DEPARTMENT OF TRANSPORTATION

RE-USE OF REGIONAL WASTE IN SUSTAINABLY DESIGNED SOILS

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Research Project
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16. Abstract (Limit: 250 words)

This project explores the potential re-use of waste materials/by-products as a soil amendment in northeastern Minnesota. The project team identified 23 waste/by-products and collected 15 of but only analyzed 11 because of the possible content of persistent chemicals in some of the materials or the unwillingness of the owner to participate. Peat screenings, peat scrapings, tree bark, harbor dredge sediment, coarse and fine taconite tailings, and street sweepings were characterized in physical, chemical, and biological properties through lab tests. The results showed that none of the studied materials were defined as hazardous based on RCRA (Resource Recovery and Conservation Act) metal levels and contained minimal or undetectable Polychlorinated biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs) or Volatile Organic Compounds (VOCs). Peat by-products were efficient in removing metals from stormwater runoff. The relatively high phosphorus content of peat by-products provided sufficient nutrients to plant growth but could be released when mixed with low-phosphorus runoff. Dredge sediment and street sweeping had low organic contents but could remove 90% or more of the copper from the runoff. Tailings could remove 50% or less of the metals. Radish or oat can successfully grow in 28 days with individual materials or a blend of materials, except for fine tailings, which are in a clay form and thus don't filter water well.

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Re-use of Regional Waste in Sustainably Designed Soils

Final Report

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EXECUTIVE SUMMARY

By-products and waste materials generated by mineral, forestry, agricultural, and industrial sectors have the potential to be recycled, re-used, and/or combined with traditional materials to create a sustainable source of value-added soil and/or soil amendments. Re-use of the waste materials or the blends could restore disturbed lands (i.e., mine land reclamation and brownfield sites), create one or more value-added soil products, and promote smarter recycling and re-use practices and strategies, all of which provide environmental and economic benefit to the state. This project aims to identify, select, and characterize regional waste, by-products, and commercially available materials to explore the beneficial re-use of waste materials.

Various waste materials and by-products were identified and collected from different industries local to northeastern Minnesota for use in this research. The materials collected and studied included four peat screenings, two peat scrapings, one tree bark, Erie Pier dredge sediment, coarse and fine taconite tailings, and street sweepings. These materials were homogenized in the lab to ensure that samples used in testing were representative of the stockpiles from which they were originally collected. These materials were then split into three parts for testing of biological properties, environmental engineering, and civil engineering characteristics. After testing was completed on the individual materials, different materials were selected for blending and re-testing. At the completion of all lab testing, a life-cycle analysis was completed on all the materials, blends, and on a topsoil material used as a control.

BIOLOGY AND CHEMICAL PROPERTIES

The waste materials/by-products were characterized for their chemical contents including organic matter, nutrients, metals, Polychlorinated biphenyls (PCBs), Polycyclic Aromatic Hydrocarbons (PAHs) or Volatile Organic Compounds (VOCs). The six peat screenings and scrapes were found to be acidic but rich in organic matter. Peat scrapings typically have higher phosphorous and nitrogen contents than peat screenings. Dredge sediment and street sweepings were found to be low in organic contents but have medium to high contents of phosphorus and nitrogen. Tailings have the lowest nutrient content and organic matter content. None of these materials are defined as hazardous because of the low content of metals, PAHs, PCBs, and VOCs.

The greenhouse tests were performed for individual materials and the mixture of the peat byproducts and inorganic materials at two mixing ratios to test the germination rates and growth rates. Among the 11 materials, fine tailings were the only material showing little capacity to support plant growth. Also, this clay-type material was difficult to mix with any other media due to its cohesive consistency. Because of this, fine tailings were not recommended to be used as the soil amendment. The plant height and biomass of radish and oat showed little to no significant difference from the remaining 10 waste materials and the mixture of the organic and inorganic materials, probably because all materials contain sufficient nutrients to support six plants as studied.

This study used two sources of peat scrapings and four sources of peat screenings, but the plant growth data showed slight differences. Due to documented variability in peat’s properties, depending on origin

and degree of decomposition, it may be prudent to evaluate peat materials on a case-by-case basis when used as soil remediation.

ENVIRONMENTAL ENGINEERING

The chemical retention or release of the waste materials/by-products was tested by lab batch tests using deionized water or synthesized stormwater. Peat materials from various locations released copper, zinc, and phosphorus when mixed with deionized water. Typically, concentrations of 10 ppb or below for metals and 100 ppb or below for phosphorus were released. The release of these chemicals indicates that the application of the peat materials should be limited to a certain ratio in order not to exceed the water-quality standard for natural water bodies when the inflow stormwater has very low chemical contents. Instead, when the stormwater contains high concentrations of metals, peat materials will be a better option than most other inorganic waste materials because of their high metal removal efficiencies. Street sweepings were a good alternative to peat materials to treat stormwater because they could retain metals and phosphorus while not releasing any of these chemicals.

CIVIL ENGINEERING

The civil engineering properties of the materials were investigated to identify the material characterization, physical properties, and hydraulic conductivity characteristics. These properties were used to identify how the materials would perform as biofiltration media. The material classification and physical properties were studied so that future studies could compare other materials to the materials used in this study. The hydraulic conductivity was studied to ensure that materials would meet the performance criteria set by state and federal law. The results from these tests allowed for materials to be selected for blending and testing. The results indicated that coarser materials have larger hydraulic conductivity than finer materials, and soil mix permeability was controlled by the finer materials. The blend materials could provide sufficient infiltration rates and retain the first inch of rain.

LIFE-CYCLE ANALYSIS

A Life-Cycle Analysis (LCA) was completed, and a geographic information system (GIS) map that included by-product, source location, description, availability, characterization data, and current uses was constructed. The GIS map product included a figure that contained the material locations and data. The LCA included the methods used and the results. The results of these analyses highlighted how important it is that these analyses are run on a by-product basis. The further a product must be transferred, the more environmental impact it has. The conclusions of this task reinforced the importance of using local waste materials to decrease project costs, meet federal and state permitting requirements, and improve project sustainability.

CHAPTER 1: INTRODUCTION

The *Re-use of Regional Waste in Sustainably Designed Soils* project is designed to identify by-products and waste materials generated by the mineral, forestry, agricultural, and industrial sectors in northeastern Minnesota. Figure 1.1 shows the general northeastern Minnesota region referenced for this project. This project aims to identify, select, and characterize regional waste by-products and commercially available materials to create designed soils (such as topsoil specified in MnDOT spec 3877) (MnDOT, 2018) or to be used in borrow pit restoration. If successful, re-use of these materials will reduce disposal and/or storage of solid wastes while providing a site-specific designed soil or soil amendment, as well as provide financial advantages for the industries that generate these by-product materials.

Figure 1.1 Location map of northeastern Minnesota.

In Minnesota, climate change has increased the annual precipitation by 5 to 10% (EPA, 2016). This increase in precipitation is causing an increase in runoff, which is also causing a pollution problem. As vehicles pass over the road, they release various pollutants that then end up on the surface of the road. When there is rain, these pollutants are washed off the road into the environment surrounding the roads. The amount of pollution in the runoff decreases as the duration of a rainfall event increases.

Stormwater management systems used to control rainwater have changed greatly over the past few decades because of the increase in rainfall and changing environmental protection standards. Previous systems were primarily concerned with moving stormwater away from the local infrastructure to reduce flood risks but emphasized less reducing the pollution in the runoff. Current systems focus on retaining and treating stormwater locally where it falls to simulate the natural process of the water cycle.

Minnesota has developed Minimal Impact Design Standards (MIDS) that are based on Low Impact Development (LID). The goals of MIDS include standardizing stormwater management and improving water-quality standards. Bioslopes and bioswales are part of MIDS. These systems work by filtering the water through the soil and encouraging plant life. The water filtering through the soil will remove solid contaminants from the runoff, and plants work to retain various chemicals and heavy metals from the runoff.

The Minnesota Pollution Control Agency (MPCA), under the National Pollutant Discharge Elimination System (NPDES)/State Disposal System (SDS), requires a Construction Stormwater General Permit for construction activity that disturbs greater that one (1) acre of land (MPCA, 2013). The Construction Stormwater General Permit specifies that the first one inch of runoff from newly constructed impervious surfaces must be retained. This is required to protect Minnesota's lakes, rivers, and streams from harmful pollutants that are carried by stormwater runoff. Biofiltration systems are designed and built to meet the requirements set by the NPDES.

The performance of biofiltration in stormwater treatment relies on the media applied. However, industrial media are typically expensive and cost a lot in transportation as well. The re-use of locally available waste materials or by-products as the media could save construction and transportation costs, reduce waste production, and save storage space.

Minnesota is rich in many natural resources, including peatland, taconite mining by-products, and forest biomass, such as timber and forestry residuals. In Minnesota, which has more peatlands than any other state except Alaska, peatland covers about 7.2 million acres of land, about 14% of the state's total acreage (Olson et al., 1979). Salvage peat is often generated during multiple land uses. Also, mining is a critically important industry in Minnesota that annually generates tens of millions of tons of by-product taconite rocks, such as blast rock or taconite tailings (Zanko et al., 2012). The iron content of these materials could improve phosphorus removal from stormwater.

Using Minnesota's natural resources and land to produce products and materials that consumers desire inherently results in generation of high volumes of by-products and waste materials. Therefore, there is potential to recycle, re-use, and/or combine these by-products and waste materials with traditional materials to create new, value-added engineered soil mixes. Even though the use of these materials could reduce the amount of waste that needs to be disposed of, conserve natural resources, and promote development of sustainable infrastructures, few studies have explored the feasibility of re-using wastes and by-products for stormwater treatment.

