Biosciences 8200-01S chamber (Lincoln, Nebraska, United States) and LI-870 analyzer (Lincoln, Nebraska, United States) system, fully integrate all the necessary sensors and automate the flux measurement process for real-time sensing.

$$F_c = \frac{PV}{RTS}\frac{dC_c}{dt} \quad \textbf{(2)}$$

The second method, infrared spectroscopy, is a common soil spectroscopy technique used to measure soil carbon *in situ*. The four main types of infrared spectroscopy methods for carbon sensing are: visible near-infrared (vis-NIR), mid-infrared (MIR), laser-induced breakdown spectroscopy (LIBS), and inelastic neutron scattering (INS) (Fultz-Waters, 2022; Gehl & Rice, 2007). The vibrations of covalent bonds in functional groups of interest such as C–H, C=O and O–H in response to specific wavelengths provides information on the quantity and type of molecules present in a given sample (Kusumo et al., 2018). Vis-NIR is considered to have a relatively high accuracy and is better suited for in-field use than MIR (Fultz-Waters, 2022; McCarty et al., 2002). Although, it is important to be conscious of factors such as moisture content and soil surface texture as they can inhibit the accuracy of the results when using Vis-NIR sensors (Kunag & Mouazen, 2013). LIBS uses atomic emission spectroscopy to form a thin plasma that replicates the composition of a soil sample using a pulsed laser (Cremers et al., 2001). The pulse laser breaks down the molecules in the plasma to elemental components and the light emitted from each component is read in a spectrophotometer to develop a wavelength graph which can be used to determine the type and quantity of elements present in the sample (Cremers et al., 2001). Lastly, the INS technique uses a neutron generator to pass a set pulse through the soil sample and the subsequent gamma rays emitted from scattered organic carbon nuclei are read in a spectrophotometer to determine the amount of carbon present (Wielopolski et al., 2000).

2.4.3. *Ex Situ* Measurements

Ex situ measurements are derived from soil and plant samples that are collected directly from the space of interest and subsequently analysed in the lab. A carbon analysis is performed to determine the carbon content present in the samples. 100-150 g samples are dried for 72 hours, finely ground and passed through a 1 mm mesh sieve, and then undergo direct combustion at 900℃ using a Thermo Finnigan Flash EA 1112 CN analyzer (Carlo Erba, Milan, Italy) to determine total carbon. Alternatively, soil samples can be sent to a third party lab to obtain a soil analysis which includes percent soil organic carbon. An appropriate lab will need to be selected based on cost efficiency, and ease of transporting the samples from the site to the lab.

2.4.4. Remote Sensing

Remote sensing provides an alternative method of estimating the aboveground biomass carbon pool with higher efficiency in terms of labor and time compared to traditional estimation methods and is also better suited for mapping large scale carbon stocks across forests. Optical sensor, radar, and LiDAR data are used to develop models that define relationships between the sensed data and biomass (Kumar & Mutanga, 2017). The sensor attachment can be on satellites, as well as unmanned aerial vehicles such as drones. Higher accuracy results were observed when fine resolution data was used (Lu, 2006). Existing models presented in the literature would have to be calibrated using data pertaining to the design site to obtain accurate results, and if a unique model was to be developed, the accuracy of the model would still be contingent on the data quality and volume used for calibration, the completeness of the model, and ultimately the validity of the model in correctly connecting the relationships between factors such as tree trunk and branch size to biomass volume.

3. Assessment of Alternative Solutions

All the researched plant species, soil additives, and carbon measurement and monitoring methods are next discussed and evaluated based on their comparative advantages and disadvantages. The elements selected to incorporate into the first design iteration are identified and explained with supporting rationale in addition to explaining why some options were intentionally excluded. Lastly, the results of the first design iteration are presented with some brief analysis.

3.1. Plant Species

As the design relies on biological methods of carbon sequestration, researching the carbon sequestration potential of various plant species was essential. In addition, the plant nativity, growth duration, lifespan, root systems, adaptability to a warming climate, and aesthetic value were also considered to assess the suitability of a plant species for the greenspace design. Throughout the evaluation process, existing literature and university professors specializing in plant biology were consulted. The general consensus was to implement a diverse range of plants that meet the following criteria:

- Native to the Montréal area
- Fast growth

- Long lifespan
- Deep and extensive root systems
- Carbon sequestration potential
- Adapted to warmer climates
- Aesthetically pleasing

Using this set of criteria, coupled with the Pugh chart shown in **Table 1** which compares the different plant species researched, the following plants were selected for the design:

- Poplar tree
- Pine tree
- Oak tree
- Beech tree
- Switchgrass
- Miscanthus grass

Description		Baseline: Lawn Grass		Poplar		Oak		Pine		Beech		Switchgrass		Miscanthus		Red Clover		Fruit Trees	
Criteria	Weight Factor	Previous Species		Species 1		Species 2		Species 3		Species 4		Species 5		Species 6		Species 7		Species 8	
		Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Fitness for Northern Temperate	2	0	0	1	2	2	4	2	4	2	4	2	4	2	4	1	2	1	2
Adapted to Warmer Climates	1	0	0	0	0	1	1	1	1	2	2	1	1	2	2	1	1	1	1
Growth Rate	2	0	0	0	0	0	0	1	2	1	2	1	2	0	0	1	2	-2	-4
Lifespan	2	0	0	1	2	2	4	2	4	2	4	1	2	1	2	-1	-2	1	2
Root System Complexity	3	0	0	2	6	1	3	1	3	2	6	2	6	2	6	0	0	1	3
Sequestration Potential	3	0	0	2	6	1	3	1	3	2	6	1	3	1	3	0	0	1	3
Aesthetic	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2
Net Score			0		17		16		18		25		19		18		5		11

Table 1. *Pugh chart of all the compared plant species.*

Poplar was chosen for its high carbon sequestration potential as well as its fast-growing properties. The speed of growth of poplar trees allows for higher levels of carbon sequestration within the greenspace's inaugural years while other tree species planted reach maturity. Poplar's relationship to carbon capture has been extensively researched, which served as further reason to include it in the greenspace design. The remaining selected tree species all have excellent lifespans, ensuring the longevity of the carbon sink. Furthermore, these species are native to the Montréal area, enabling animal habitat creation. Additionally, beech trees possess a complex root system, and thus have a comparatively higher carbon sequestration potential. Conversely, apple trees have a slower growth rate than poplar trees, and a shorter lifespan than pine, oak, and beech. The main advantage of fruit trees is their aesthetic and food-bearing capability. However, these factors are not weighed as heavily in the consideration of the greenspace design.

Both switchgrass and miscanthus grass scored considerably higher than the baseline of lawn grass, particularly in the categories of suitability for the northern temperate zone and root system complexity. It should be noted that "fitness for the northern temperate" refers to a species' native region. That is, whether the plant is native to the Montréal area and areas south of Québec. A plant that is native to Montréal, but found mostly in even colder climates, would not receive a maximum score. Relatedly, miscanthus grass is also found in warmer climate zones, proving to have strong resilience to projected rising temperatures. The red clover outperformed switchgrass and miscanthus grass in only visual appearance. Thus, miscanthus grass and switchgrass were selected over red clover.

3.2. Soil Additives

Some of the key deciding factors in choosing which soil conditioners and additives to include in the greenspace design included the complexity of the additives, specifically in relation to carbon measurements, as well as the benefits they provide to the greenspace, which area compared in the Pugh chart shown in **Table 2**. Compost is a primarily carbon-based soil conditioner which is used to add nutrients to the soil and more importantly in this case, support and foster proper soil health. This is the only relatively biologically active soil additive researched and was found imperative to include in the design to augment carbon sequestration of the biomass by dramatically improving soil health. With these benefits, however, comes some complexity in calculating organic matter in the soil and carbon flux of the site; by adding carbon to the site, the raw measurement data obtained by measurement devices will be over exaggerated as carbon has artificially been added to the site. This may be relatively easy to account for however as compost nutrient calculations are simple when the feedstock of the compost has been well accounted for, or if the compost is directly tested. If compost is obtained from the City of Montréal's municipal composting system, as is expected due to its low cost, this data can be easily acquired and thus, the added nutrients to the soil in the compost can be accounted for in carbon sequestration calculations. In summary, compost is seen as a highly important soil conditioner primarily for its soil health and microbiome benefits and thus, while it makes carbon sequestration calculations more difficult, its addition can be easily accounted for.

Biochar initially seemed clear to include in the greenspace design as it is highly concentrated carbon which also has nutrient balance regulatory benefits for plants. After researching different soil conditioners however, its drawbacks became more clear; primarily, its relatively high cost of synthesis compared to the other additives. It is also expected that regular re-treatment of the soil with these additives will be required to maintain their benefits, so the cost of the additive will be recurring and quickly accumulate. Secondly, Biochar has the same carbon addition complexity compost has but is made dramatically more difficult to account for as it is relatively less researched than compost. Therefore, variables such as the relative percent of carbon volatilized to the atmosphere can't be accounted for as accurately and the carbon content of the Biochar itself is also not as easy to quantify. Finally, its soil nutrient regulation benefits were found to be carried out at a marginally lower quality by incorporating hydrogels into the design. Hydrogels also regulate soil nutrients in addition to having more desirable drainage properties and thus, Biochar was decided not to be included in the design.

Because of the inherent poor water drainage properties of the primarily clay-loam soil on Macdonald Campus, bio-based hydrogels, with their excellent water management properties, were decided to be highly essential to the greenspace. Hydrogels also aid in soil nutrient regulation and retention and thus maintain several of the properties of Biochar, but with no added carbon complexity in measurements and with better water retention in the soils. It is expected the addition of compost with the hydrogels in the soil will achieve a high quality microbiome for the plants by adding nutrients and microorganisms in the compost and regulating soil nutrients and water management with the addition of hydrogels. Most importantly, the combination of the plants and hydrogels is expected to be sufficient soil water management to not necessitate environmentally and economically expensive artificial water drainage installations.

Description		Baseline: Lawn Grass Management		Compost		BioChar		Hydrogels	
Criteria	Weight	Previous Treatment		Additive 1		Additive 2		Additive 3	
	Factor	Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Carbon Sequestration	3	0	0	1	3	2	6	0	0
Cost	2	0	0	3	6	-2	-4	0	0
Complexity	3	0	0	-1	-3	-3	-9	2	6
Other Benefits	1	0	0	0	0	1	1	2	2
Plant Benefits	2	0	0	3	6	2	4	1	2
Net Score			0		12		-2		10

Table 2. *Pugh Chart of all the compared soil additives.*

3.3. Carbon Measurement Systems

When assessing the suitability of each monitoring approach, the options were evaluated based on accuracy, cost, user-friendliness, time commitment, and resource intensiveness. The Pugh chart depicted in **Table 3** was constructed to aid in the decision-making process. The physical-based calculations are simple and fast, but do not consider fluctuations and variations in the carbon sequestration mechanisms of different plants. *In-situ* measurements have a higher accuracy than physical-based calculations, but there is a trade-off with respect to the cost of purchasing the sensors and flux measurement devices. The CO_2 flux measurement devices mentioned in section 2.4.2 are portable, but since they are expensive, theft may also be an issue when using the system in a shared capacity, i.e., when students or members of the public are participating in the carbon measurement process. Of the four spectroscopy techniques presented, INS is the most accurate, with vis-NIR being the least accurate, but sufficient for field use (Fultz-Waters, 2022; Gehl & Rice, 2007). LIBS and INS are relatively the most expensive, and are not portable (Fultz-Waters, 2022; Nayak et al., 2019), whereas vis-NIR can be applied to portable applications in a sensor system using an inexpensive infrared reflectance sensor. However, adequate site-specific calibration will be required to obtain reliable results. *Ex situ* measurements are comparatively the most accessible due to the established carbon analysis protocols in the plant science labs at Macdonald Campus, but this method requires soil sampling and in-lab analysis. Finally, remote sensing is well suited for mapping carbon stocks across large forests but is not as user friendly and has a steep learning curve. Therefore, upon assessment of the advantages and disadvantages of the different options, the selected carbon measurement and monitoring method will be a combination of *ex situ* lab analysis and *in situ* infrared sensing. The soil sampling and lab analysis will be conducted semi-annually and produce high-accuracy results. On a regular basis, the infrared reflectance sensor will be deployed to collect more frequent measurements. This combination will maximize the benefits of each method and bridge the gap that would otherwise exist in selecting a single monitoring approach. Remote sensing could be considered for future larger-scale projects, but is not suitable for the size of the current greenspace design.

Description		Baseline: Field Measurements		Direct Field Measure-ments (*in situ*)		Lab Measurements (*ex situ*)		Remote Measurements	
Criteria	Weight Factor	Previous Method		Method 1		Method 2		Method 3	
		Rating	Weighted	Rating	Weighted	Rating	Weighted	Rating	Weighted
Accuracy	3	0	0	2	6	2	6	1	3
Cost	2	0	0	-1	-2	-1	-2	-1	-2
User Friendliness	3	0	0	1	3	1	3	-1	-3
Time Consuming	2	0	0	1	2	0	0	-1	-2
Resource Intensive	2	0	0	-1	-2	-1	-2	1	2
Net Score			0		7		5		-2

Table 3. *Pugh Chart of all the compared carbon flux measurement methods.*

3.4. First Design Iteration

During the first iteration of the design, the carbon sequestration potential of the initial site was estimated under the assumption only one plant species would be planted and that planting space was optimized. These calculations were performed using AutoCAD and Excel. Guidelines pertaining to the distance between vegetation and existing structures were respected, with the smaller trees closer to the field boundary and larger trees further away. In **Table 4**, it is concluded that poplar sequesters by far the most carbon per hectare. Thus, a high number of poplar trees were made sure to be included in the final design.

Genus	Diameter (m)	Max. No. of Plants	Long-term Cseq/Plant (t-C yr^{-1})	Long-term Cseq (t-C yr^{-1})	Long-term Cseq/ha (t-C yr^{-1})
Poplar	1.5	1012	0.0044	4.50	20.14
Oak	6.85	28	0.012	0.35	1.58
Beech	13.7	5	0.22	1.13	5.07
Pine	2.7	221	0.0046	1.01	4.54
Switchgrass	0.3	-	-	0.29	1.30
Miscanthus	1.35	-	-	0.43	1.96

Table 4. *Carbon calculations of the various plants considered for the design.*

The Facilities Management and Ancillary Services, Department of Buildings and Grounds at the McGill Macdonald Campus was consulted when discussing which sites were available to be used for this design. For the purpose of this project, it was important to design on an existing plot of land in order to simulate the real world challenges, such as needing to adapt to existing buildings, roads, and vegetation. The selected plot for this hypothetical design is located just south of the Eco residences (45.406190, -73.935330), and right beside the Macdonald garden, pictured in **Figure 4**. This space measures approximately 2000 square meters in area, or 0.2 hectares. Specific dimensions of the space are outlined below in **Figure 5** which depicts the 2D AutoCAD rendering.