The re-use of waste and by-product materials in engineered soil mixes for stormwater treatment is limited by many requirements, including water retention and infiltration capacities, hazardous contents of the materials, potential chemical leaching, and any effects inhibiting plant growth. A study considering these factors is necessary to evaluate if the waste materials or by-products are suitable to be used as the soil amendment.

CHAPTER 2: BACKGROUND

Stormwater runoff is a major source of pollution that threatens ecosystems surrounding roads in Minnesota. "Urban drainage from paved areas transports dissolved, colloidal, and solid constituents in a heterogeneous mixture, which includes metal elements and organic and inorganic compounds" (Sansalone et al., 1998). The sources of these materials transported by runoff stormwater include vehicle damage, vehicle emissions, road salt, and pollution. "The pollutant concentrations in urban stormwater runoff can often exceed those of treated wastewater […] thus degrading surface water quality and ecosystems" (Ekka et al., 2021). It is important that stormwater management systems deal with these pollutants to avoid affecting waterways and ecosystems.

Stormwater management systems have evolved over the past decades. As society pays more attention to the impacts of climate change, there has been an increase in scrutiny on the impacts humans are having on natural systems. Stormwater management systems are one of the systems that has been identified as having a large impact on the environment. "Historically, the goal was to move water off the landscape quickly and reduce flooding concerns" (MPCA, 2021). Previous systems were more concerned with protected infrastructure than potential contaminants in the stormwater runoff. More recently, there has been a push to re-create the natural process through engineering controls. The idea is that new stormwater systems will allow runoff to infiltrate through the soil before it reaches waterways. This allows the water to be "filtered" to help remove contaminants.

2.1 STORMWATER POLICIES

The MPCA currently enforces a permit to discharge stormwater under the NPDES / SDS. The requirements laid out in this permit specify that the stormwater retention system "must provide a live storage volume of one-inch times all the impervious area draining to the basin" (MPCA, 2013). If the area of the infiltration systems typically is the same size as the impervious area that is draining towards the system, then the system needs to be able to capture the first one inch of rainfall per rainfall event.

2.2 BIOFILTRATION SYSTEMS

The MPCA has released the Minnesota Stormwater Manual, which aims to answer questions regarding Best Management Practices (BMPs) for stormwater management. The Minnesota Stormwater Manual identifies integrated stormwater management as a process that accounts for how stormwater moves from the land that it falls on to the waterways it ends up in. One of the design principles that the MPCA has for integrated stormwater management systems is that each system "mimics pre-development hydrology. The practice should operate in a manner to replicate pre-development hydrology for a range of storm events such that it safely recharges groundwater, protects downstream channels and reduces off-site flood damage." (MPCA, 2021). Table 2.1 was been adapted from the Minnesota Stormwater Manual website and contains a summary of volume reduction processes.

Table 2.1 Summary of volume reduction processes (MSKF).

Process	BMP	Comments	Used for CSW Permit compliance
Infiltration	Low impact development/better site design/sustainable development	Includes such things as reduced street and sidewalk width, less curb and gutter drainage, scattered bioretention, shared pavement.	Yes if water is retained on site, typically through infiltration
	Trench or basin	Must be properly engineered in adequate soils; proper maintenance essential	Yes[1]
	Perforated sub-surface pipes, tanks and storage systems	Expensive but effective and space-saving.	If part of an infiltration stormwater practice
	Disconnected imperviousness	Includes primarily rooftop drains and roadway/parking surfaces	By itself, disconnection does not meet CSW permit requirements. Runoff must be diverted to an infiltration stormwater practice
	Pervious (porous pavement)	Includes a number of paving and block methods, or simple parking on reinforced grassed surfaces.	Yes[2]
	Bioretention (if contains infiltration element)	Some bioretention facilities are designed to infiltrate.	Yes if bioinfiltration. Biofiltration practices may achieve some volume reduction that can be credited toward permit compliance[3].
Evapotranspiration	Bioretention (rain gardens)	Exposes runoff water to plant roots for uptake; can be under-drained and still effective.	
	Vegetated swales	Provides water a chance to soak into the ground and be filtered as it flows.	Yes, though swales typically achieve limited volume reduction unless designed with check dams and/or occurring on permeable soils[4].
	Wetland/pond storage	Combination of standing water surface and vegetative root exposure yields volume reductions.	No
	Vegetated drainage corridor	Connecting numerous features increases opportunities.	No
	Recessed road/parking drainage	Routing paved surface runoff to vegetated sump areas keeps it out of receiving waters.	No, unless part of an infiltration practice
Storage	Rain barrel/cistern	Small-scale runoff collectors keep water around for later re-use or slow release.	Yes if captured water is infiltrated or otherwise used on site
	Rooftop (green roof)	Storage on a roof prevents water from leaving the site; combining with vegetation (engineered green roof) makes it even better.	Yes if captured water is retained on site (typically through evapotranspiration)
Conveyance	Vegetated swale	Provides water a chance to soak into the ground and be filtered as it flows.	Yes, though swales typically achieve limited volume reduction unless designed with check dams and/or occurring on permeable soils[5].
	Filter strips/buffers	Variation of vegetated swale with side slope protection.	No
Landscaping	Low Impact Development/Better Site Design	Includes such things as scattered bioretention, shared pavement, native or prairie plantings.	Yes if water is retained on site, typically through infiltration
	Bioretention (rain gardens)	Exposes runoff water to plant roots for uptake, can be under-drained and still effective.	Yes if bioinfiltration. Biofiltration practices may achieve some volume reduction that can be credited toward permit compliance[6].

As shown in Table 2.1, bioretention systems and vegetated swales are common volume-reduction systems recommended in the Minnesota Stormwater Manual. Bioslopes and bioswales are two common ways to reduce stormwater runoff and are commonly built in conjunction with each other in a “treatment train” to capture and treat runoff from roadways.

2.2.1 Bioslopes

Bioslopes, otherwise known as media filter drains (MFDs), can be constructed in various ways, depending on the roadway they are being constructed adjacent to. A MFD “is a linear flow-through stormwater runoff treatment device that can be sited along highway side slopes (conventional design) and medians (dual media filter drains), borrow ditches, or other linear depressions” (WSDOT, 2019). MFDs allow stormwater to infiltrate the soil media to filter out large contaminants and to remove dissolved contaminants using vegetation. Bioslopes are often constructed with vegetated filter strips and bioswales to completely capture and treat stormwater to meet MPCA regulations.

The Washington Department of Transportation (WSDOT) has developed standards for bioslope design. WSDOT has developed seven different design types, depending on application. MFD types 1 through 3 are used to capture sheet flow runoff. MFD types 4 through 7 are for capturing runoff that is diverted using a pipe (WSDOT, 2019). Figures 2.1-2.7 show the various bioslope types.

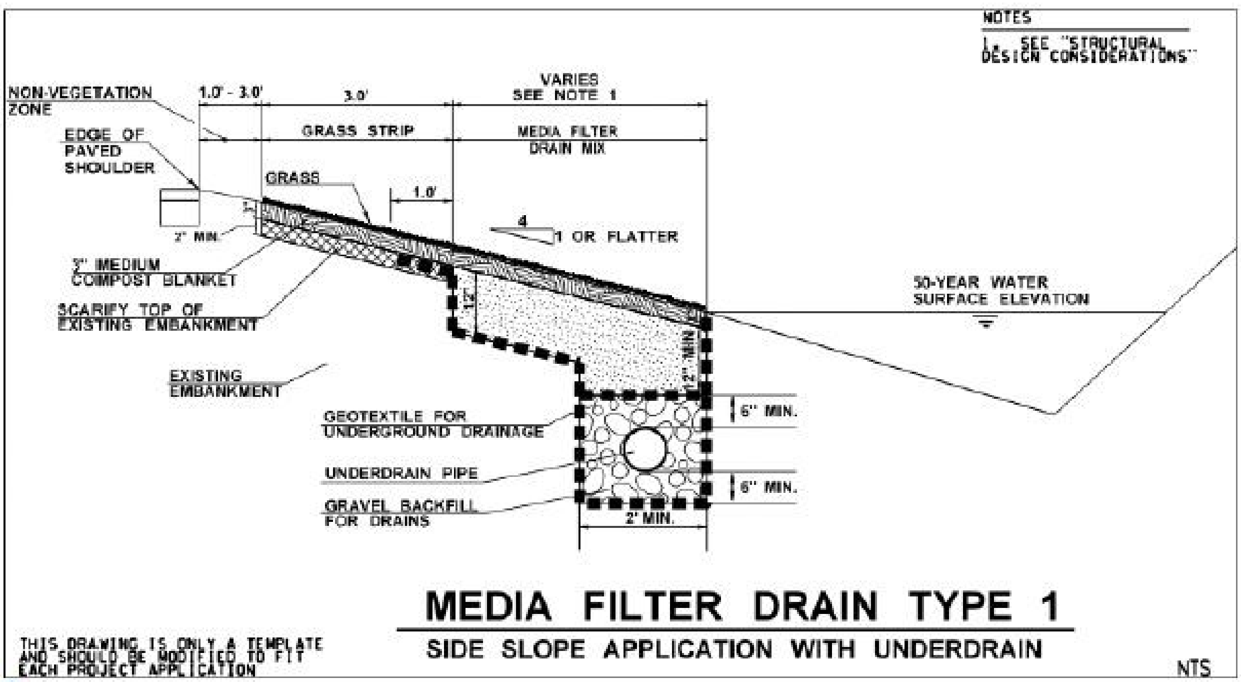

Figure 2.1 Cross section of Media Filter Drain Type 1 (WSDOT, 2019).

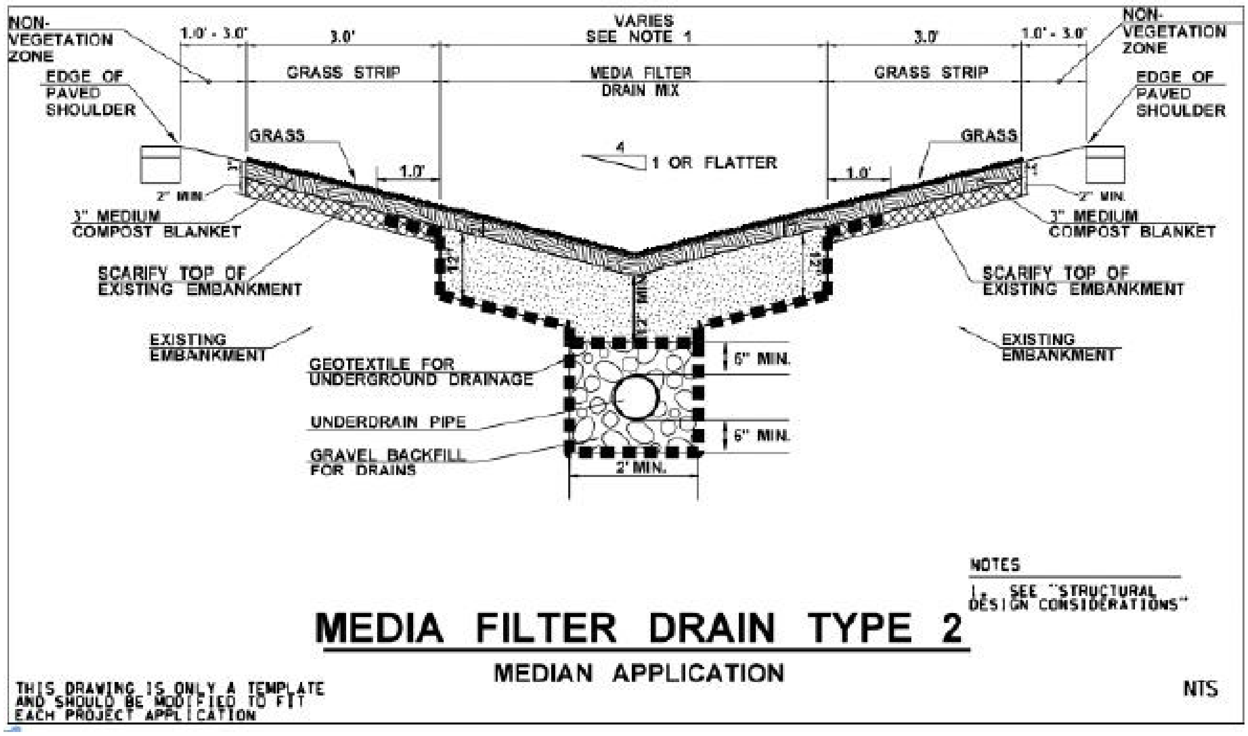

Figure 2.2 Cross section of Media Filter Drain Type 2 (WSDOT, 2019).

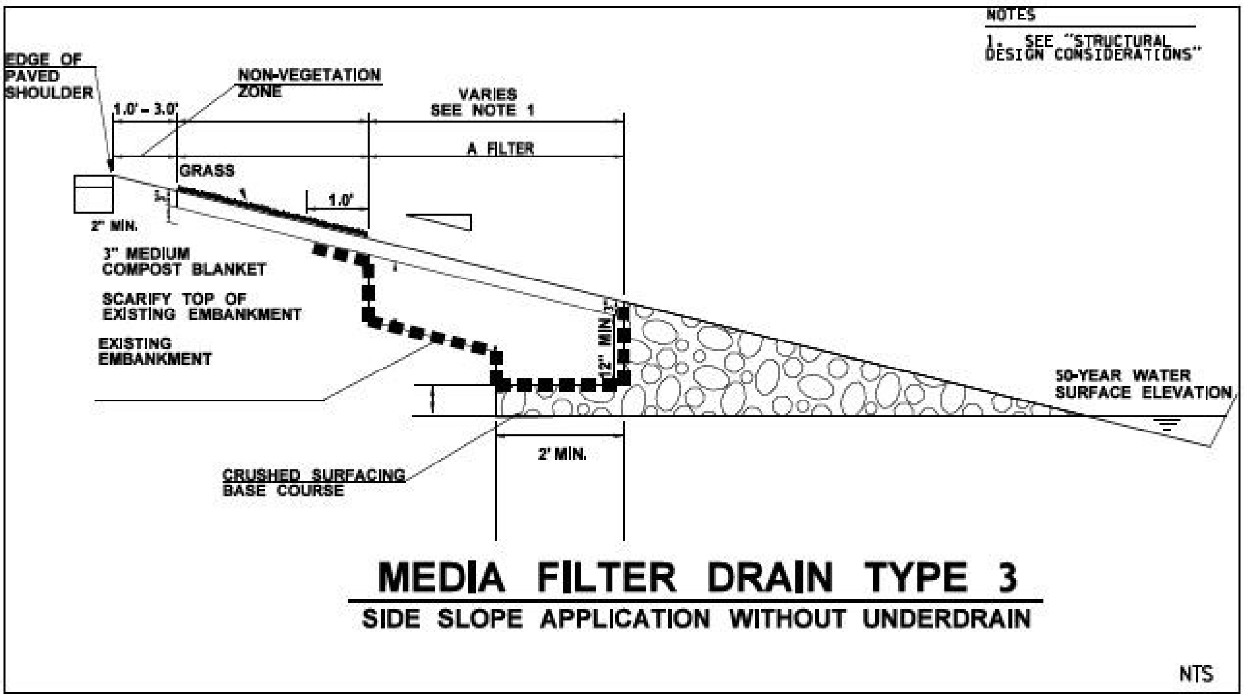

Figure 2.3 Cross section of Media Filter Drain Type 3 (WSDOT, 2019).

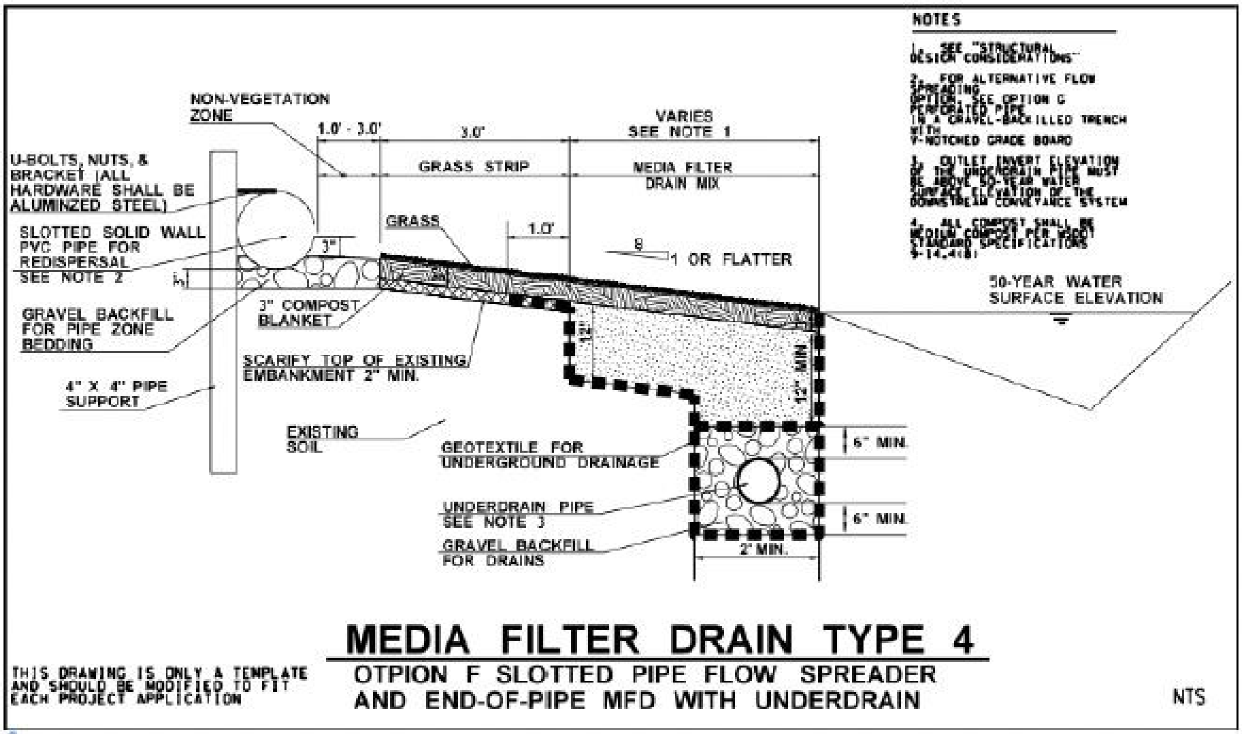

Figure 2.4 Cross section of Media Filter Drain Type 4 (WSDOT, 2019).