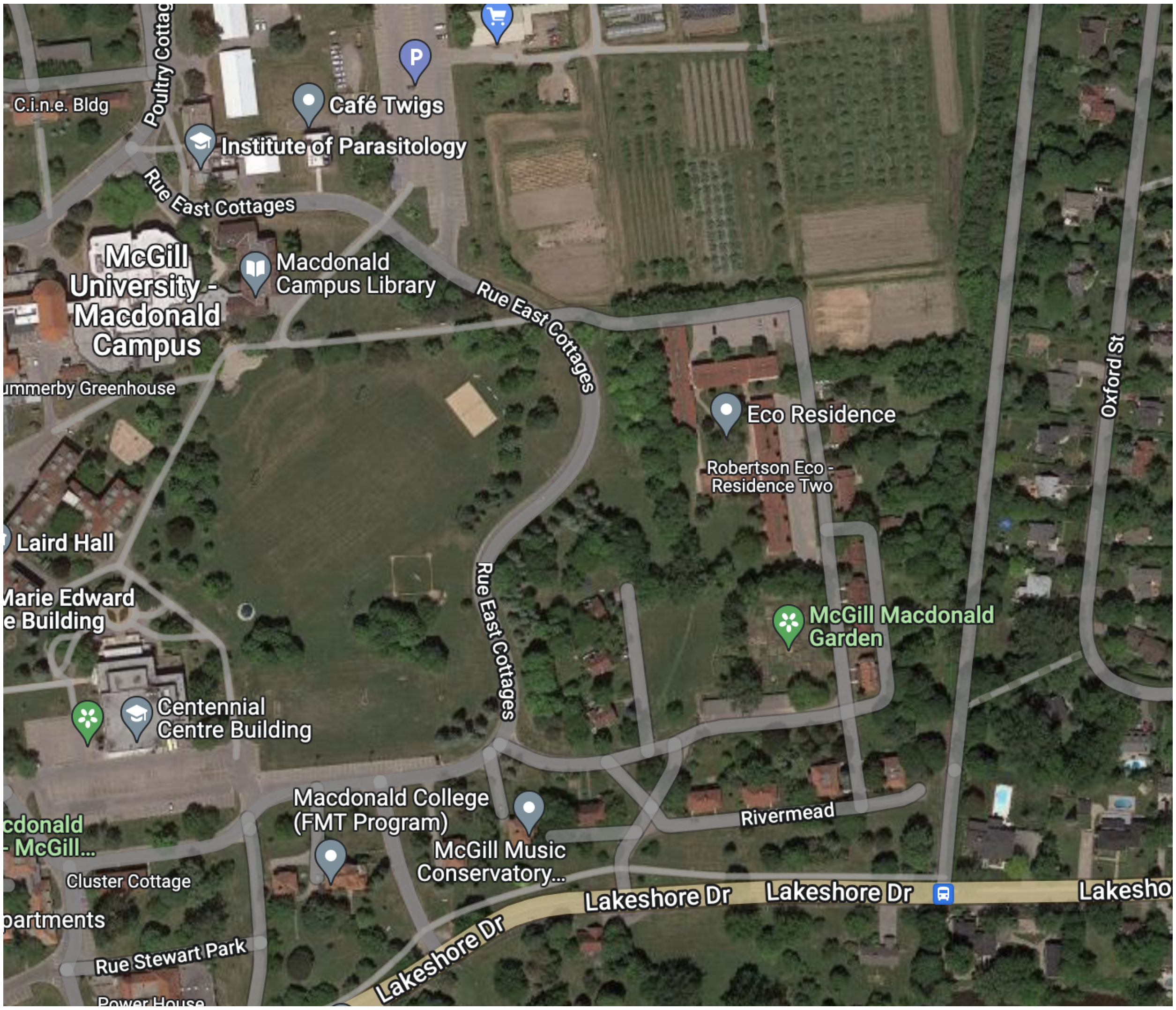

***Figure 4**. Aerial image of land used for the previous greenspace design.*

The first iteration of the design includes 6 individual plots and 4 combination plots. Each of the 6 chosen plant species will be featured on an individual plot, where its growth and soil carbon content will be monitored. Additionally, the combination plots will each include a different mix of the selected species, enabling the evaluation of inter-species relationships, i.e., how well different plants work together to sequester carbon. While designing the layout, industry standards for sidewalk widths, required distances between trees and existing structures were considered. All walkways are at least 2 m wide, demonstrating adequate space for both accessibility and comfort. The hypothetical design is depicted in **Figure 5**. Starting from the top-left, there is a combination plot consisting of oak, pine, and poplar. Directly adjacent is a study space featuring 15 picnic benches, and to the right of that space is a beech tree. Only one beech tree was used due to its size. On the second row of plots (from left to right) there is an individual plot for pine trees, a combination plot of oak, pine, poplar, switchgrass, and miscanthus grass, and an individual plot of oak trees. The third row features the following: a combination plot of pine, poplar, switchgrass, and miscanthus grass; a recreational or study space with 6 picnic tables; a combination plot of poplar, switchgrass, and miscanthus grass; and an individual plot of poplar trees. Lastly, there is an extended walkway that hosts 10 benches, and two plots of grass surrounding the existing tree. To the left of the tree is switchgrass and to the right is miscanthus grass. In total, the design incorporates 94 poplar trees, 35 pine trees, 8 oak trees, and 1 beech tree. The boundary lines in red represent a neighbouring building, while the lines in green represent existing trees. This design is estimated to sequester over 2 times more carbon than McGill's current greenspaces.

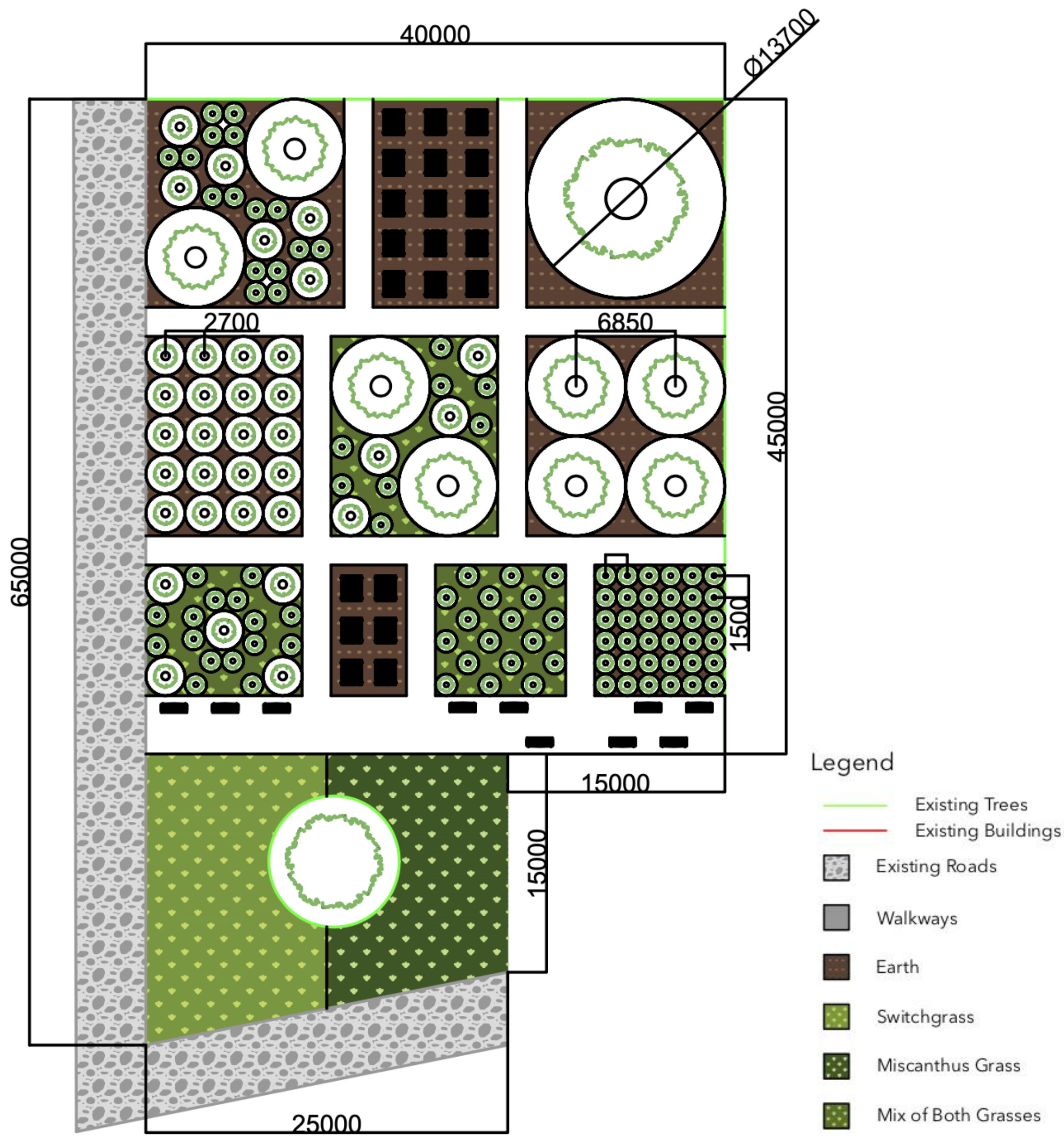

Figure 5. *Hypothetical design incorporating all 6 chosen species on an existing plot of land.*

After developing the first iteration of the greenspace design, a similar procedure to what was previously outlined to calculate the carbon sequestration potential of the design was employed. All values are summarized in **Table 5**. The total carbon sequestered in t-C ha^{-1} yr^{-1} is approximately double the 2 t-C ha^{-1} yr^{-1} that McGill University reported in their 2020 Greenhouse Gas Inventory (McGill Office of Sustainability, 2020). Considering the amount of carbon that current greenspaces at McGill (The Morgan Arboretum and The Gault Nature Reserve) are sequestering, this design accomplishes the objective initially outlined.

Genus	Plot Area (m^2)	Max No. of Plants	Long-term Cseq/Plant (t-C yr^{-1})	Long-term Cseq (t-C yr^{-1})
Poplar	-	94	0.0044	0.41
Oak	-	8	0.012	0.10
Beech	-	1	0.22	0.22
Pine	-	35	0.0045	0.16
Switchgrass	235	-	-	0.030
Miscanthus	203	-	-	0.039
Total C Sequestered (t-C yr^{-1})			0.97	
Total C Sequestered/ha (t-C yr^{-1})			4.37	

Table 5. *Carbon calculations for previously proposed design.*

4. Final Solution

Upon completing the first iteration of the design process, the re-designing phase led to an improved solution. This solution is composed of four main technical components: a 2D AutoCAD design of the greenspace layout, *ex situ* soil carbon measurements, an *in situ* infrared reflectance sensor, and a website mockup.

4.1. Final Greenspace Design

The final greenspace design is approximately 2950 m^2 in area and includes 7 individual plots, 8 combination plots, and 2 study spaces. Each of the 6 selected species are featured on an individual plot, in addition to Kentucky Bluegrass, which will serve as the control plot. As the poplar tree has the highest carbon sequestration potential and the lowest area requirement, it is used heavily throughout the greenspace. Alongside the individual poplar plot, there is also a plot featuring poplar with hydrogels and a plot with poplar and compost. The two with soil additives can be compared to the one without to identify any effects the soil additives have on plant growth, plant health, and soil carbon. As for the combination plots, there are two variations:

- Combination 1: poplar and oak
- Combination 2: poplar and pine

Both types of combination plots are then tested with no additional grasses, miscanthus grass, and switchgrass. These plots will demonstrate the effects and interactions different species have on one another, as well as how they contribute to carbon sequestration.

In addition to the 15 experimentation plots, there are also 2 study spaces to improve community engagement. These spaces can be used to socialize, study, or simply relax and sit alongside nature. As the greenspace is located just minutes from the Macdonald Campus Library, it presents an excellent alternative to studying indoors.

Based on the greenspace layout in **Figure 6**, the site includes 170 poplar trees, 8 oak trees, 1 beech tree, and 52 pine trees. Additionally, there is 100 m^2 of switchgrass and 150 m^2 of miscanthus grass. The total carbon sequestered is calculated in **Table 6** and the final results are presented in **Table 7**. Approximately 1.69 t-C yr^{-1} is sequestered by the whole greenspace, which translates to approximately 7.57 t-C ha^{-1} yr^{-1}, a value 3.75 times greater than the amount McGill's existing greenspaces are sequestering.