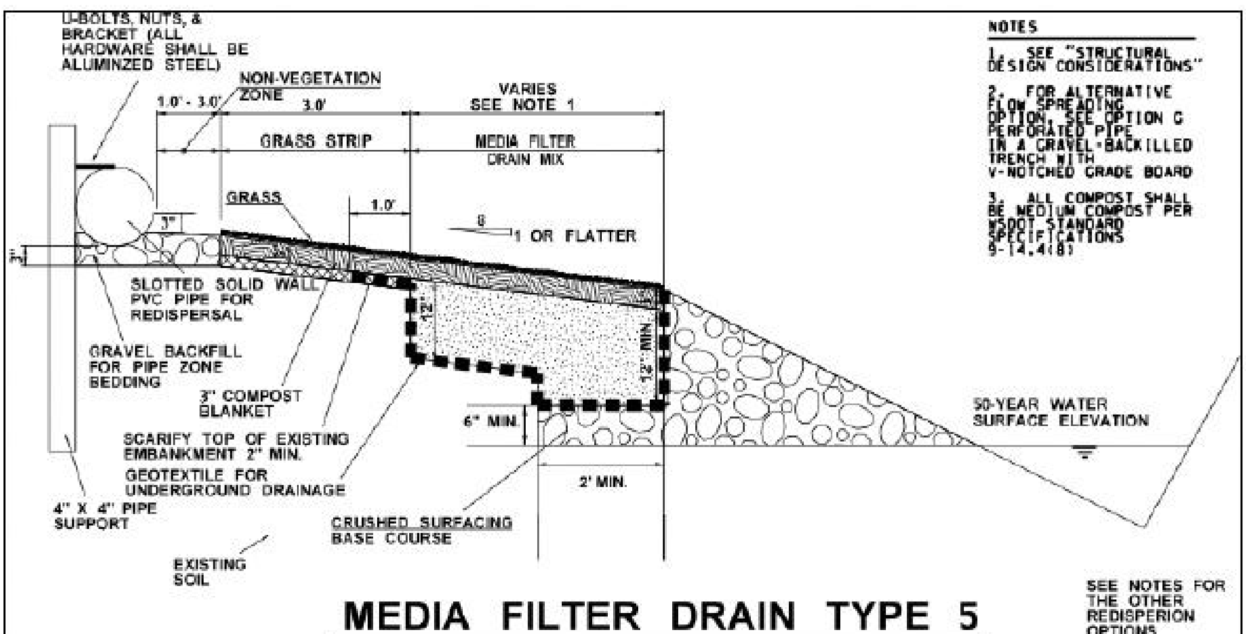

Figure 2.5 Cross section of Media Filter Drain Type 5 (WSDOT, 2019).

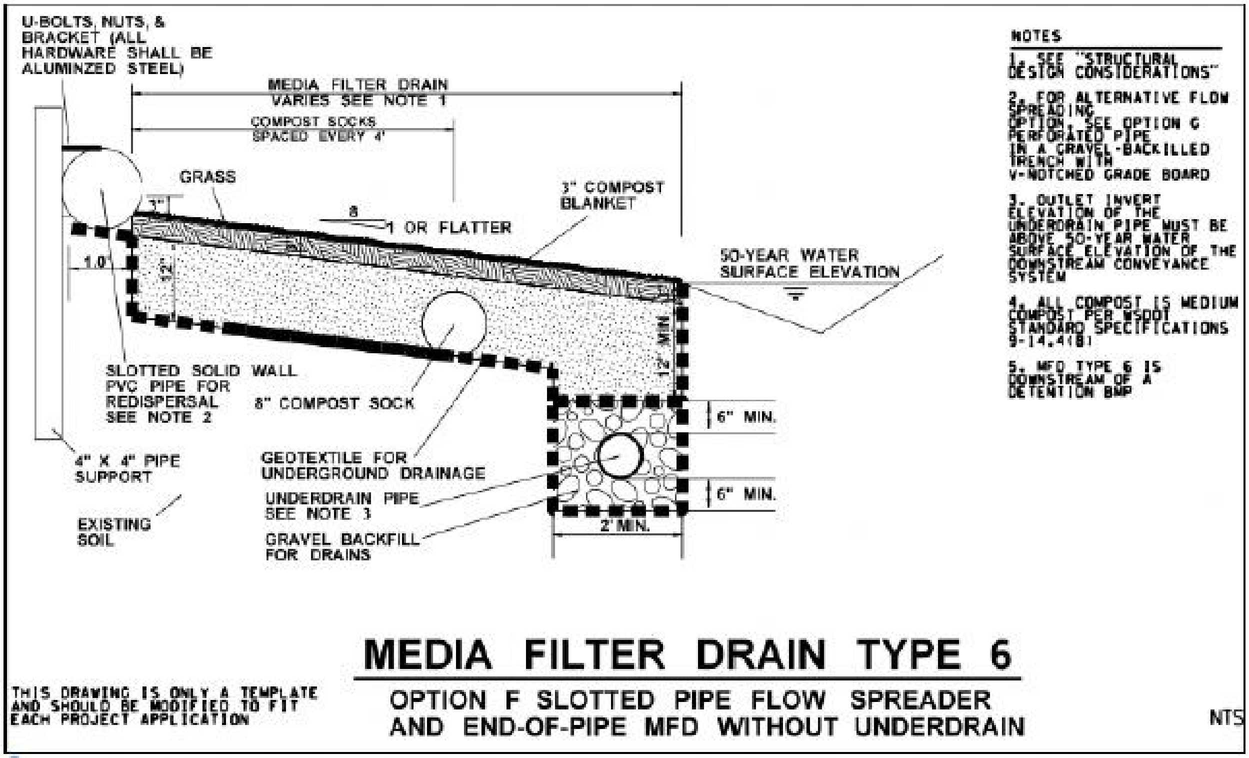

Figure 2.6 Cross section of Media Filter Drain Type 6 (WSDOT, 2019).

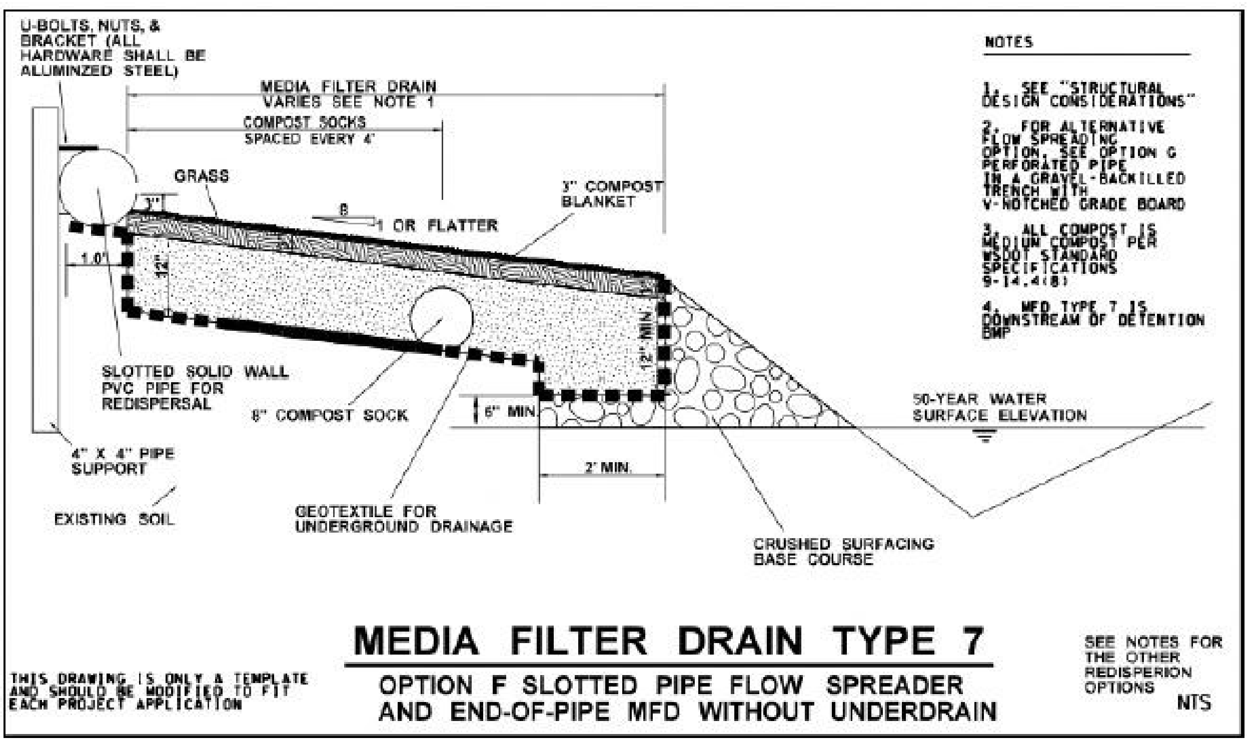

Figure 2.7 Cross section of Media Filter Drain Type 7 (WSDOT, 2019).

Each of the seven different MFD types shown above have a unique design that makes them applicable for different situations. MFD types 1 through 3 are designed to treat stormwater runoff that is being directly drained to the bioslopes. MFD type 2 is further differentiated from the rest because it is designed for depressions (such as medians) between two impervious surfaces. MFD types 4 through 7 are designed to treat stormwater that has to be diverted from the roads, to the bioslope, through pipes. MFD types 1, 2, 4, and 6 all contain underdrains. Underdrains are used to ensure that there is free flow through the MFD mix. If it can be ensured that there will be continuous free flow through the MFD mix without an underdrain, the underdrain can be omitted from the design (WSDOT, 2019).

There are limitations to the MFDs, which means that they are not suitable for all projects. The slope of MFDs constructed alongside roadways (Type 1-3) cannot exceed 4H:1V and cannot exceed 8H:1V for MFD Type 4-7 (WSDOT, 2019). MFDs are also not suitable for construction in wetlands, on unstable slopes, or in locations with shallow groundwater. Shallow groundwater can impact MFD performance by saturating the MFD mix (WSDOT, 2019).