Genus	**Plot Area (m^2)**	**Number of Trees**	**Cseq (t-C ha^{-1} yr^{-1})**	**Cseq/Plant (t-C yr^{-1})**	**Total Cseq (t-C yr^{-1})**
Poplar	-	170	27.43	0.006	1.049
Oak	-	8	3.77	0.018	0.142
Beech	-	1	8.15	0.153	0.153
Pine	-	52	7.92	0.006	0.300
Switchgrass	100	-	2.76	-	0.028
Miscanthus	150	-	1.50	-	0.023

Table 6. *Carbon calculations for the proposed greenspace layout.*

TOTAL	1.69
Per ha	7.57

Table 7. *Total amount of carbon sequestered according to the proposed greenspace layout.*

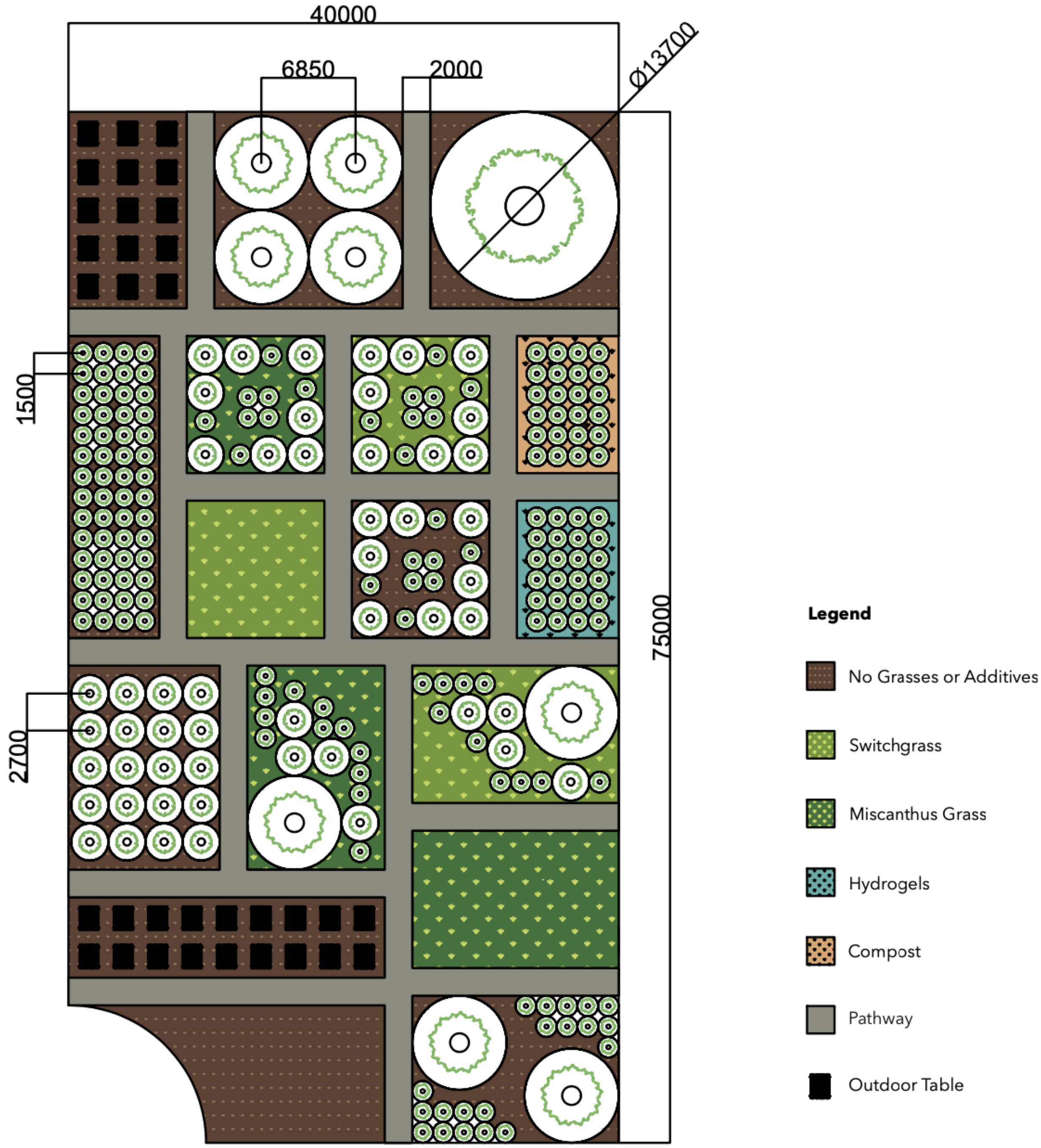

Figure 6. *2D green space layout created using AutoCAD.*

4.2. Soil Carbon Measurement & Monitoring

The ability to measure and record the carbon within the greenspace is central to achieving the educational and experimental purposes of the space. The *ex situ* and *in situ* method selected for soil carbon measurement and monitoring were prototyped and executed. For a more precise, yet labor and cost intensive result, soil samples were sent for laboratory testing to determine percent soil organic carbon. Conversely, for a more user-friendly and cost-effective, real-time sensing approach, an infrared soil carbon sensor system was built and tested.

4.2.1. *Ex Situ* Method

After research regarding precise *ex situ* soil measurement methods was conducted, lab analysis of soil samples was decided to be the most practical method for semi-annual, accurate soil carbon measurement. As a part of Macdonald Campus's farms yearly *Plan Agroenvironnemental de Fertilisation* (PAEF), soil samples are sent to *Agro Enviro Lab* in the Gaspé Peninsula of Québec and thus, it was decided to use this same lab to test soil samples from the design site and nine additional sites of varying soil texture, land management, and plant cover to (1) increase data reliability and (2) provide input for model calibration as described in section 4.2.2.2.

4.2.1.1. Soil Samples

Ten soil samples were collected throughout the Macdonald Campus with explicit intent of high variation in texture, organic material, moisture, land usage, and distance. The chosen soil samples are shown in **Table 8.** Approximately 2-3 cups of each sample was collected into Ziploc bags and sent for analysis the following day. The sample numbers correspond to the samples described in the soil report from *Agro Enviro Lab* in **Appendix 2**. Samples were sent for standard analysis in addition to a texture analysis.

Sample No.	Sample Location	Location Reasoning
1	Elevated grass field near the lake shore	Observe changes between soil adjacent and near the lake
2	Soil at the lake shore	Year-round water saturated soil

3	Mac-Stewart Field	Typical grass field
4	Tilled Apple Orchard soil	Tilled soil
5	Designed plot	Site of interest
6	Corn field (field 020)	Active farming soil
7	Inside the Arboretum	Natural, highly biologically active soil
8	Permaculture Garden	Gardened soil with compost added to it
9	Sandy soil outside the Arboretum	Differently textured soil
10	Heavily walked on soil	Highly carbon-depleted and low nutrient soil

Table 8. *The ten soils sampled and correspondingly tested by Agro Enviro Labs.*

4.2.1.2. *Agro Enviro Lab* Results & Analysis

Before analyzing the lab soil analysis, it is important to mention some specificity of a few of the measured parameters. Firstly, aluminum holds onto carbon tightly and thus while it may be detrimental to some plants in high levels, this would dramatically improve carbon sequestration. Secondly, a density higher than 1.3 g/cm^3 would be considered heavily compacted or very dense though it is important to remember that carbon aggregates lower this density. The cation exchange capacity (CEC) is a measure of the soil's ability to hold on to and retain nutrients, and finally, a soil pH of 6.5 is ideal, but anywhere between 5.5 to 7.5 is acceptable and will vary heavily based on the plants and microbiome in the soil. Also, because some of the soils sampled were from actively farmed fields and given that phosphorus is highly controlled on farming operations in Québec, phosphorus content was also analyzed. Thus, soil pH, percentage of organic material, phosphorus concentration, aluminum concentration, CEC, and soil density were all compared and discussed.

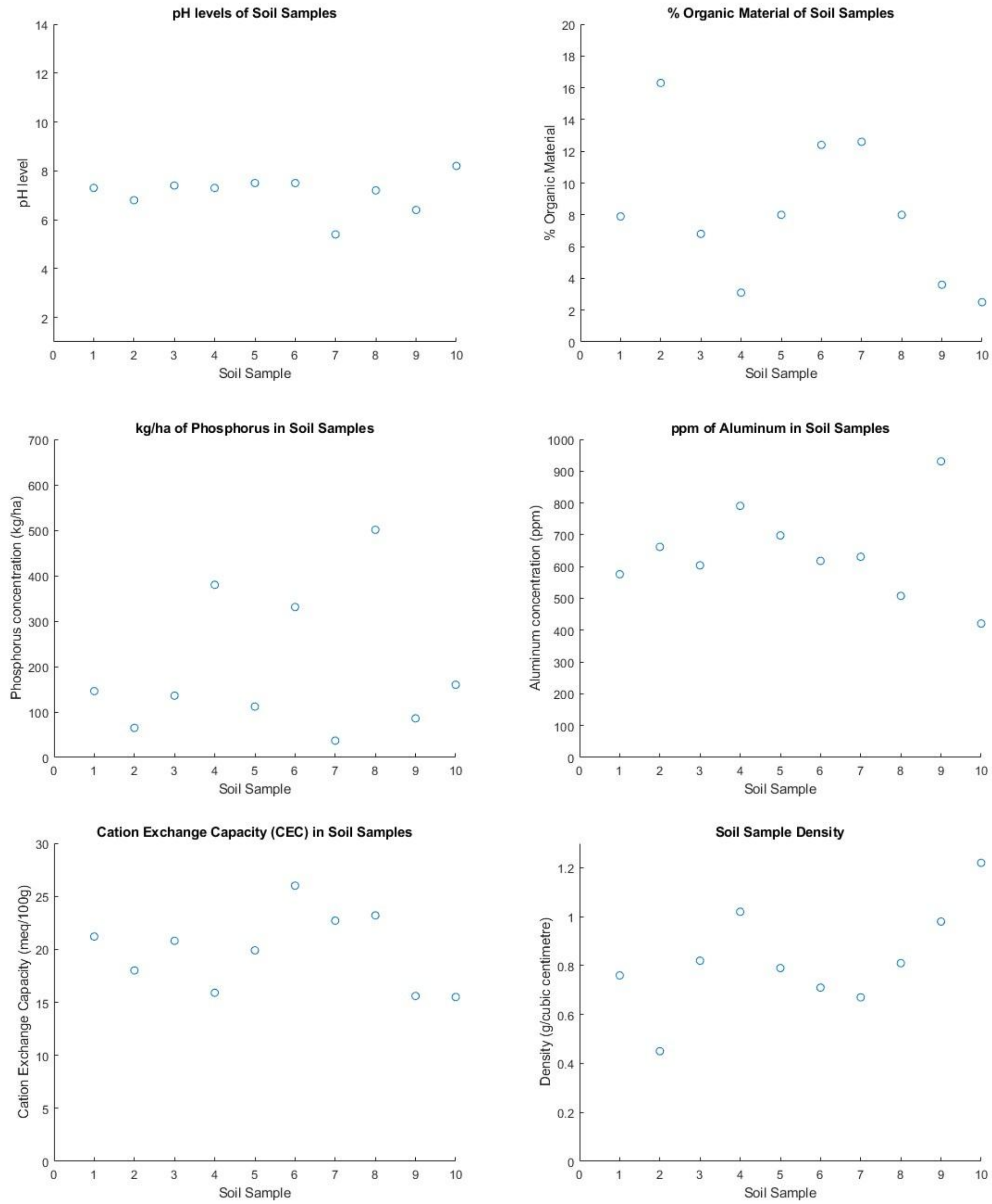

Figure 7. *Plots of analyzed soil parameters which were of most relevant to discussion of the project.*

Samples 1, 3, and 5 were very similar in terms of the measured parameters; these are all relatively typical lawn grass areas sampled and thus consistent results here makes sense. Sample 5 being the intended plot for construction of the greenspace shows promising results as all the important parameters show relatively good results; a relatively neutral pH, no excess of any individual element or nutrient, a modest CEC, and a good enough density without any indication of compaction. On every graph in **Figure 7**, these three samples are within margin or error of each other.

Sample 2 was unique as it stood out as the soil with the highest organic material content, relatively low in nearly every element tested, and maintained the lowest density of all the samples. It has been shown in research that ecosystems such as wetlands and peat bogs often sequester the most carbon as they are largely anaerobic systems. The constant water saturation of the soil doesn't allow aerobic organisms to survive and metabolize organic compounds; the effect being that carbon is never volatilized and thus remains in the soil. Sample two being taken right at the lake shore where it is saturated year-round maintains a similar effect to wetlands in that aerobic microorganisms can't survive to metabolize carbon and thus it remains in the soil. This sample was also unique for its notably lower CEC and density; this can also be attributed to the flowing water saturating and loosening the soil as well as preventing some exchange capacity.

Sample four was notable for its high levels of phosphorus, low levels of organic matter, high levels of aluminum, low CEC, and high density. This soil is farmed and was freshly tilled when it was sampled; high legacy phosphorus is expected in a farming operation such as this and tillage is expected to dramatically reduce organic material, increase soil density, and lower the soil CEC. Of all samples tested, only three (samples 4, 6, and 8) tested high in phosphorus levels and these three samples being the only farmed samples taken corroborates these measurements.

Sample six, like sample four, is a farmed field; these corn fields however are managed very differently than the tilled apple orchards and the data reflects these differences in management. The corn fields (specifically field 020) are not tilled and are managed in an effort to improve soil health; the percentage of organic material indicates this difference most strongly as sample four had approximately 4% organic matter but sample six reported over 12% organic matter. In addition, sample six reported the highest CEC while sample four was within margin of the samples with the lowest exchange capacity; this wide difference is also likely due to the dramatically improved soil health of the samples which was also visually noted. Sample six was very dark with good tilth relative to sample four which was light and rough by comparison. Sample six also reported very high phosphorus levels as previously mentioned.

Sample seven was frequently the most unique soil reported with data; it was listed with by far the lowest pH, maintained the second highest organic matter, contained the lowest levels of phosphorus, and had a relatively low density. Sample seven was taken inside the Morgan Arboretum and functioned as the most "natural" and ecologically active soil. It is important to note *Agro Enviro Labs* is an agricultural soil science lab and thus adjust their parameters for agricultural soils. As previously mentioned, legacy phosphorus buildup and thus its fresh application is highly controlled and regulated in Québec on agricultural soils. The lab analysis lists the phosphorus content of sample seven as ”very poor" but this is likely calibrated towards the expected high levels of phosphorus in traditional cultivated soils. In addition, the low pH is likely due to the trees next to the soil sample site; these were identified as conifers which are well known for releasing acids into the soil through their roots which in effect reduces the soil pH. This sample had the highest aerobic organic material content which comes from the carbon cycling in the ecosystem including plant material such as leaves and branches, fungi, and animals on the forest floor. Manure and animal trampling of the soil are often identified as key contributors to soil health and organic content. The ecosystem maintenance of the soil likely contributes to its low density.

Sample eight measured highest in phosphorus levels and relatively high in its CEC, in addition to measuring high in several other elements measured. This soil sample was the only known soil to which compost is regularly added to; legacy phosphorus buildup as well as the high levels of other nutrients would be explained by this addition, as well as the relatively good soil health which improves its CEC.

While the other samples were the area's typical clay-loam soil type, sample nine was chosen as it is a more sandy texture and thus carries different properties compared to the rest; sample nine had a relatively low pH, very low organic matter, very low levels of phosphorus, by far the highest concentration of aluminum, one of the lowest CECs, and a relatively high density. Clay in soil is one of the largest compounds that fosters aggregate pools of carbon; sandy soil inherently has much lower levels of clay in the soil and thus less carbon can aggregate which lowers the measured organic matter, lowers the soil's CEC, increases density, and lowers overall nutrient content. The lower soil pH can be attributed to the nearby conifer trees. The high aluminum concentration is an outlier in this data and its not clear why aluminum here was so high.

Sample ten was chosen to be a heavily walked-on soil sample and thus was expected to report some of the worst results of the samples tested; sample ten had the highest pH, lowest organic fraction, lowest aluminum concentrations, the lowest CEC, and by far the highest density. The majority of these values can be attributed to being next to a road and being a walkway; salt is added to the road which likely affects the pH of the soil dramatically and added elements in the salt may also account for some of the high nutrient levels. Pollution from cars may also play a large role in some of the measured differences here but it can't be identified to what extent though the heavy walking on the soil certainly increases its compaction and thus lowers its CEC.

4.2.2. *In Situ* Method

In addition to the *ex situ* method, an *in situ* method for measuring soil carbon in the greenspace will be used to (1) allow for more frequent measuring and (2) to provide real-time data. A soil carbon sensor system integrating the infrared spectroscopy technique was developed as a cost-effective, easy-to-use method for participants to engage in the collection of soil carbon data and track the fluctuations in soil carbon, study seasonal variation, and compare the soil carbon in different plots. This two-pronged approach to measuring and monitoring soil carbon in the greenspace leverages the accuracy of results from a lab analysis and the feasibility of more frequent data collection using an infrared reflectance sensor. The result is an overall robust monitoring system for soil carbon that supports the environmental, experimental, and educational purpose of the greenspace.

4.2.2.1. Sensor System Design

The developed soil carbon sensor system consists of three primary parts: (1) TCRT5000 infrared reflectance sensor (brand: DollaTek), (2) Arduino UNO R3 microcontroller (Ivrea, Italy), and (3) the 3D-printed frame. The overall dimensions of the system, as shown in **Figure 8,** are 122 mm × 84 mm × 52 mm.

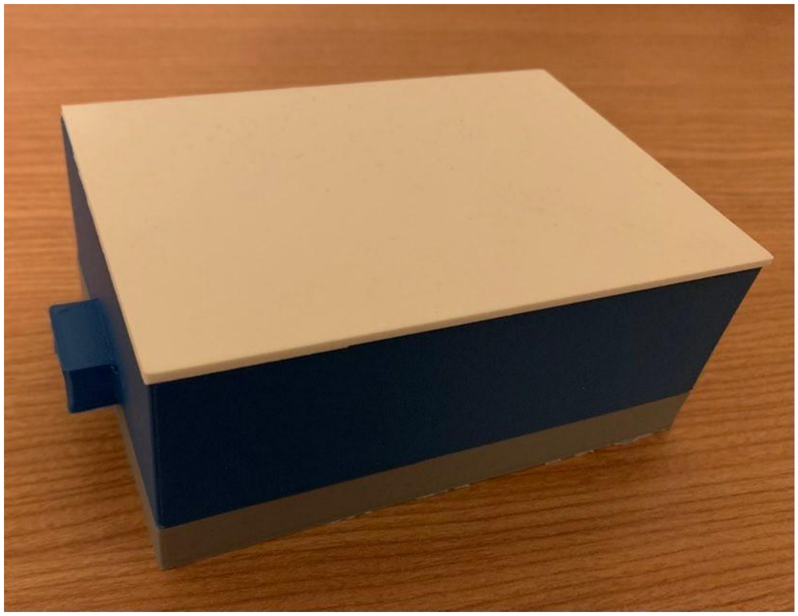

Figure 8. *Isometric view of soil carbon sensor system.*

The sensor is wired to the Arduino microcontroller as shown in **Figure 9**. To obtain optimal data from the sensor, the sensor's emitter and receiver LED should be pointed at a consistent distance of 2.5 mm from the sample surface (BC Robotics, n.d.). The sensor is programmed using the Arduino IDE version 1.8.17. Arduino was chosen for its user-friendly program interface and built-in functions that allow external sensors to be easily integrated into a singular system. Data collected from the sensor is sent to the Arduino IDE serial monitor where an analog integer output is displayed between 0 to 1500. The analog output is ultimately converted to a percent carbon quantity using the calibration equation derived in the following section.

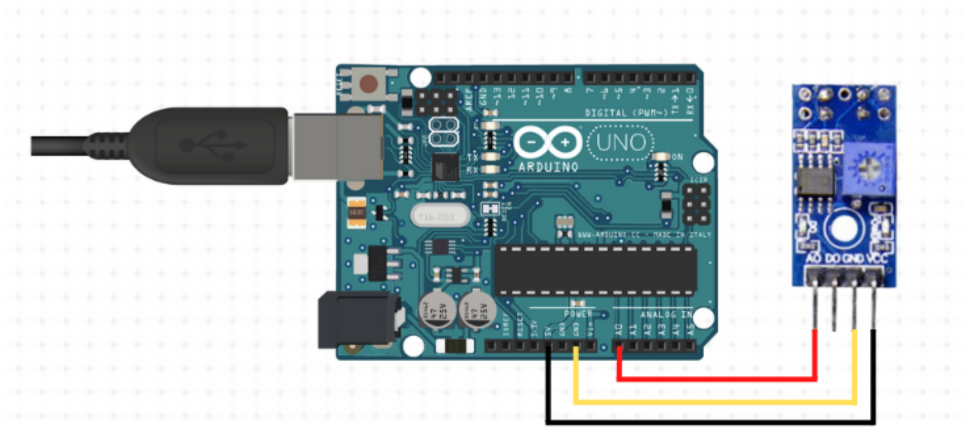

Figure 9. *Circuit diagram for soil carbon sensor system.*

The frame was designed to house the hardware components of the system, improve the usability of the system in the field, and ensure the sensor stays at a consistent 2.5 mm from the sample surface. The frame was 3D-printed using polylactic acid (PLA) material as it is adequately durable for field purposes and water resistant. The frame was designed on AutoCAD, and an exploded view showing the three individual components is displayed in **Figure 10**. The thickness of all the components is 2 mm. The central component is 122 mm × 84 mm × 52 mm, with a 20 mm × 10 mm × 12 mm protrusion to secure the sensor. There are also two 25 mm × 2 mm × 1 mm ridges extending into the frame from the protrusion to secure the sensor in place. The top component is 122 mm × 84 mm × 2 mm and serves to cover the hardware inside the central compartment of the frame. The bottom component is 122 mm × 84 mm × 13 mm. The frame was designed to have a wide base to increase stability when placing the system on the soil surface. The back of the frame is left uncovered to facilitate easy cable connection from the microcontroller to an external power source. Additional photos of the frame are included in **Appendix 3**.

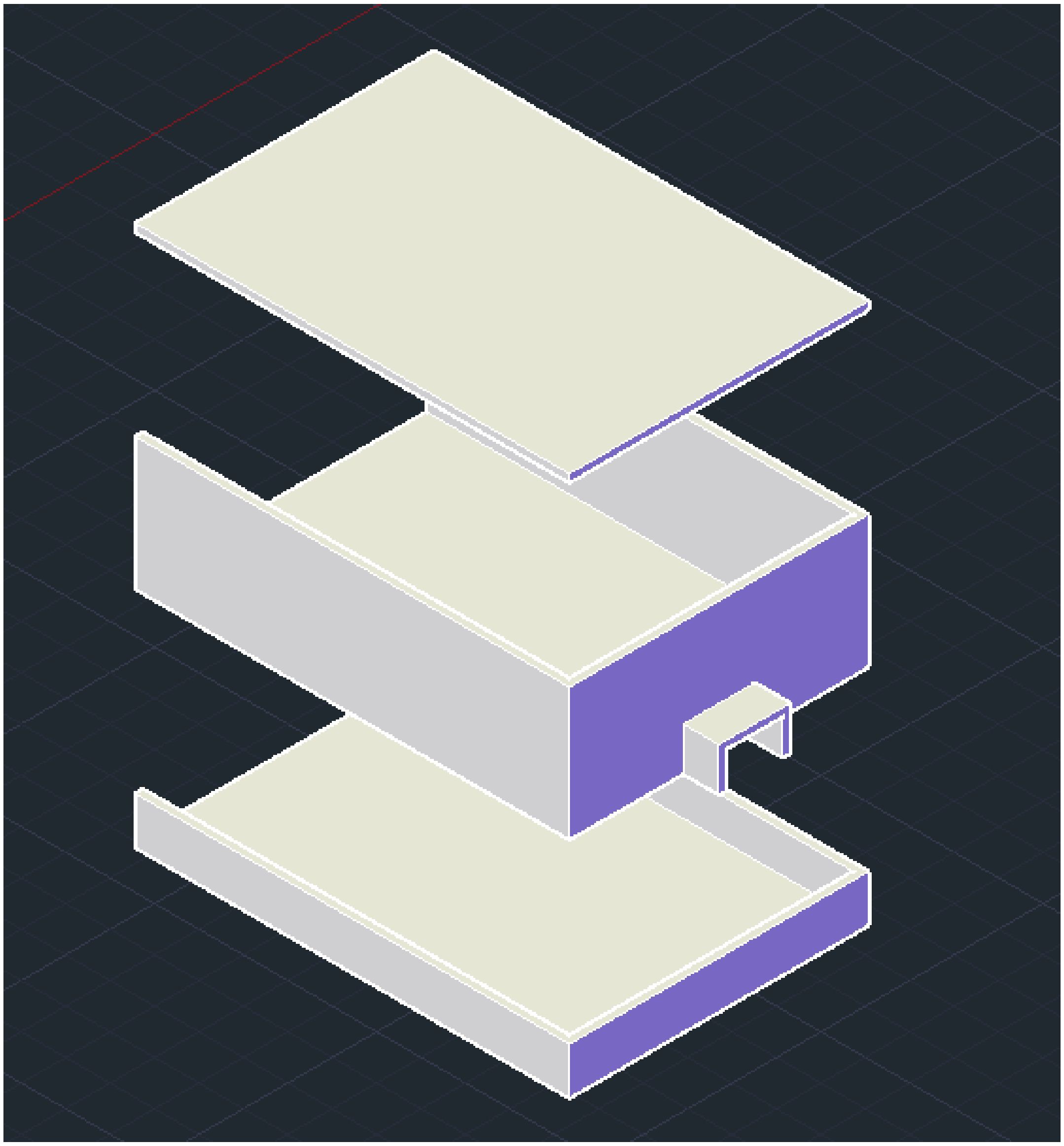

Figure 10. *Exploded view of sensor frame in AutoCAD.*

4.2.2.2. Model Calibration

The calibration equation is used to calculate percent soil organic carbon as a function of soil infrared reflectance, as measured by the soil carbon sensor system. To develop the calibration equation, the soil infrared reflectance data was collected at the ten sites outlined in **Table 8**. The data collected at the sites is shown in **Figure 11**. The soil carbon sensor system was able to successfully detect relative differences in soil reflectance. As expected, the variation in soil reflectance corresponded with the variation in soil carbon content. The arboretum, a site with undisturbed and heavily forested area, was predicted to have the highest soil carbon content and had the highest detected reflectance as well. Furthermore, some of the sites predicted to have low carbon content like the Mac-Stewart field, which only has lawn grass cover and is heavily walked on, had lower reflectances.

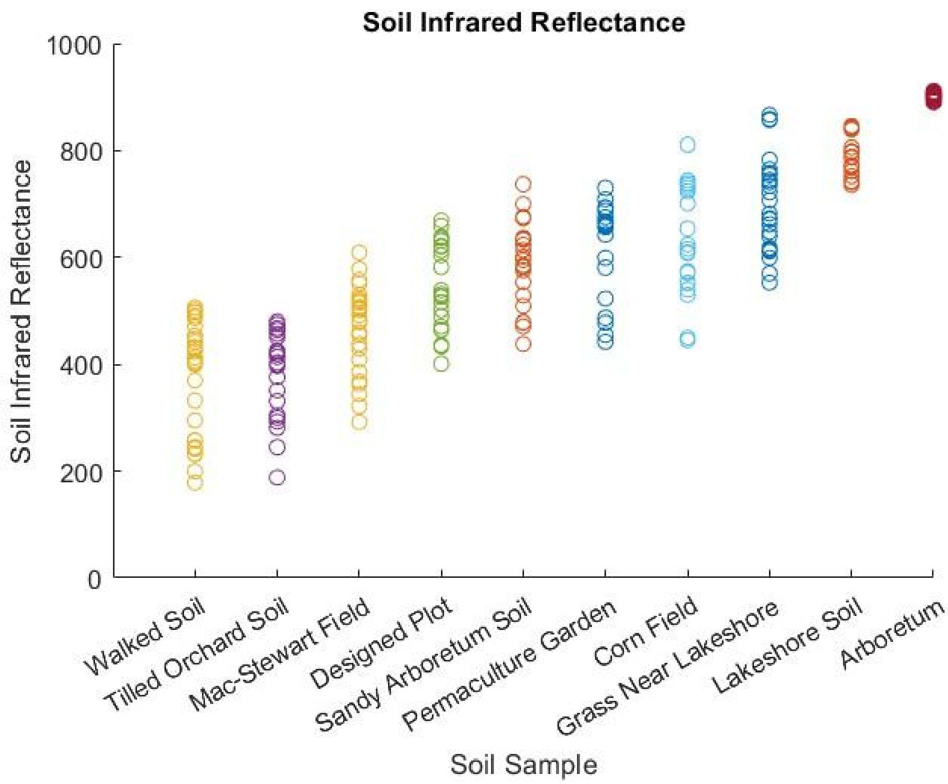

Figure 11. *Scatter plot of soil infrared reflectance data collected at each of the ten sites.*

To develop the calibration curve shown in **Figure 12**, first, the average soil infrared reflectance was calculated using the collected data for each site, except site 5, which will be used for model validation. Then, the average infrared soil reflectance at each of the nine locations was plotted with their corresponding percent soil organic carbon from the lab results. This plot is shown in **Figure 11**. It was assumed that 58% of soil organic matter is soil organic carbon (Allison, 1965; Nelson & Sommers, 1983; Hoyle & Murphy, 2013). A linear trendline showed the best fit to the data with an R^2 value of about 0.9. Using the data for sample 5, which is the design site, for validation, the percent error of the model was approximately 4%. Therefore, the soil carbon sensor system shows fairly accurate performance, however calibration and validation can be performed with an even larger dataset to increase model reliability.