2.2.2 Vegetated Filter Strips

Vegetated filter strips are typically constructed adjacent to the shoulder of a roadway. Vegetated filter strips are long strips of vegetated ground that act to slow down runoff and remove sediments and other large contaminants from stormwater (WSDOT, 2019). Vegetated filter strips also protect roadsides from erosion, as the roots help hold the soil in place. Figure 2.8, taken from Washington Department of Transportation's Highway Runoff Manual, shows a typical vegetated filter strip.

There are also limitations for when vegetated filter strips can be used. Vegetated filter strips are not suitable on steep slopes, in narrow construction zones, or in areas where vegetation struggles to grow. These limitations are typically not an issue in Minnesota but are important to know about when designing a stormwater management system.

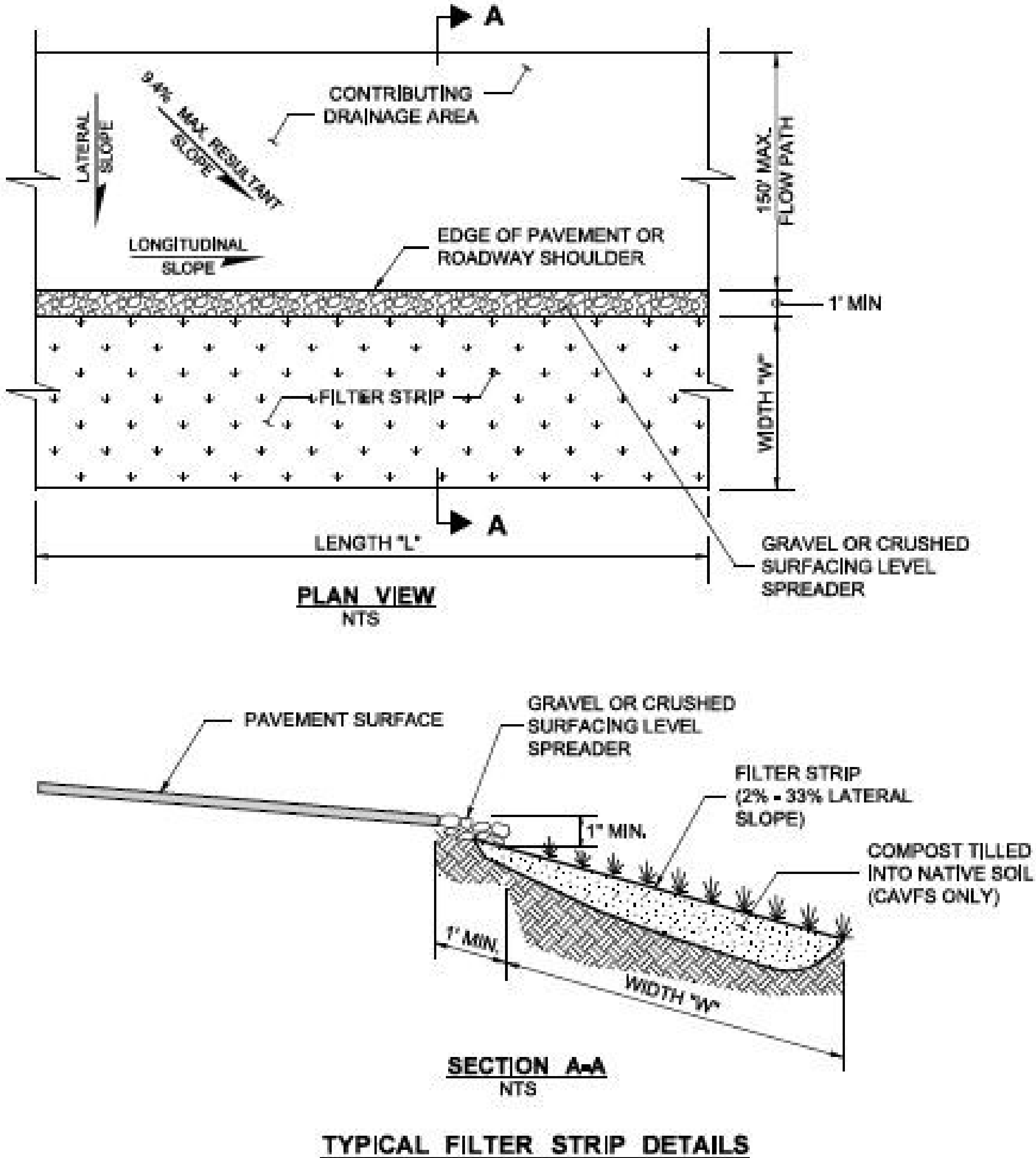

Figure 2.8 Typical Vegetated Filter Strip Plan View and Cross Section (WSDOT, 2019).

2.2.3 Bioswales

Bioswales are another biofiltration system that are commonly used in Minnesota. Bioswales are open channels that feature shallow slopes, wide cross sections, and vegetation (ODOT, 2014). Bioswales use the vegetation to slow down the flow of runoff as it flows through the channel. This serves two purposes: reducing channel erosion of the channel and giving the runoff more time to seep into the soil to be treated (ODOT 2014). As with vegetated filter strips, the vegetation also removes sediments and other large contaminants from the runoff. The wide cross section of the channel allows for a shallower flow of water and provides for surface area for filtration and treatment (ODOT, 2014). The Oregon Department of Transportation (ODOT) has produced a hydraulics manual that gives a typical cross section of a bioswale, shown in Figure 2.9.

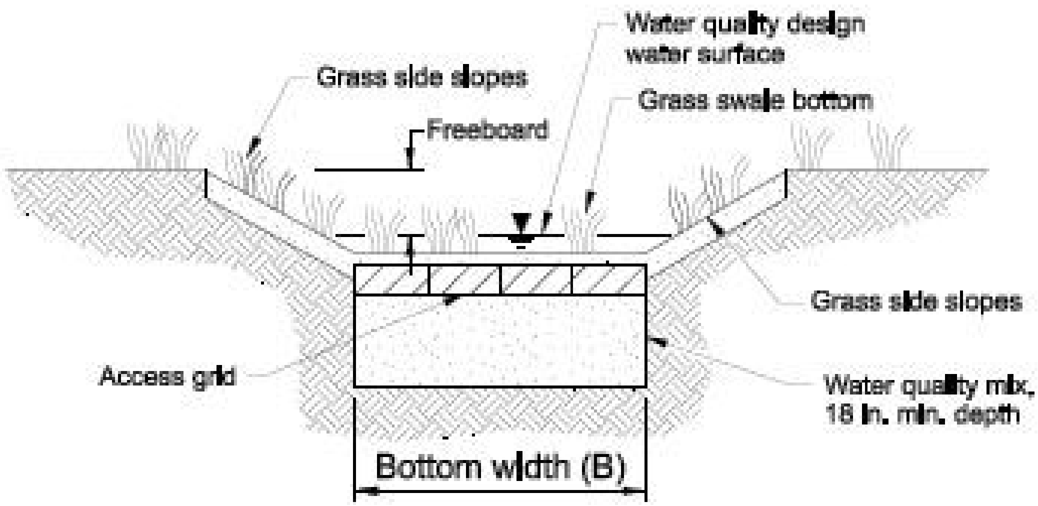

Figure 2.9 Typical bioswale cross section (ODOT, 2014).

2.3 BY-PRODUCTS USE AS FILTRATION MEDIA

Currently, MnDOT uses compost or peat materials as soil amendments to *in-situ* soils for bioslope and bioswale construction. There is concern for nutrient leaching when compost is used as a soil amendment (Saftner et al., 2019). This research aims to replace compost and peat as soil amendments with by-product materials. In order to replace compost and peat, the byproducts must meet the requirements set in the Minnesota 2018 Standard Specifications for Filter Topsoil Borrow. MnDOT 3877.2G defines Filter Topsoil Borrow as being 60%-80% sand meeting the gradation requirements of MnDOT 3126, and 20%-40% Grade 2 compost per Mn/DOT 3890-2 (MnDOT, 2018). The gradation requirements for MnDOT 3126 are shown in Figure 2.10. The requirements for MnDOT 3890-2 are shown in Figure 2.11.

Table 3126-3 Fine Aggregate Gradation Requirements	
Sieve Size	Percent Passing*
⅜ in	100
No. 4	95 – 100
No. 8	80 – 100
No. 16	55 – 85
No. 30	30 – 60
No. 50	5 – 30
No. 100	0 – 10
No. 200	0 – 2.5
* Percent passing by weight through square opening sieves.	

Figure 2.10 Fine Aggregate Gradation Requirements (MnDOT, 2018).

Table 3890-2 Grade 2 Compost Requirements	
Requirement	Range
Organic matter content (dry weight)	≥ 30 %
C/N ratio	6:1 – 20:1
NPK ratios (Max. % dry weight)	1:1:1
pH	5.5 – 8.5
Moisture content	35% – 55%
Bulk density	700 lb per cu. yd – 1,600 lb per cu. yd
Inert material *	< 3% at 0.15 in
Soluble salts	≤ 10 mmho per cm
Germination test ‖	80% – 100%
Screened particle size	≤ ¾ in.
* Includes plastic bag shreds. ‖ Germination test must list the species of Cress, cucumber, or lettuce seed used.	

Figure 2.11 Grade 2 compost requirements (MnDOT, 2018).

CHAPTER 3: BY-PRODUCT IDENTIFICATION & COLLECTION

Waste and by-product information was collected from businesses and government facilities. Site visits were conducted on selected sites when permitted. During these visits, more information was obtained about the by-products such as amounts of material available/being produced and the process that produced the material. Sites that were visited by the research team include Plaisted Companies, Erie Pier, Verso Corporation, and the Duluth Street Maintenance Facility.