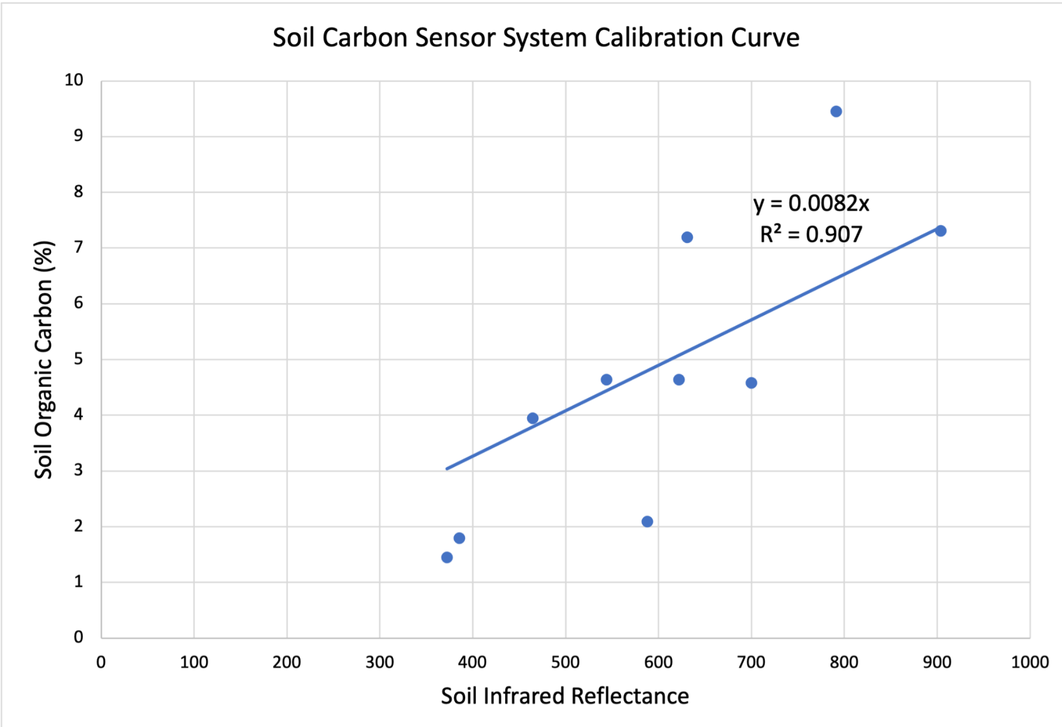

Figure 12. Calibration curve for soil carbon sensor system with a linear trendline.

4.3. Education, Website Design & Stakeholder Feedback

The website designed for the project will facilitate the social, educational and experimental aspects of the greenspace design. **Figures 13.1, 13.2,** and **13.3** show mockups of the website created using Figma, a web application for interface design. The mockups are a static design of the web page demonstrating its features and design elements. QR codes can be found on signage throughout the greenspace, leading users to an interactive and informative website. Users will first be directed to the landing page, as shown in **Figure 13.1**. Although not pictured in the mockups, the website will also include a thorough description of the greenspace, along with its mission and vision statements. It will also feature articles and posts with additional information on the plant species, soil additives, and monitoring devices used within the greenspace. It will be important to keep the website regularly updated and maintain an active online presence in order to further increase community engagement.

Pictured in **Figure 13.3** is another essential feature of the website. It will include a simple chart illustrating the soil carbon content of each individual and combination plot. Using regular sensor readings, and semi-annual lab analyses, stakeholders will be kept updated on the health and progress of the greenspace. Appealing to the educational purpose of the space, students and the public will also gain insight to the ongoing experimental trials performed on the greenspace.

Perhaps one of the most important features of the website is the feedback page, depicted in **Figure 13.2**. It serves to maintain regular communication between the design team and the public. Setting up a channel for ongoing and consistent feedback from users and stakeholders will not only mitigate risk, but also ensure the continuous improvement of the greenspace.

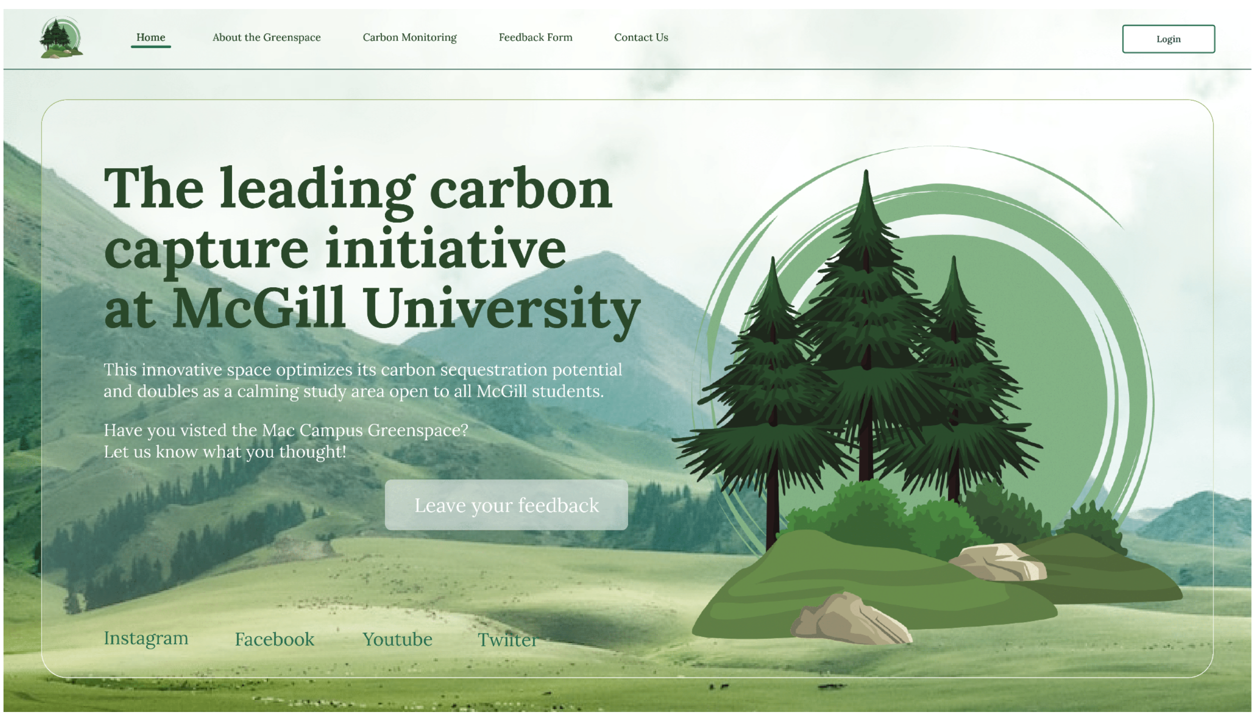

Figure 13.1. *Landing page of the greenspace website.*

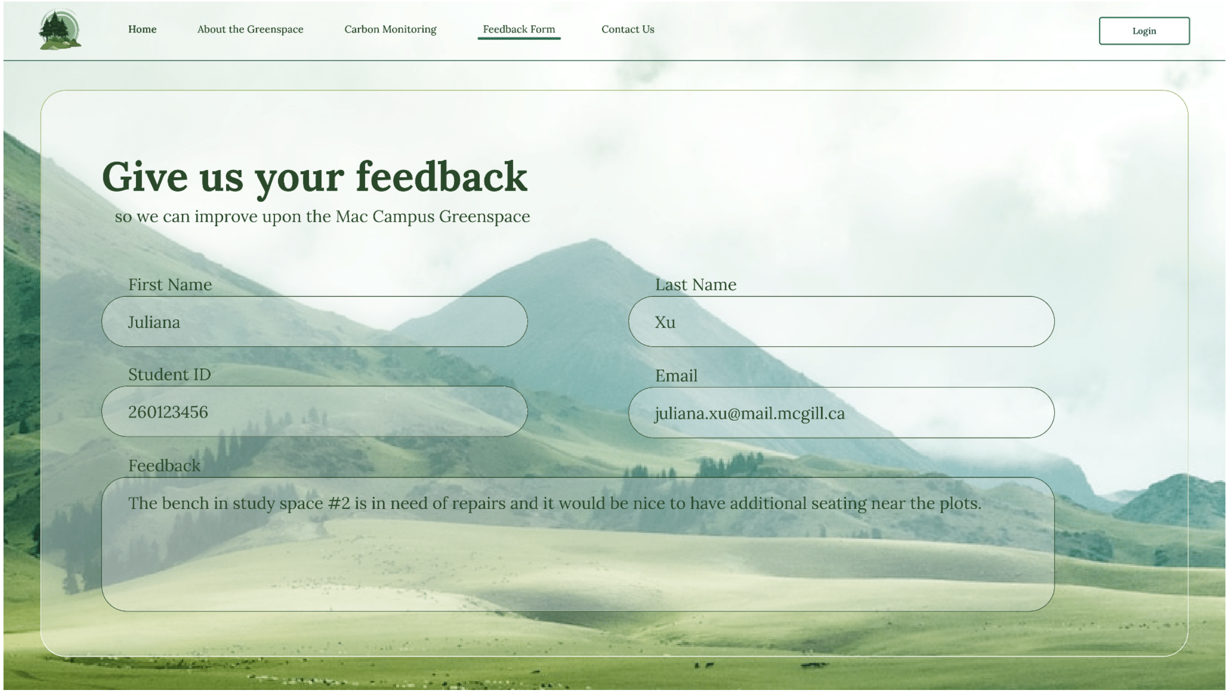

Figure 13.2. *Feedback form on the greenspace website for communication with stakeholders and the public.*

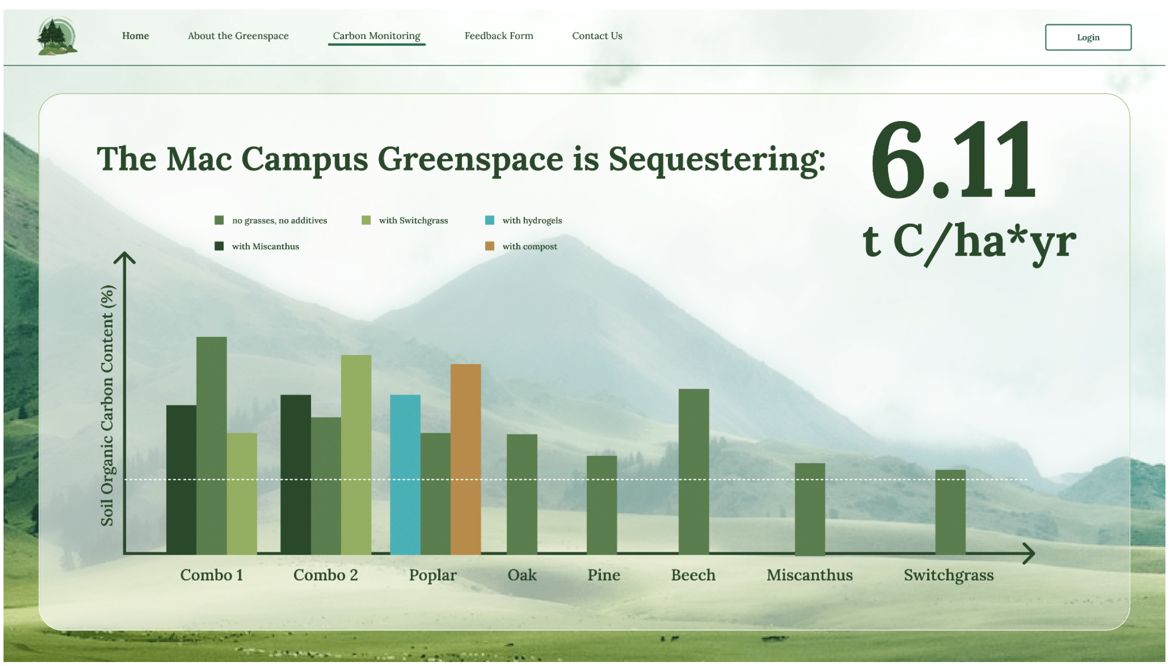

Figure 13.3. *Soil carbon data display on the greenspace website, showcasing the soil organic carbon content for all plots.*

4.4. Engineering Standards and Regulations

The final greenspace was designed to adhere to specific regulations as per Montréal's municipal by-laws. Although the design site is located on McGill University's private property, the municipal by-laws are followed to be in accordance with best practices. First, the design plots with trees are organized such that they maintain a 1 m distance from the gravel path in the northwest corner of the site, the field to the east, and the fenced garden north of the site (Ville de Châteauguay, n.d.), Additionally, the poplar trees used in the greenspace are located more than 15 m from the building foundation and gravel path, satisfying the municipal by-law for this species (Ville de Châteauguay, n.d.). There are two utility poles with overhanging wires that traverse the design site. Therefore, using the Hydro-Québec "Choose the Right Tree or Shrub tool" (n.d.), the pine and oak trees have to be planted a minimum distance of 2 m from the power line, and the beech tree has to be planted a minimum distance of 3 m from the power line. The location of different species' plots was determined taking into account the full grown size of the plants, as per Ville de Québec guidelines (n.d.). Additional potentially relevant municipal and city of Québec regulations were available only in French. Therefore, an external consultant would be hired to review the greenspace design and ensure the necessary regulations are met.

In addition to by-laws, additional standards and regulations were considered in the development of the design. As per the McGill University's Natural Resource Sciences pruning guide (2008), new growth on pine trees must be pinched half way as it forms each season, and to maintain the desired size branches should be cut to the trunk of the tree. The ANSI A300 standards will be followed for tree planting and maintenance as it is the industry standard in the United States for tree care practices. The different sections of the ANSI A300 that are most relevant to the greenspace design are pruning, soil management, planting and transplanting, and tree risk assessment (Tree Care Industry Association, n.d.). Additionally, the Urban Tree Foundation provides an extensive and detailed, step-by-step specifications document which will be followed to supplement planting and site maintenance protocol to ensure industry best management practices are applied to the greenspace. The document specifically outlines the rights, responsibilities, and requirements of the contractor and owner (Urban Tree Foundation, n.d.), which will be applied to the building of the greenspace to ensure there are clear and documented agreements and expectations with contracted parties. The Urban Tree Foundation also has compliance requirements for the use of compost, which will be followed for the plot with compost additive. The standards and regulations mentioned provide only a high-level overview of the different regulatory elements that pertain to the greenspace design, and professional consultation will be required to ensure proper execution.

4.5. Environmental Considerations

A greenspace design inherently considers several environmental elements and thus far, a handful of these considerations have already been discussed. The central goal of the design is to biologically and environmentally sequester atmospheric carbon and thus, current atmospheric carbon levels and methods of carbon capture and sequestration must be considered. Rising atmospheric greenhouse gases, primarily carbon dioxide, in addition to rising average global temperatures from human activity has been identified as the central problem requiring innovative design solutions (Humlum et al., 2012). While the proposed greenspace design will sequester relatively small amounts of carbon, its themes of designing greenspaces for carbon sequestration, education, and allowing research regarding carbon sequestration to be carried out are all aimed to increase public awareness of projects such as these.

4.5.1. Sequestration Time

Carbon sequestration is only as effective as how long it can be maintained in the plant biomass, or more ideally, in the soil. While semi-accurate plant biomass-carbon estimates can be made, it is near impossible to simply measure carbon content in the soil. This is because carbon exists in several forms in the soil and behaves differently in each fraction. Even though the most stable fraction of carbon storage in the soil is often the largest, sequestration measurements require a thorough understanding of the carbon in all fractions in the soil, as well as the soil properties itself in order to estimate the time scales at which the carbon will remain sequestered. While it isn't possible to initially estimate the length of carbon storage for the proposed sequestration design, a diachronic approach is proposed in which soil carbon is measured beginning at time t=0 until a desired end time. Using the previous ecological system steady state carbon sequestration as a reference point, the quantity and time scale of carbon sequestered over time can be calculated (Bernoux et al., 2005).

4.5.2. Global Climate Change & Plant Nativity

As mentioned when considering the inclusion of specific plant species in the design, the average temperature each species was adapted to was also a key criteria as atmospheric temperatures are predicted to steadily increase worldwide (Humlum et al., 2012), species were chosen whose lower temperature ranges aligned with the average temperatures on Macdonald Campus. This selection will allow temperatures to increase, but not immediately be harmful to the chosen plant species. If species were chosen where the Montréal area's temperature was the maximum bearable temperatures, the plants may be short-lived. Thus, plant temperature ranges were a heavy consideration when being chosen and this to some extent led to primarily native species being chosen as it was easier to incorporate native species by their temperature ranges.

A balance often became apparent in decisions to include plant species of whether to include native species or to include genetically optimized or non-native species with much higher carbon sequestration potential. In the end, more native species were chosen with relatively higher sequestration levels while incorporating some species optimized for sequestration, namely the poplar species. Fostering habitat creation, non-native species invasion, and effects on the local ecosystems all contributed to the favour of native species though researching carbon potentials of native and non-native species found marginal differences in sequestration unless the plants were modified for sequestration like previously mentioned.

4.5.3. Seasonal Variation

Factoring into carbon sequestration time as well as environmental considerations is the seasonality of the Montréal area and the effects the variation of conditions will have on the average soil carbon content. Stewart Wuest, 2014 analyzed the seasonal changes in organic soil carbon content in the Pacific Northwest of the United States. While not exactly the same climate as southern Quebec, the climates are similar enough that the data can be generally extrapolated to southeastern Canada with caution. Wuest focused primarily on organic carbon in the soil as this tends to be the most variable fraction of carbon, especially when considering temperature and moisture of the environment and soil. Both shallow and deep soil samples were taken and tested.

Organic material was found to vary by quite a bit, as much as a difference of 300g/m2 between the highest and lowest peaks of the year. Interestingly enough, the deeper soils sampled varied more dramatically than the more shallow samples; this can be due to the carbon aggregates in the clay portions of the soil changing with weather and temperatures more dramatically than the more relatively raw organic matter higher in the soil. The primary conclusion however was that while carbon varied heavily by season and even by month, the overall carbon sequestration was not affected and instead often increased over several months of measuring. While events such as snow cover, flooding, and dramatically high and low temperatures acutely alter the soil organic matter, these events have little, if any, effect on the chronic soil carbon levels.

4.5.4. Site Construction

Construction of the site is expected to be by far the most environmentally demanding step of the designed greenspace. Transportation of products, path construction throughout the site, planting of the trees and grasses, and application of the soil conditioners are all going to contribute to the environmental costs of the greenspace site. While calculating firm numbers of exact emissions of each of these steps is incredibly difficult, measures can be taken to reduce carbon emissions of each of these steps. Incorporating primarily native species reduces transportation costs of trees and grasses to the site since local nurseries are likely to include these species. Using path alternatives in the site as opposed to concrete or asphalt will reduce the carbon emissions of their synthesis and pouring, and making efforts to not till the soil when adding conditioners and only making small pockets in the soil where necessary to add desired additives will all make significant strides to reduce the greenhouse gas emissions of the construction of the site.

4.6. Economic Considerations

While there is a growing interest in academic research regarding urban greenspaces and their social and environmental benefits, few discuss the economics of these spaces. This is often due to either the lack of implementation of these designs or because of the funding nature of public greenspaces. As greenspaces are not inherently expected to generate income and are instead seen as a public service, funding often comes from governments and typically from a government's "green city initiative" fund. Thus, unless a greenspace is designed, contracted, and built, detailed economic considerations of the design are often not considered. Based on the life cycle analysis carried out by Zhang et al. (2022), installation costs are estimated to constitute the majority of the expenses for the first few years of the system.

The two primary expenses of a greenspace project are expected to be in initial construction of the site and salaries of personnel for maintenance and coordination of the site after being built. For reference and cost estimates, a combination of published research papers and the SPF Application Form for the Macdonald Permaculture Garden are employed; the Permaculture expense report is of particular interest and makes a good estimate of costs as it is relatively adjacent to the proposed greenspace, was also a McGill student project, and was funded by the McGill Sustainability Project Fund (Wrobel & Wagner, 2017).

Salaries will constitute a considerable size of the initial costs of the greenspace and by far the majority costs after initial construction of the site, as detailed in **Table 9**. A summer position to oversee the greenspace activity, manage plants, engage education, coordinate experimentation, and engage in stakeholder feedback during the most popular seasons of the year is expected to constitute a full-time position. During the winter when recreation, experiments, and education is expected to drop dramatically this management can drop to a part-time position and be regularly dispersed throughout the winter with intervals of minimal management. Salary estimates are provided in the corresponding figure alongside proposed work hours and weeks.

Position	Hrs/Wk	# of Wks	Hourly Wage	Subtotal	Benefits	Total Cost
Full-Time Summer Manager	35	20	$13.75	$9,625	1.2	$11,550
Part-Time Winter Manager	15	20	$13.75	$4,125	1.2	$4,950

Table 9. *Estimated yearly wages for required job positions to oversee the greenspace management, education, and experimentation. Costs are based on the published Macdonald Permaculture Garden SPF Application (Wrobel & Wagner, 2017).*

The largest cost in the initial construction of the site will be the infrastructure of the design. Pathway construction of the site is expected to be the largest investment; the site requires approximately 650m^2 of pathway and with a conservative estimate of $4.5 per square foot of path and including labour costs, the entire construction cost of the paths is expected to reach $35,000. This is recognized as by far the highest cost of the design and thus opting for lower cost options such as dirt paths or cheaper building materials is also an option. Estimating benches to cost approximately $500 each and with 33 benches in the design, benches are expected to total $16,500. This is rounded up to $20,000 to include signage costs associated with the educational design elements. Initial plant costs are estimated to be very similar to the Permaculture Garden costs as a similar number of plants will be used in the proposed design. Website maintenance and its associated educational interactive elements are estimated to cost approximately $350 per year to maintain (Wrobel & Wagner, 2017). Soil compost is expected to be obtained from the City of Montréal for little to no cost and bio-based hydrogels can be obtained or synthesized for very little cost; a $200 yearly cost is estimated to acquire and add these conditioners to the soil each spring. While an exact cost of engineering design consultation can not be estimated, an hourly wage of $100 for consultation can be considered in the budget. These costs are summarized in **Table 10.**

Item Description	Estimated Cost	Recurring or One-Time Cost
Pathway Laying	$35,000[1]	One-Time Cost
Benches & Signage	$20,000[2]	One-Time Cost
Plants, Soil, and Seeds	$4,000[2]	One-Time Cost
Website & Interactive Element Management	$350[2]	Recurring, Yearly
Soil Additives & Conditioners	$200[2]	Recurring, Yearly
Project Consulting Fees	$100/hour	One-Time Final Cost

[1]*Cost estimated from Porch Pathway Remodelling Estimates*
[2]*Cost estimates drawn from Macdonald Permaculture Garden SPF Application*

Table 10. *Estimated cost breakdown of the greenspace project.*

McGill's Sustainability Project Fund in particular is of interest to the project as the goals of the fund closely align with the proposed greenspace project. Dialogue with committee members and previous similar projects such as the Macdonald Permaculture Garden ensure the majority of the funding could come from the fund (Wrobel & Wagner, 2017). This greenspace project also has the potential of collaborating with one or more classes on Macdonald Campus to complement education in the courses and in return provide a portion of funding for the site;

several classes would well suit this project including soil science courses, environmental engineering courses, as well as global-climate related plant science classes.

4.7. Social Considerations

A greenspace design primarily geared towards the public and education about biological carbon sequestration requires several social considerations regarding the design. The proposed greenspace is also designed to be heavily integrated into Macdonald Campus and thus the research and student communities are also large stakeholders in this project; the greenspace impacts on the university campus and its community as well as the wider west Montréal island public must be considered including inclusion, stakeholder feedback, and equality.

4.7.1. Impact on Student Life

Several studies have documented greenspaces to provide a variety of benefits including environmental effects such as improving air quality and reducing urban heat as well as social impacts. Greenspaces have the potential to provide recreational opportunities, cultural services, psychological and health benefits (Maxwell et al., 2018; Nero et al., 2017). They have been found to reduce levels of obesity, symptoms of mental illness, and even the rate and impact of chronic diseases (Kingsley, 2019). Given the space and context of the project, the social impact of the greenspace can be expected to be concentrated on the improvement of student life and nearby neighbourhoods.

In a national survey conducted by Nunes et al. (2014), it was reported that mental health issues are especially prevalent among young adults aged 18-25. Moreover, undergraduate students are lacking adequate support for mental health problems. While the Macdonald Campus does not lack greenery, there is value in the appearance of these green covers. Aesthetics, landscaping, and quality perception contribute to the restorative potential of a greenspace (Wang et al., 2019). Our greenspace considers these aspects of design by adding visually pleasing greenery to our campus which the students of Macdonald Campus may benefit from, as well as the general public. Implementing outdoor study spaces and recreational areas within the greenspace will encourage students and the community to spend more time outdoors. In addition to being a study or recreational space for all members of the MacDonald community, students and researchers can benefit from the educational and experimental aspect of the design. The goal is to offer opportunities for students to receive hands-on interaction with the greenspace, and explore the options of doing so through coursework or extracurricular activity in the fall and summer semesters.

4.7.2. Considerations of Public & Stakeholder Feedback

A key consideration during the design of the greenspace was to build a space that will be mutually beneficial to all parties involved. In order to ensure the longevity and sustainability of the space, all stakeholders must be considered. This includes everyone who might be affected by the space, ranging from students and faculty to maintenance and facilities workers. The goal is to design a space that will encourage maximum public use from members of the Macdonald community. This will be achieved by designing the space to be easily used by researchers for experiments, ample recreation area for students and the public, and ensuring simple and minimal upkeep of the plot for Facilities Management of Macdonald Campus. Excessive clean-up or overall maintenance required from gardeners and landscape workers may make the greenspace less desirable to invest in and thus has been optimized for minimal upkeep in its design.

4.7.3. Community Inclusion

It is important to acknowledge that projects such as greenspaces are often high risk in terms of failure. Students or the public may not find the recreation or educational aspects of the site socially valuable, researchers may not find the plot convenient for research, or Facilities may find the maintenance of the site too high to keep operational. Because of these potential failures, consistent public involvement in the construction of the greenspace is seen as necessary for its success and to make the project as advantageous as possible to each group of users.

When the first draft of the greenspace is finalized, Molin et al. (2014) discovered early engagement through public feedback of the design is highly beneficial to a successful project. Publicizing the proposed design to the Macdonald and surrounding communities to hear feedback on the site's recreation opportunities, research potential, and educational aspects will be very important to gauge public reception of the project and make changes the community sees fit. Public involvement however must be maintained throughout the project and regular hearing after each draft of the design is necessary to hear feedback on any changes made to the project. This kind of continued public involvement not only improves the success rate of greenspace designs such as this but also gives a sense of community ownership of the design and increases public awareness of the project. These kinds of engagement have also been studied to lead to higher chances of financial investments from the community and more sustained funding (Vargas-Hernandez et al., 2017).

4.7.4. Social Equality

There is a large body of research describing the health benefits that correlate with environmental factors around where one lives. Higher accessibility to greenspaces often results in more physical activity, lower rates of obesity, and lower rates of cardiovascular diseases (Heynen et al., 2006) in addition to the previously mentioned mental health benefits. Several studies in the past decade have analyzed greenspace inequalities in cities. Lower socioeconomic neighbourhoods are less likely to have access to greenspaces which relates to the Deprivation Amplification phenomena, the concept that the more disadvantaged a community is, the higher the environmental burdens are on the population (Schule et al., 2017). All these studies support that people have a right to be protected from negative environmental effects like climate change and pollution, a right termed Environmental Justice (Chen et al., 2020).

The greenspace design being situated on Macdonald Campus addresses several of these potential inequalities. Macdonald Campus is highly accessible by various modes of transit as well as being surrounded by a wide variety of neighbourhoods. The focus of experimentation and education will bring public and student participants from a broad range of social, economic, and cultural classes to the greenspace. With open access to the public, anyone nearby is able to equally benefit from the greenspace design.

4.8. Educational & Experimental Considerations

One of the key objectives of the greenspace design is to promote educational and experimental endeavours on topics such as terrestrial carbon sequestration, novel nature-based carbon sequestration techniques, and carbon measurement and monitoring. Thus, ultimately raising public awareness and engagement in climate change mitigation through carbon sequestration. There are several design features of the greenspace that facilitate this goal.

First, the design and layout of the plots allows for easy comparison of the carbon sequestration capabilities of different plant species and soil additives, as well as the potential cumulative effects of combining specific plant species with certain soil additives. As such, there is a control plot with the original soil and vegetation of the design site to establish a baseline for comparison of the other treatments. Then, there are plots where a singular species is planted with no soil additives to determine the carbon sequestration as a function of only plant type. Lastly, there are combination plots with multiple plant species and soil additives to quantify the multivariable carbon sequestration potential of the plots. Thus, being able to study how the combination plots compare to the single species plots, how much the soil additives contribute to overall carbon sequestration, and the optimal method for terrestrial carbon sequestration that is specific to the environmental conditions of the area. Therefore, this design is expected to attract researchers as a testing hub for new and innovative carbon sequestration strategies.

Second, the location selected for the design is on the McGill Macdonald Campus and is easily accessible by students. The site is within walking distance of the campus library and cafe, which are two of the most frequented spots by students and is also located in close proximity to other student initiatives such as the McGill, Macdonald Student-Run Ecological Gardens (MSEG). Thus, making the greenspace more attractive to students who want to enjoy time outdoors by utilizing the workspace and benches available, participate in caring for the plants, and engage in achieving the mission of the greenspace towards climate change mitigation.

Third, the *in situ* carbon measurement and monitoring method was designed with user experience keenly in mind. Arduino is a relatively easy to use interface and the steps needed to run the program are simple to learn and use. The process of using the soil carbon sensor system to collect data consists of only a few simple steps, allowing a wider audience to participate in the measurement and monitoring of the greenspace. Additionally, the shallow learning curve associated with operation of the system will allow for students to be trained faster and ready to start collecting data.