3.1 POTENTIAL MATERIALS

Our team has identified 23 by-products and waste materials from 14 companies/agencies (shown in Figure 3.1) to be considered for characterization and potential use in the production of sustainably designed soils. Table 3.1 contains a list of the identified materials, the industries and companies that produce them, the locations where they are produced and quantities produced, and whether or not there is existing data from previous research for the samples.

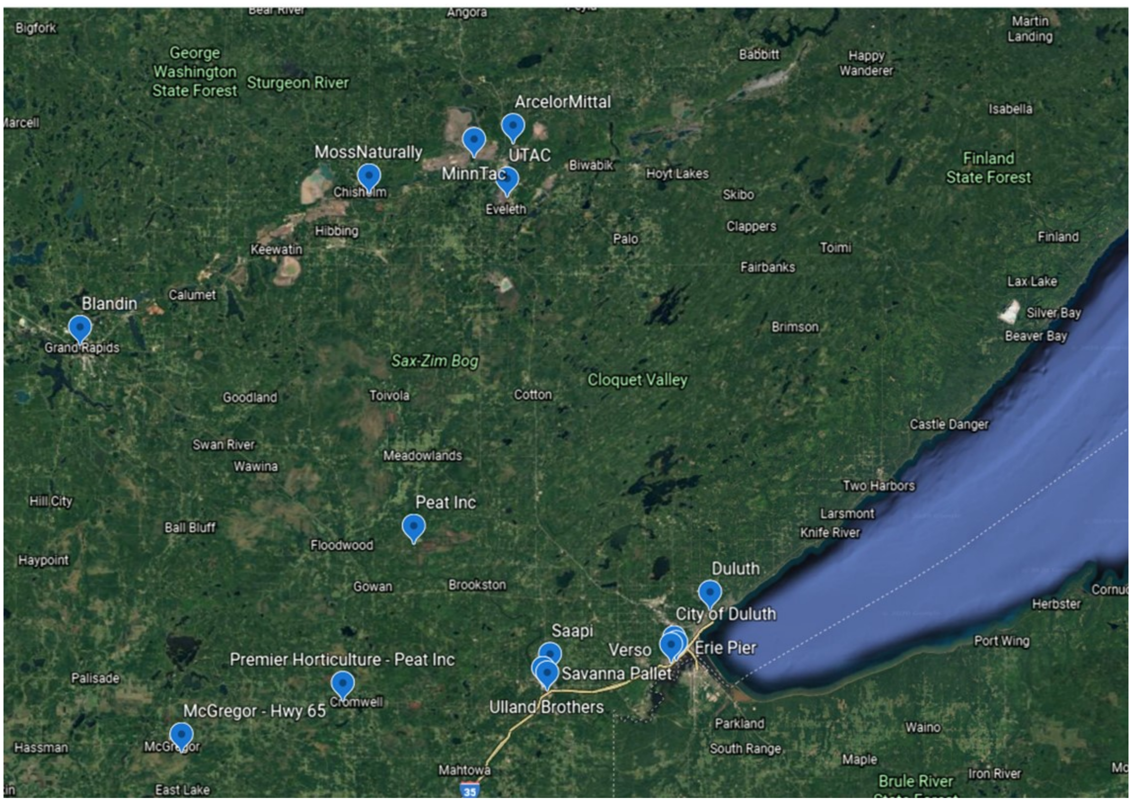

Figure 3.1 Location map, northeastern Minnesota, potential by-product businesses.

Table 3.1 Regional by-products identified for potential use in sustainably designed soils.

No.	Industry	Name	By-product	Location	Quantities	Existing Data Y/N
1	Wood Products	Blandin	Tree Bark	Grand Rapids	--	Y
2	Paper	Verso	Paper sludge	Duluth	--	Y
3	Paper	Sappi	Wood/Mixed Ash	Cloquet	--	N
4	Road Construction, Storm debris	St. Louis County	Wood, trees, branches	Duluth and County	--	N
5	Iron Mining	Arcelor Mittal	Fine Tailings	Virginia	--	Y
6	Iron Mining	Arcelor Mittal and Yawkey	Coarse Tailings	Virginia	--	Y
7	Iron Mining	MinnTac	Coarse Tailings	Mt. Iron	--	Y
8	Iron Mining	MinnTac	Fine Tailings	Mt. Iron	--	Y
9	Iron Mining	UTAC	Baghouse Fines	Eveleth	4000 tons/yr	N
10	Rock Quarry & Gravel Pits	Ulland	Rock chips, flour, fragments	Duluth	--	N
11	Peat Mining	Peat Inc.	Peat Scrapings	Cromwell	7 – 10,000 cy/yr	Y
12	Peat Mining	Peat Inc.	Peat Screenings	Cromwell	--	Y
13	Peat Mining	Peat Inc.	Peat Screenings	Floodwood	20,000 cy stockpile	Y
14*	Peat Mining	Peat Inc.	Peat Screenings	McGregor	7 – 10,000 cy/yr	Y
15	Peat Mining	Peat Inc.	Peat Scrapings	McGregor	--	Y
16	Peat Mining	Premier Horticulture	Peat Screenings	Cromwell	--	Y
17	Moss processing	MossNaturally	Stems	Chisholm	--	N
18	Harbor Dredging	USACE	Fine grained sediment	Duluth	100,000 cy/yr	Y
19	Sanitary District	WLSSD	Biosolids, Grit	Duluth	--	Y
20	Public Works Dept	City of Duluth	Street Sweepings	Duluth	6,000 t/yr	Y
21	Ditch cleaning materials	St Louis County	Road Maintenance & Construction	Duluth and County	--	N
22	Ground Tires	TDA	Tire aggregate	Isanti	--	Y
23	Hospital	Essentia Health	Food waste	Duluth	--	N

*Sample was delivered to lab, sample was not of sufficient quantity to use in research.

3.2 PLAISTED COMPANIES TOUR

Plaisted Companies, Inc. is a large-scale soil manufacturing and composting company located in Elk River, Minnesota. Plaisted Companies is the parent company for Peat Inc., which has several peat bogs in northern Minnesota. They provide custom blended soil mixes to the golf and athletic fields market as well as to contractors, nurseries, and greenhouses, primarily in the Twin Cities metro area. The project research team toured their Elk River facility on October 24, 2019 to observe large-scale bark composting and soil mixing. This visit gave the team a good idea of what a large-scale mixing operation would entail. Figures 3.2 through 3.5 show various aspects of the operation.

Figure 3.2 Plaisted compost mixing site.

Figure 3.3 Plaisted compost piles.

Figure 3.4 Machine used at Plaisted to mix soil blend components.

Figure 3.5 Plaisted soil blend material.

3.3 WOOD WASTE

Minnesota's forest industry contributes to the production of products like paper, lumber, and pallets. Wood waste generated by these businesses can include tree branches, tree bark, sawdust, ash, and sludge. We collected samples of several different waste materials, including sludge at Verso and bark at Blandin paper mill. Our team toured the Verso Corporation paper mill, located in Duluth Minnesota, in November 2019. The Verso mill has a paper mill making traditional paper and a recycled pulp mill that makes a plywood-like material made from recycled cardboard and paper called wet lap. When these materials are being produced, there is a fibrous waste material that is also produced. This fibrous waste contains the fibers that are too low quality to be included in the wet lap material, so they traditionally have been discarded as waste. For use in sustainably designed soils, the Carbon to Nitrogen (C:N) ratio from wood products will have to be carefully considered when blending with other materials in order to sustain an optimal environmental for soil microbe, therefore, to release nitrogen or phosphorus for plant growth.

3.4 IRON MINING

The Mesabi Iron Range can generate over 125 million tons per year of by-products from mining and processing of taconite iron ores (Oreskovich et al., 2007). By-products include materials that range from very fine sand to boulders. Coarse tailings are sand-sized waste material with few fines. There have been numerous studies to evaluate the engineering and environmental properties of tailings. They have been used regionally in road constructions as fill and in bituminous pavements since the 1960s. A previous study evaluated taconite tailings for use in bioslope/bioswale design (Johnson et al., 2017). Based on the results, using this material could add a sandy fraction to the soil blends.

3.5 PEAT MINING

3.5.1. Peat Inc.

Peat Inc. is a subsidiary of Plaisted Companies. They currently harvest peat for their bulk soil mixes from three bogs in northern Minnesota located near McGregor, Cromwell, and Floodwood. As a part of this commercial production, they generate waste materials including peat screenings and peat scrapings. Peat screenings are the oversized bits of peat and wood that result from the screening process. Peat scrapings are the spilled peat materials that are scraped off the loading sites. Samples of both peat screenings and scrapings were collected from waste stockpiles at the McGregor and Cromwell sites. Peat screenings were collected from a long-standing waste stockpile at the Floodwood site. Figure 3.6 shows the stockpile on the day of sample collection.

Figure 3.6 Peat screening waste pile at Peat Inc. in Floodwood MN.

3.5.2. Premier Horticulture, Inc.

Premier Horticulture harvests Sphagnum moss peat for horticultural purposes at their site located near Cromwell, Minnesota. Premier Horticulture generates large quantities of peat screenings during the processing of the Sphagnum moss peat product. A stockpile of the peat screenings can be seen in Figure 3.7.

Figure 3.7 Peat screenings stockpile at Premier Horticulture Inc. in Cromwell MN.

3.5.3. MossNaturally

A MossNaturally representative expressed an interest in providing by-products from their operation to be analyzed in this study. The by-product material from MossNaturally is the stems that accumulate as part of the company's peat moss processing activities.

3.6 DREDGE SEDIMENT

The city of Duluth is located on Lake Superior and supports a national and international shipping industry. Maintenance dredging of sediment that accumulates in the shipping channels is required, and approximately 100,000 cubic yards of material must be dredged annually. This sediment is either used for beneficial uses in the harbor or stored at Erie Pier. Erie Pier is a placement and re-use facility where dredge material is separated based on grain size and then stored on site. The fine-grained material at this site has few alternative uses; as a result, the site is filling up. A site visit to the 89-acre site was done to determine available volume and to see how this fine-grained material is separated from sand-size materials. Figure 3.8 is a representative photo of the material found at the site.

Figure 3.8 Dredge material stockpile from Erie Pier in Duluth MN.

The U.S. Army Corps of Engineers (USACE) is interested in exploring the potential uses of the dredge sediment. To support our project, USACE performed the greenhouse tests with the single material and the blend of the dredge sediment and other materials collected through one in-kind contract. Their findings are included in Appendix A.

3.7 OTHER MATERIALS

Other facilities that could provide useful material for manufacturing topsoil include wastewater treatment facilities, city and county public works departments, and hospitals. Some of these materials already have alternative beneficial re-use options, and others do not have any current re-use options.

3.7.1 Wastewater Treatment - Western Lake Superior Sanitary District (WLSSD)

Personnel from WLSSD were interviewed to determine what types of waste products generated by wastewater treatment could be available and utilized for soil blends or amendments. Approximately 30,000 tons of wet Grade B biosolids are produced annually. Most of this material is marketed as Field Green and is sold as crop and field fertilizer. They also produce about 500 tons of grit per year. This is an inorganic waste that is approximately ¾ to ¼ inch in size. This material is currently landfilled after generation.

3.7.2 Public Works Departments

3.7.2.1 City of Duluth

The City of Duluth's street sweeping results in the accumulation of sand and fine-grained material. These materials are stockpiled at a street maintenance facility in Duluth. Figure 3.9 shows the stockpile of material that is collected and stored by the City of Duluth.

Figure 3.9 Stockpile of street sweepings collected by the city of Duluth in Duluth MN.

3.7.2.2 St. Louis County

St Louis County is looking for a beneficial use for several waste materials that include sediment from ditch cleaning, wood, trees and branches from road construction and storm damage. These materials are currently landfilled after they are collected.

3.7.3 Tire Derived Aggregate (TDA)

TDA approached our team to provide information about their product. Used tires are ground to a variety of sizes and used in place of traditional aggregate in a variety of applications. Their material is more of an existing product than a by-product.

3.7.4 Essentia Health

Food waste was determined to be a potential by-product for use in this study. Health care is a large industry in Duluth, and it was assumed that local hospitals generate large quantities of food waste. After getting into contact with Essentia Health, it was discovered that food waste is already collected by WLSSD.

CHAPTER 4: SAMPLE SELECTION AND COLLECTION

Of the 23 by-products that were initially identified as having potential for beneficial re-use in sustainably designed topsoil, only 15 were sampled for use in the study. Site visits were completed on select sites in the fall of 2019, and all samples were collected by spring of 2020. Samples were delivered to NRRI by representatives from companies who wished to participate in the study but were not able to allow site visits. Table 4.1 shows which samples were collected and which were analyzed in the study.

Table 4.1 Sampled and potential regional by-products sampled, and to be tested for potential use in sustainably designed soils.

No.	Industry	Name	By-product	Location	Sampled	Characterized
1	Wood Products	Blandin	Tree Bark	Grand Rapids	Y	Y
2	Paper	Verso	Paper sludge	Duluth	Y	N
3	Iron Mining	Arcelor Mittal	Fine Tailings	Virginia	Y	N
4	Iron Mining	Arcelor Mittal and Yawkey	Coarse Tailings	Virginia	Y	N
5	Iron Mining	MinnTac	Coarse Tailings	Mt. Iron	Y	Y
6	Iron Mining	MinnTac	Fine Tailings	Mt. Iron	Y	Y
7	Peat Mining	Peat Inc.	Peat Scrapings	Cromwell	Y	Y
8	Peat Mining	Peat Inc.	Peat Screenings	Cromwell	Y	Y
9	Peat Mining	Peat Inc.	Peat Screenings	Floodwood	Y	Y
10	Peat Mining	Peat Inc.	Peat Screenings	McGregor	Y	Y
11	Peat Mining	Peat Inc.	Peat Scrapings	McGregor	Y	Y
12	Peat Mining	Premier Horticulture	Peat Screenings	Cromwell	Y	Y
13	Harbor Dredging	USACE	Fine grained sediment	Duluth	Y	Y
14	Sanitary District	WLSSD	Biosolids, Grit	Duluth	Y	N
15	Public Works	City of Duluth	Street	Duluth	Y	Y

Samples that were previously identified as a beneficial re-use were removed from the study, as they are already benefiting another industry. The only material that was eliminated from the study due to this reason was the food waste from Essentia Health.

TDA was removed from the study due to the difficulties associated with working with the material. TDA contains the steel reinforcement wires from the tires, and therefore it poses an injury risk. Testing TDA is also difficult because of the large relative nominal aggregate size.

Some businesses were reluctant to participate due to the possibility that the benefits of finding a re-use for their by-products would not outweigh potential future liabilities from discoveries during lab testing of the materials. Per ArcelorMittal's request, two of the tailing samples collected were removed from the study.

The ditch cleaning by-product material from St. Louis County was eliminated from the study due to the variable nature and quantities of the material that is generated. These by-products vary from sediment to fallen trees, meaning the by-products are not homogenous. Furthermore, the quantities of these materials depend heavily on weather events and road construction; therefore, a constant supply of these materials cannot be guaranteed.

The possibility that a contaminated by-product may create an environmental issue where one did not exist before was also a concern. Perfluorinated chemicals (PFCs) are a group of man-made compounds that are classified as "emerging contaminants." The Minnesota Department of Health (MNDoH) defines this term as "contaminants about which we have a new awareness or understanding about how they move in the environment or affect public health. PFCs, like other emerging contaminants, are the focus of active research and study" (MNDoH, n.d.). Currently there are no EPA developed and approved PFC test methods or standards for solid/soil like materials. The MPCA has developed some soil reference values, but chemical analysis methods are not standardized. Due to this concern, the research team decided to focus on using by-products less likely to contain PFCs, especially those produced from physical and not chemical processes. Verso paper sludge and WLSSD samples were not be included in the rest of the project due to the potential presence of PFCs.

CHAPTER 5: METHODS

5.1 INTRODUCTION

This chapter provides a description of tests and procedures used to classify and characterize materials being studied for re-use in sustainably designed soils. The materials being characterized include fine tailings, coarse tailings, peat scrapings, peat screenings, street sweepings, dredge material, and tree bark. The materials were sampled in buckets and needed to be homogenized prior to any lab tests. The lab testing procedures were selected after a review of the literature. The lab tests were completed to determine the biological, environmental, and physical properties of each material. Based on the results of the lab tests for each material, soil blends would then be determined for further lab testing. These soil blends would be re-tested to determine the same properties that were investigated for each by-product. After the completion of lab testing, a Life-Cycle Analysis (LCA) was completed on all of the materials and blends that were tested in order to determine their environmental and economic impacts.

5.2 HOMOGENIZING MATERIALS

All of the samples that were taken as part of this study were taken in buckets and then stored in a cooling room at NRRI. In order to have enough material for the entirety of the testing, multiple buckets of each material were taken. Because the samples in the buckets could not be guaranteed to be individually representative of by-product, it was determined that the buckets of the samples needed to be mixed in order to homogenize the samples to ensure repeatable results. The researchers blended the materials using a large-scale soil mixer, shown in Figure 5.1, to mix the buckets together for 15 minutes. After the mixing was completed, the samples were split back into buckets for delivery to the labs for lab testing.

Figure 5.1 Soil mixer used to homogenize by-product samples.

5.3 INDIVIDUAL BY-PRODUCT CHARACTERIZATION

5.3.1 Biological

The chemical contents of 10 waste materials were characterized for nutrient contents, Resource Conservation and Recovery Act (RCRA) metals, Polycyclic Aromatic Hydrocarbons (PAHs), Polychlorinated Biphenyls (PCBs) and volatile organic compounds (VOC). These materials were also used in plant growth tests in a greenhouse. These tests were all done to ensure that the materials did not contain any chemicals that would inhibit or contaminate plant growth that would occur in the soils.

5.3.1.1 Chemical Characterization

The chemical compositions of the waste materials were characterized in order to evaluate if the materials could provide sufficient nutrients to support plant growth and if hazardous chemicals would be leached. Nutrient characterization was completed for all waste materials, but the hazardous chemical properties were only identified for the peat materials and the dredge sediment. A summary of the tests that were run is shown in Table 5.1.

Table 5.1 Chemical characterization of waste materials.

Waste materials	Chemical compositions	Standard method	Laboratory	Results
All 10 waste materials	Nutrient compositions (pH, %OM, Olsen P, Bray P, K, NO3-N, soluble salts)	--	UMN Soil Testing Laboratory	Table 6.1
Peat scrapings and peat screenings at Cromwell, Peat scrapings at McGregor, Erie Pier Dredge Sediment	RCRA metals (As, Ba, Cd, Cr, Pb, Hg, Se, Ag)	Hazardous Waste Test Methods / SW-846 EPA Method 6010-D Inductively Coupled Plasma – Optical Emission Spectrometry	PACE	Table 6.2
	PAH	--		Figure 6.1
	PCB	--		<Detection Limit
	VOCs	--		<Detection Limit

5.3.1.2 Seed Germination and Plant Growth Test

Greenhouse trials were conducted to determine the ability of the individual materials and the mixture of waste materials to support plant growth. This test consisted of seed germination and plant growth tests for both radishes and oats in the NRRI greenhouse. The trials were performed in three 21-day runs. The first run was done using the individual materials as the growth media. The second and third trials used various mixtures as the growth media. The blend mixtures of the various growth mediums tested are shown in Table 5.2.