Fourth, as mentioned in section 4.6, the greenspace can be integrated into an existing course offered on the Macdonald Campus. As Macdonald Campus offers several soil science, plant science, and environmental engineering classes, the project could be a unique opportunity for professors to provide students with a hands-on learning experience. Students will be able to gain an operational perspective on soil carbon dynamics, plant carbon sequestration and greenspace design, as well as apply and hone their technical skills, such as data collection and analysis, through a real-world project. Reciprocally, the collaboration would help provide the manpower necessary to maintain the upkeep of the greenspace.

Lastly, the creation of a website provides the project with a platform to connect with stakeholders and further accelerate the educational impact of the greenspace. With interactive features such as a real-time carbon sequestration tracker, the public can feel invested in the success of the project and be more inclined to learn about carbon sequestration methods and approaches that can further improve the performance of the space. The website also provides a platform through which relevant information on carbon sequestration and climate change mitigation topics can be shared. Thus, building community interest and knowledge in the topics. Reciprocally, feedback provided by the public through the website will allow for further advancement of the space and continuous improvements to be implemented, which will develop the knowledge base needed to inform future greenspace developments.

4.9. Risk Management

The first, and a crucial step of risk management is risk identification. There are many obvious risks associated with any project, these are considered to be "known risks" (Scavetta, 2021). In contrast, there are others which require more research to uncover (Scavetta, 2021). Ideally, one would conduct interviews with project stakeholders and industry experts to unveil all potential risks. However, given the limited time and resources for this project, this report will focus on managing and mitigating known risks.

4.9.1. Occupational Health & Safety

For this greenspace project, occupational health and safety is primarily with respect to members of McGill's Facilities unit, which includes groundskeepers, landscapers, and horticulturalists. Some of the health and safety issues for these professionals include pain or injury from lifting heavy objects, working under extreme weather conditions, UV exposure, working with machinery such as chainsaws, and working at tall heights (Canadian Centre for Occupational Health and Safety, n.d.). During construction and planting, operation of large machinery such as earth augers and hydraulic drills also pose a safety risk. As there are power lines within the design site, care should be taken while working around the poles and wires to ensure the maintenance team is protected from electrical shock or flash burn. Potential hazards are present with respect to falling or fallen tree branches and plant debris. In future stages of the greenspace, any chemicals applied to the site, such as pesticides, should be handled according to the product safety protocol and while wearing gloves. Some applicable risk mitigation practises include using proper lifting technique for heavy objects, ensuring the staff are provided with and use industry-grade personal protective equipment, including safety vests, hard hats, and protective eyewear, and there are clear safety procedures and training for operating power tools (Canadian Centre for Occupational Health and Safety, n.d.). Additionally, a first aid kit should be present at all times on the greenspace site in case of emergencies, and a designated resting area that is shaded to allow for staff to avoid heat exhaustion and stress.

4.9.2. Public and Stakeholder Acceptance

Another risk to consider is the reaction from stakeholders and the public. There are measures which can be considered to increase the likelihood of a positive reaction from stakeholders and the public alike. Firstly, it was important to reflect upon the effect that the geographic location of the greenspace will have on social acceptance. Additionally, where it will have the greatest impact and ease of accessibility. With any public service, comes the consideration of accessibility. It was crucial that the space be easily accessible to all students, faculty, and staff at Mac Campus. The chosen site is one not far from the main campus, in fact, the greenspace will be adjacent to the Machinery Hall where undergraduate classes are frequently held. Although travelling to the location by foot involves traversal over a fairly steep bridge, there are buses which run between the main campus and the buildings across the bridge. Moreover, the selected site is significantly closer to the main campus than the nearest existing greenspace (the Morgan Arboretum) which is inaccessible by foot.

In addition to measures taken pre-installation, there are numerous benefits in establishing a continuous and consistent line of communication with project stakeholders to ensure the long-term acceptance of the greenspace. The website helps to serve this exact purpose. There will be a dedicated section to encouraging public feedback via an online form or email. Maintaining a channel for communication between the design team and the users of the greenspace will be beneficial for both parties. It will allow the designers to better understand the strengths and flaws of the design and implement ongoing improvements according to user feedback. Additionally, any required repairs or inspections to greenspace equipment can be relayed directly to the designers with ease.

4.9.3. Long-Term Viability and Maintenance

To ensure long-term viability of the greenspace, there are two main questions of interest. Who will be responsible for maintaining and operating the space? How will maintenance and operation of the space be funded? The long-term survival of this greenspace will rely on the answers of those two questions. Two potential avenues for the continued viability and upkeep of the space is (1) through the McGill Office of Sustainability (MOOS), and (2) through partnership with a course or field-based learning opportunity offered on the Macdonald Campus. If the project is selected by the MOOS as an initiative that fulfills their commitment to improve carbon sinks on campus as per the McGill Climate Action Plan (McGill Office of Sustainability, 2020), they have the resources, means and incentive to fund the operation and maintenance of the site. Alternatively, the greenspace can be adopted by the university as a learning centre for knowledge-building on the Macdonald Campus and can serve in a similar way as the Macdonald Farm Community Engagement Centre to provide students and the public with hands-on practical experience on the environmental issues at the forefront of today's world.

4.10. Future Developments

This greenspace design proposal will allow McGill University to sequester approximately 3.75 times more carbon per hectare per year than the existing carbon sinks on campus. Seeing this project as an outline to be adapted into a project that can better suit the needs of a class on campus, a research project to be carried out, or a design McGill Facilities can build on would all be exciting developments of the project. Additional research on carbon measurement devices, particularly systems which are relatively cheap, accurate, user-friendly, and can be permanently installed to report live data, would be a promising development for the project. Some next steps include further refinement of the project cost and launch of the proposed website, stakeholder feedback system, and associated educational programming with respect to the greenspace. The long-term goal is that the fully actualized, implemented project will develop into a robust testing hub for new and innovative research on carbon sequestration strategies and support the conventionalization of these tested strategies in future greenspace developments.

5. Conclusion

Rising greenhouse gas emissions from human activity show little to no indication of slowing down to levels required to prevent the adverse impacts of climate change. Thus, measures regarding carbon sequestration are being increasingly researched in an effort to offset these effects. While more artificial methods of capture are being explored, the rising interest in urban greenspaces in conjunction with research on terrestrial carbon sequestration methods presented an opportunity to develop a greenspace with carbon sequestration as a key environmental function of the space. A greenspace is designed for the McGill University Macdonald Campus that not only sequesters approximately 3.75 times more carbon than existing carbon sinks on campus, but also facilitates educational and experimental objectives to raise awareness for the potential of nature-based solutions in achieving climate change mitigation, and encourages further research into these strategies. The various combination plots included in the greenspace, as detailed in the AutoCAD design developed, serve as excellent experimentation sites to test the interactions of different species and soil additives, and how they affect soil carbon storage. The lab analysis and soil carbon sensor prototype allowed for testing of the greenspaces' measurement and monitoring system, and showed reliable results for further development and use. Furthermore, all experimentation and monitoring of the greenspace is made publicly accessible through a dynamic and interactive website. Public and stakeholder feedback will solidify the continuous improvement of the greenspace to meet user needs. Upon considering the environmental, social, and economic aspects of the project, a holistic perspective is provided on the costs and benefits associated with the implementation of this greenspace design. It is hoped that public-facing initiatives such as this greenspace project will inspire the public to get involved in the joint effort for climate change mitigation and popularize the use of engineering innovation to scale existing natural systems to create a transformative impact in global climate action.

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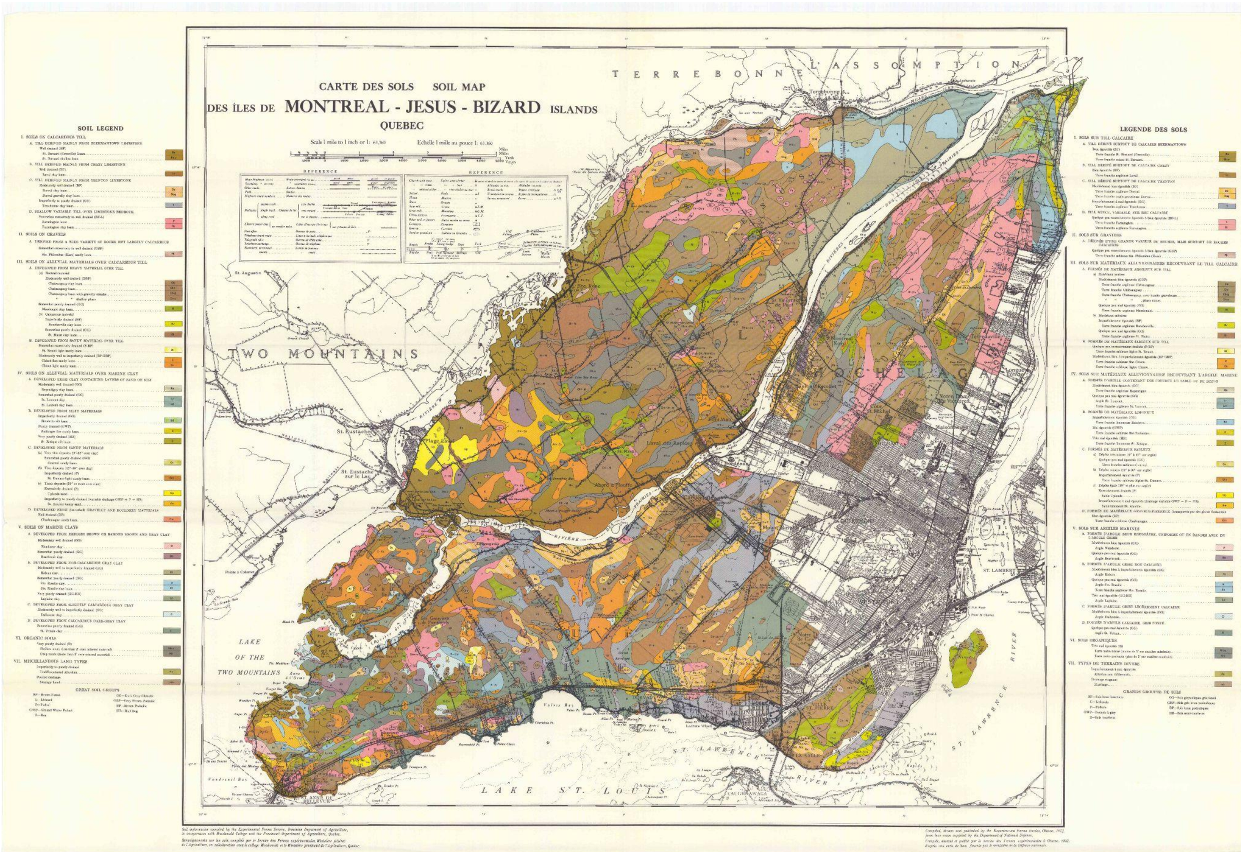
Appendix

Appendix 1. Carte des sols des Îles de Montréal, Jesus, et Bizard (Lajoie & Baril, 1954).



Appendix 2. Agro Enviro Lab Analysis of Sampled Soils.

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Accrédité pour pH, pH tampon, K, Ca, Mg, Al, Mn, Cu, Zn, par CEAEQ

Date de réception	16 nov 22	Provenance	Échantillons
Date du rapport	29 nov 22		Trevo Bell
No. demande d'analyse	226632		2111, Lahesbone Road
Numéro d'accréditation	459		Sainte-Anne-de-Bellevue
Méthode Extraction Mehlich 3			H9X3V9
Résultats en base sèche			
		Échantillonné le :	Par :

Résultats d'analyses

Méthode	Unité	Paramètre	1	2	3	4
Numéro laboratoire			SO-0745201	SO-0745202	SO-0745203	SO-0745204
Identification champ			1	2	3	4
Culture prévue						
AEL-I-SOL-006		pH	7.3 B	6.6 B	7.4 R	7.3 B
AEL-I-SOL-007		pH tampon	7.3 TR	7.0 R	7.4 TR	7.3 TR
AEL-I-SOL-005		Mat. Org. %	7.9 TR	16.3 TR	6.8 R	3.1 M
AEL-I-SOL-003+AEL-I-EQP-028	kg/ha	P	146 B	65 P	136 B	380 TR
	kg/ha	K	548 R	133 M	462 R	408 R
	kg/ha	Ca	7241 R	4558 MB	7092 R	4568 MB
	kg/ha	Mg	669 TR	857 TR	987 TR	909 TR
	ppm	Al	576 M	662 M	604 M	791 MB
	ISP	P/Al*	11.3 1	4.4 1	10.0 1	21.4 1
	ppm	Mn	31.7 TR	16.6 R	47.1 TR	36.9 TR
	ppm	Cu	5.35 TR	1.32 TR	3.45 TR	4.49 TR
	ppm	Zn	18.29 TR	6.34 R	4.88 MB	5.49 B
	ppm	B	2.18 B	0.53 TP	1.45 M	1.02 P
	ppm	S				
	ppm	Fe	149	443	192	216
%		N total				
		C / N				
ppm		$N\text{-}NH_4$				
ppm		$N\text{-}NO_3$				

TP=Très pauvre, P=Pauvre, M=Moyen, MB=Moyen bon, B=Bon, R=Riche, TR=Très riche

Besoins en chaux IVA 100%

No laboratoire	SO-0745201	SO-0745202	SO-0745203	SO-0745204
No champ	1	2	3	4
Culture prévue				
Quantité t/ha				
Type de chaux	Calcique	Calcique	Calcique	Calcique

CEC et saturations en bases

No champ		1	2	3	4
CEC (meq/100g)		21.2 B	18.0 MB	20.8 B	15.9 MB
Base	Marge moy.	Saturation en bases			
K	0.3 - 2.0	3.0 R	0.8 M	2.5 R	2.9 R
Ca	25 - 60	76.4 TR	56.5 B	76.0 TR	64.0 R
Mg	1 - 10	11.7 R	17.7 TR	17.6 TR	21.2 TR
Total	10 - 90	91.1 TR	75.0 R	96.1 TR	88.1 R
Rapport	Marge moy.	Rapports entre les éléments			
K/Mg	0.1 - 0.5	0.25 B	0.05 P	0.14 M	0.14 M
K/Ca	.01 - .06	0.04 B	0.02 M	0.03 B	0.05 B
Mg/Ca	.03- 0.25	0.15 B	0.31 TR	0.23 B	0.33 TR

Autres résultats

			1		2		3		4	
Na / RAS	ppm	<5	32	0.5	271	4.6	6	0.1	10	0.2
Conductivité électrique	mS/cm									

* P/Al Valeur environnementale critique = limite entre bon et riche. Valeurs agronomiques critiques = limite entre pauvre et moyen, et, entre riche et très riche.

Physique du sol

Granulométrie		1	2	3	4
Sable	%				
Limon	%				
Argile	%				
Classe texturale					
Type de sol					

Estimé		1	2	3	4
Densité estimée	g/cm³	0.76 B	0.45 B	0.82 M	1.02 M
Porosité estimée	%	57.8 B	68.7 M	56.0 B	49.0 B
Perméabilité estimée					
Coef. Perméabilité	cm/h				
Coef. de réserve eau utile (CRU)	g eau / 100 g sol				

TF = Très faible, F = Faible, B = Bon, E = Élevé, TE = Très élevé

Remarques

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Une ou plusieurs remarques ont été trouvées pour l'échantillon "SO-0745204", veuillez-vous référer au rapport individuel pour plus de détails.

Contrôle qualité Valeurs attendues: 85 à 115 % — Résultats des échantillons contrôles passés avec vos échantillons, résultats en % des valeurs attendues pour chacun des paramètres

pH	MO	P	K	Ca	Mg	Al	Mn	Cu	Zn	B	S	Na	Fe	N total	C.E.
100.0	99.8	102.2	100.8	99.7	100.6	100.0	103.2	100.8	99.3	104.8					

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Page **1** sur **3**

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Accrédité pour pH, pH tampon, K, Ca, Mg, Al, Mn, Cu, Zn, par CEAEQ

Date de réception	16 nov 22	*Provenance*	*Échantillons*
Date du rapport	29 nov 22		Trevo Bell
No. demande d'analyse	226632		2111, Lahesbone Road
Numéro d'accréditation	459		Sainte-Anne-de-Bellevue
Méthode	Extraction Mehlich 3		H9X3V9
Résultats en base sèche			
		Échantillonné le :	Par :

Résultats d'analyses

Méthode	Unité	Paramètre				
		Numéro laboratoire	SO-0745205	SO-0745206	SO-0745207	SO-0745208
		Identification champ	5	6	7	8
		Culture prévue				
AEL-I-SOL-006		pH	7.5 R	7.5 R	5.2 M	7.2 B
AEL-I-SOL-007		pH tampon	7.5 TR	7.5 TR	5.6 MB	7.2 R
AEL-I-SOL-005		Mat. Org. %	8.0 TR	12.4 TR	12.6 TR	8.0 TR
AEL-I-SOL-003+AEL-I-EQP-028	kg/ha	P	112 MB	331 TR	37 TP	501 TR
	kg/ha	K	297 B	224 B	120 M	865 TR
	kg/ha	Ca	7562 R	9002 TR	1882 P	7173 R
	kg/ha	Mg	610 TR	1449 TR	352 R	928 TR
	ppm	Al	698 MB	618 M	631 M	508 M
	ISP	P/Al*	7.1 1	23.9 1	2.6 1	44.1 1
	ppm	Mn	22.9 TR	7.5 M	5.9 P	34.8 TR
	ppm	Cu	1.90 TR	4.94 TR	1.05 TR	2.35 TR
	ppm	Zn	6.61 R	10.25 TR	6.94 R	10.15 TR
	ppm	B	1.41 M	1.51 M	0.22 TP	1.96 MB
	ppm	S				
	ppm	Fe	151	267	287	189
	%	N total				
		C / N				
	ppm	N-NH_4				
	ppm	N-NO_3				

TP=Très pauvre, P=Pauvre, M=Moyen, MB=Moyen bon, B=Bon, R =Riche, TR=Très riche

Besoins en chaux IVA 100%

No laboratoire	SO-0745205	SO-0745206	SO-0745207	SO-0745208
No champ	5	6	7	8
Culture prévue				
Quantité t/ha			13.5	
Type de chaux	Calcique	Calcique	Calcique	Calcique

CEC et saturations en bases

No champ		5	6	7	8
CEC (meq/100g)		19.9 MB	26.0 R	22.7 B	23.2 B
Base	Marge moy.	Saturation en bases			
K	0.3 - 2.0	1.7 B	1.0 M	0.6 M	4.3 TR
Ca	25 - 60	84.7 TR	77.3 TR	18.5 P	68.9 R
Mg	1 - 10	11.4 R	20.7 TR	5.8 B	14.8 R
Total	10 - 90	97.7 TR	99.0 TR	24.9 P	88.0 R
Rapport	Marge moy.	Rapports entre les éléments			
K/Mg	0.1 - 0.5	0.15 M	0.05 P	0.11 M	0.29 B
K/Ca	.01 - .06	0.02 B	0.01 M	0.03 B	0.06 R
Mg/Ca	.03- 0.25	0.13 B	0.27 R	0.31 TR	0.22 B
Autres résultats					
Na / RAS	ppm <5	7 0.1	104 1.3	15 0.4	7 0.1
Conductivité électrique	mS/cm				

* P/Al Valeur environnementale critique = limite entre bon et riche. Valeurs agronomiques critiques = limite entre pauvre et moyen, et, entre riche et très riche.

Physique du sol

Granulométrie		5	6	7	8
Sable	%				
Limon	%				
Argile	%				
Classe texturale					
Type de sol					

Estimé		5	6	7	8
Densité estimée	g/cm³	0.79 M	0.71 B	0.67 B	0.81 M
Porosité estimée	%	56.8 B	58.8 B	60.6 M	56.1 B
Perméabilité estimée					
Coef. Perméabilité	cm/h				
Coef. de réserve eau utile (CRU)	g eau / 100 g sol				

TF = Très faible, F = Faible, B = Bon, E = Élevé, TE = Très élevé

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Une ou plusieurs remarques ont été trouvées pour l'échantillon "SO-0745208", veuillez-vous référer au rapport individuel pour plus de détails.

Contrôle qualité Valeurs attendues: 85 à 115 % — Résultats des échantillons contrôles passés avec vos échantillons, résultats en % des valeurs attendues pour chacun des paramètres

pH	MO	P	K	Ca	Mg	Al	Mn	Cu	Zn	B	S	Na	Fe	N total	C.E.
100.0	99.8	102.2	100.8	99.7	100.6	100.0	103.2	100.8	99.3	104.8					

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Accrédité pour pH, pH tampon, K, Ca, Mg, Al, Mn, Cu, Zn, par CEAEQ

Date de réception	16 nov 22	
Date du rapport	29 nov 22	
No. demande d'analyse	226632	
Numéro d'accréditation	459	
Méthode	Extraction Mehlich 3	
Résultats en base sèche		

Provenance

Échantillonné le :

Échantillons
Trevo Bell
2111, Lahesbone Road
Sainte-Anne-de-Bellevue
H9X3V9

Par :

Résultats d'analyses

Numéro laboratoire			SO-0745209	SO-0745210		
Identification champ			9	10		
Culture prévue						
AEL-I-SOL-006		pH	6.3 MB	8.2 TR		
AEL-I-SOL-007		pH tampon	6.5 B	8.2 TR		
AEL-I-SOL-005		Mat. Org. %	3.6 M	2.5 P		
AEL-I-SOL-003+AEL-I-EQP-028	kg/ha	P	86 M	160 B		
	kg/ha	K	179 MB	208 MB		
	kg/ha	Ca	2393 P	6440 B		
	kg/ha	Mg	377 R	247 R		
	ppm	Al	931 MB	421 M		
	ISP	P/Al*	4.1 1	16.9 1		
	ppm	Mn	6.5 P	36.7 TR		
	ppm	Cu	6.24 TR	5.18 TR		
	ppm	Zn	1.65 P	15.66 TR		
	ppm	B	0.34 TP	1.41 M		
	ppm	S				
	ppm	Fe	347	178		
%		N total				
		C / N				
ppm		$N\text{-}NH_4$				
ppm		$N\text{-}NO_3$				

TP=Très pauvre, P=Pauvre, M=Moyen, MB=Moyen bon, B=Bon, R =Riche, TR=Très riche

Besoins en chaux IVA 100%

No laboratoire	SO-0745209	SO-0745210		
No champ	9	10		
Culture prévue				
Quantité t/ha	3.8			
Type de chaux	Calcique	Calcique		

CEC et saturations en bases

No champ		9	10		
CEC (meq/100g)		15.6 MB	15.5 MB		
Base	Marge moy.	**Saturation en bases**			
K	0.3 - 2.0	1.3 B	1.5 B		
Ca	25 - 60	34.3 M	92.6 TR		
Mg	1 - 10	9.0 B	5.9 B		
Total	10 - 90	44.6 B	100.0 TR		
Rapport	Marge moy.	**Rapports entre les éléments**			
K/Mg	0.1 - 0.5	0.15 M	0.26 B		
K/Ca	.01 - .06	0.04 B	0.02 M		
Mg/Ca	.03- 0.25	0.26 R	0.06 M		

Autres résultats											
Na / RAS	ppm	<5	9	0.2	1068	16.8					
Conductivité électrique	mS/cm										

* P/Al Valeur environnementale critique = limite entre bon et riche. Valeurs agronomiques critiques = limite entre pauvre et moyen, et, entre riche et très riche.

Physique du sol

Granulométrie		9	10		
Sable	%				
Limon	%				
Argile	%				
Classe texturale					
Type de sol					

Estimé		9	10		
Densité estimée	g/cm^3	0.98 M	1.22 É		
Porosité estimée	%	50.5 B	41.9 B		
Perméabilité estimée					
Coef. Perméabilité	cm/h				
Coef. de réserve eau utile (CRU)	g eau / 100 g sol				

TF = Très faible, F = Faible, B = Bon, E = Élevé, TE = Très élevé

Remarques

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Contrôle qualité		Valeurs attendues: 85 à 115 %				Résultats des échantillons contrôles passés avec vos échantillons, résultats en % des valeurs attendues pour chacun des paramètres									
pH	MO	P	K	Ca	Mg	Al	Mn	Cu	Zn	B	S	Na	Fe	N total	C.E.
100.3	99.8	102.2	100.8	99.7	100.6	100.0	103.2	100.8	99.3	104.8					

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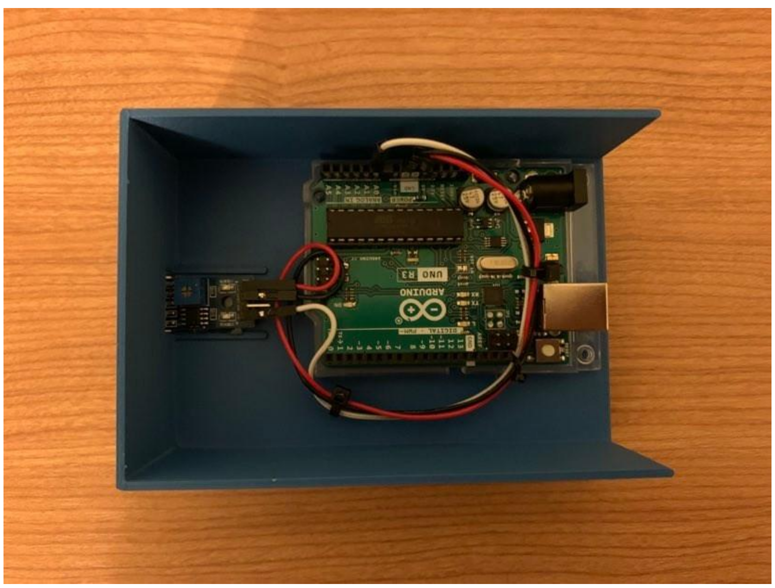
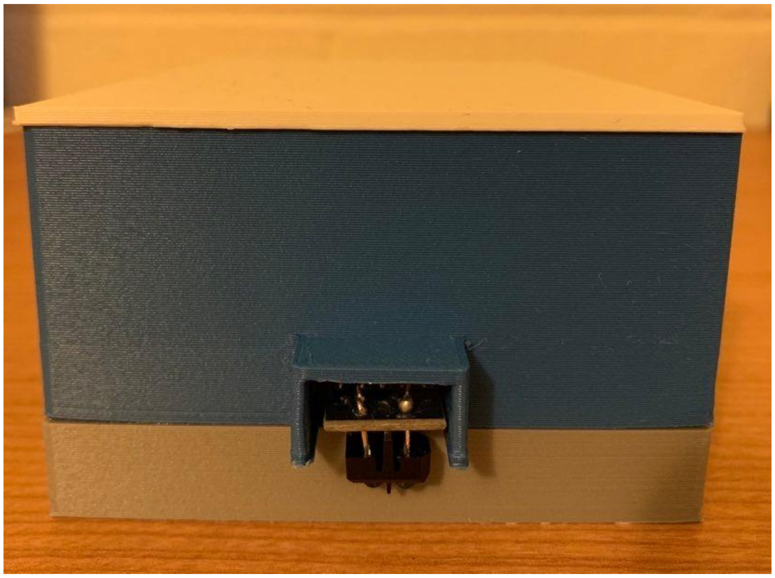
CHIMISTE Katy Beaulieu 2012-192 QUÉBEC

Appendix 3. Multiple perspectives of the soil carbon sensor system as follows: (a) covered top view, (b) uncovered top view, (c) front view, (d) side view, and (e) back view.

(a)

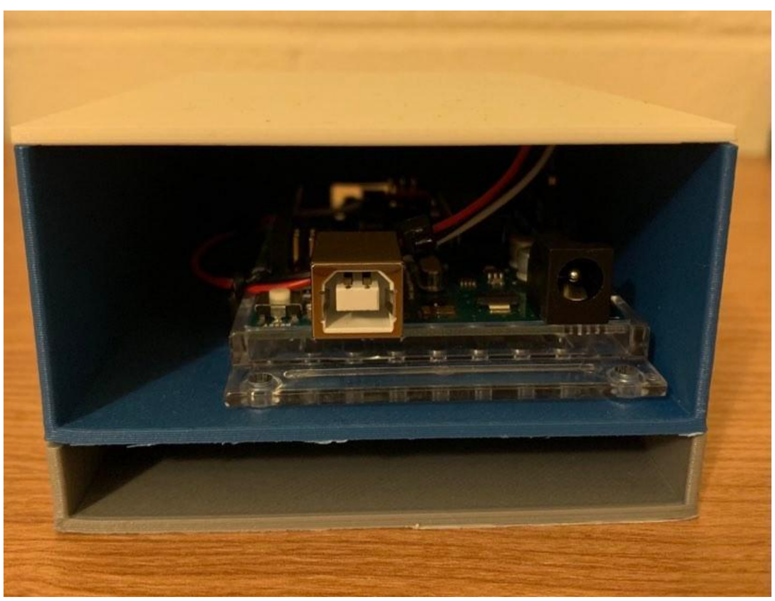


(b)



(c)

(d)



(e)