Table 5.2 The individual and mixture of waste materials used for the greenhouse trials.

Individual Material, the first run		
By-product	***Company***	***Location***
Tree Bark	Blandin	Mt. Iron
Street Sweepings	City of Duluth	Duluth
Coarse Tailings	MinnTac	Mt. Iron
Fine Tailings	MinnTac	Mt. Iron
Peat Scrapings	Peat Inc.	Cromwell
Peat Scrapings	Peat Inc.	McGregor
Peat Screenings	Peat Inc.	Cromwell
Peat Screenings	Peat Inc.	Floodwood
Peat Screenings	Peat Inc.	McGregor
Peat Screenings	Premier Horticulture	Cromwell
Dredge sediment	USACE	Erie Pier
Mixture, the second run		
75% McGregor peat scrapings + 25% street sweepings		
75% Cromwell peat scrapings + 25% street sweepings		
75% McGregor peat screenings + 25% street sweepings		
75% McGregor peat scrapings + 25% coarse tailings		
75% McGregor peat screenings + 25% coarse tailings		
75% Cromwell peat scrapings + 25% coarse tailings		
Mixture, the third run		
25% McGregor peat scrapings + 75% street sweepings		
25% McGregor peat scrapings + 75% street sweepings		
25% McGregor peat screenings + 75% street sweepings		

The procedure consists of seed germination and plant growth tests that were conducted using both radishes and oats in the NRRI greenhouse. Growth mediums were placed in 7" x 5" x 2" containers and placed in the greenhouse under constant temperature (68°F-75°F) and watered for 10 minutes daily by an automatic sprinkler watering system as shown in Figure 5.2. For each media/mixture, six replications were planted with six oat seeds or six radish seeds for each replicate. Germination/survival was recorded after seven days. After 21 days, the plant heights were measured, and the plants were harvested. The harvested plants were dried at 105°C for 48 hours to determine the plant biomass (shoots and roots) dry weights.

Figure 5.2 Pictures of the greenhouse plant growth test for individual materials.

5.3.2 Environmental

The chemical release or removal capability of the waste materials was tested using batch tests by mixing either deionized water or synthesized stormwater with the waste materials. The metal and phosphorus concentrations of the mixture solutions after shaking for 24-hours were measured to determine if any chemical was released or retained.

5.3.2.1 Environmental Characterization

To be used as a soil amendment, the media are expected to remove contaminants by adsorption, reaction, or biological activities while no (or minimal) chemicals are leached from the media. In order to test the chemical retention capability of each waste material, the materials were mixed with synthesized storm water. To test the chemical release capacity of each waste material, the soil media were mixed with distilled (DI) water. Both tests were done using batch experiments.

Batch experiments were performed in 250 ml bottles by mixing 250 ml DI water or synthesized stormwater and 2.5 g waste material that was dried at 105°C for 24 hours immediately before use. The mixture was shaken at 100 rpm for 24 hours and vacuum filtered through a 0.45 µm membrane. The supernatant was stored in 4°C cooling room for phosphorus measurement by colorimetric spectroscopy or acidified by concentrated nitrate (trace metal grade) for metal measurement by Atomic Absorption Spectrometry (AAS).

The synthesized stormwater solution was prepared by dissolving $NaNO_3$, $Na_2HPO_4{\cdot}H_2O$, $CuCl_2{\cdot}2H_2O$, $Pb(NO_3)_2$, and $Zn(NO_3)_2{\cdot}6H_2O$ into deionized water. This was done to mimic pollutant concentrations at Minnesota maximum concentrations of stormwater of NO_3 at 7.7 mg/L, PO_4 at 5.71 mg/L, Cu at 857 µg/L, Pb at 688 µg/L and Zn at 1182 µg/L (Kurt et al., 2017). For each solution and waste material mixture, three replicates were run at the same time.

5.3.3 Civil Engineering

The ten selected materials were tested to determine their civil engineering properties. Materials were physically characterized using the organic content, moisture content, gradation, specific gravity, hydrometer, and Atterberg limits tests. These tests helped classify each waste material.

It was determined that the hydraulic conductivity properties of each material would be used to select which materials were chosen for mixing. Per the MPCA, the first inch of stormwater runoff must be captured in the roadside embankment material. If the embankment material's hydraulic conductivity is too high or too low, this requirement will not be met. The hydraulic conductivity test conducted on the materials were chosen because the results obtained from these tests represent the saturated hydraulic conductivity of the material. The saturated hydraulic conductivity is the worst-case scenario because the voids in the material are already full of water, and the soil cannot absorb more water without displacing the water already in the voids. The hydraulic conductivity of the final material can be estimated by multiplying the ratio of materials by their respective hydraulic conductivities (Johnson et al., 2017). In order to test the materials' hydraulic conductivity in field conditions, a Proctor test was run on each applicable material. Following the Proctor test, the hydraulic conductivity test was able to be run at 85% relative compaction as an approximation for field compaction.

5.3.3.1 Physical Characterization

The physical characterization of a material helps create an understanding of the behavioral characteristics. The material characterizations in this study were determined to help future projects understand the applicability of the research presented in this paper.

5.3.3.1.1 ORGANIC/MOISTURE CONTENT TESTING

ASTM D2974-20 and ASTM D2216-19 were used to determine the organic and moisture content of each material. Certain tests cannot be run on materials with a high organic content. Additionally, organic content is an indication of soil behavior. Both tests require that the sample be dried in an oven at 110°C to remove moisture; the organic content test requires that the materials be ashed by placing them in an oven at 440°C for 16 hours.

5.3.3.1.2 GRADATION, HYRDOMETER, AND SPECIFIC GRAVITY TEST

Gradation tests are conducted to get a sense of a material's grain size distribution. The test works by running the material through a series of sieves of descending order. The weight of material retained on each sieve is then recorded. Next, a graph is constructed of the mass of material retained versus the opening of the sieves corresponding to the grain size. It is important to note that, per the recommendations in ASTM D6913/D6913M-17, this test is not to be performed on fibrous peat. When the results of a gradation test show that the percent of material passing the #200 (0.075 mm) sieve is greater than 5%, the hydrometer (ASTM D7928-17) and specific gravity (ASTM D854-14) test should also be conducted. Similar to the gradation test, the hydrometer and specific gravity tests should not be run on organic materials. The hydrometer test suspends small particle sizes in a tube of an aqueous salt solution and allows the particles to slowly settle. The particles' fall velocity is correlated to size by applying Stoke's Law. As Stoke's Law is a function of its specific gravity, the specific gravity test was also conducted.

5.3.3.1.3 ATTERBERG LIMIT TEST

The Atterberg limits tests were completed in order to determine a material's plastic limit, liquid limit, and plasticity index. This test helps determine how cohesive a soil is numerically. The Atterberg limits tests were conducted in accordance with ASTM D4318-17 on the inorganic materials.

5.3.3.2 Proctor Testing

The hydraulic conductivity of a material is a function of the material's density. For example, higher density yields lower hydraulic conductivity. Therefore, to obtain a comparable hydraulic conductivity for each material, a Proctor test was conducted. Similar to previous research (Johnson et al., 2017; Saftner et al., 2019), the materials were tested at a relative compaction of 85% to match the expected *in situ* conditions.

ASTM D698-12 was used as the test method. This test method is not applicable for materials with large particle sizes. As the peat screenings and bark material had large chunks of roots and tree bark, they were not tested.

5.3.3.3 Hydraulic Conductivity Testing

As the saturated hydraulic conductivity represents the soil's worst-case infiltration rate and, therefore, controlled the design, it was used to determine the quantity of material required for composite testing. The composite materials' hydraulic conductivity can be estimated by summing the product of the percentage of each individual material in the composite mix and the individual hydraulic conductivity value (Johnson et al., 2017). Two different test methods were used to determine the hydraulic conductivity values. The falling head test (Germaine & Germaine, 2009) was used for materials that had an expected hydraulic conductivity in the range of values expected for clay and silt material. The constant head test (ASTM D2434-19) was used for materials with a hydraulic conductivity in the range of values expected for gravel and sand material.

5.3.4 Life-Cycle Analysis

The materials that are included in this survey vary in characterization, location of generation, generation amounts, and current uses. A Geographic Information System (GIS) map has been created that shows the locations of all of the materials that are included in this study. Some of the materials were not sampled, some were sampled and not characterized, and others were sampled and characterized. This map was created to show graphically where the materials were and to help assist with the LCA.

The goal of this LCA is to determine the environmental and economic impacts of using waste and by-product material from northeastern MN to create sustainably designed topsoil. This LCA will be looking at 17 different materials to analyze their effects, 10 individual by-products, 6 by-product mixes, and 1 top-soil material. The top-soil material was included in this LCA to compare alternatives to current practice. The LCA was split into two different parts, environmental impacts and economics.

Figure 5.3 shows the life-cycle stage diagram for by-product materials, and the red box located around the diagram shows the parts of the life-cycle that will be included in this LCA. Because the transportation, use, and mixing are different for every by-product, these stages are all included in the LCA. By-product generation and the waste/re-use scenario for each material will be approximately the same. For this reason, these stages of the life-cycle were omitted from the study.

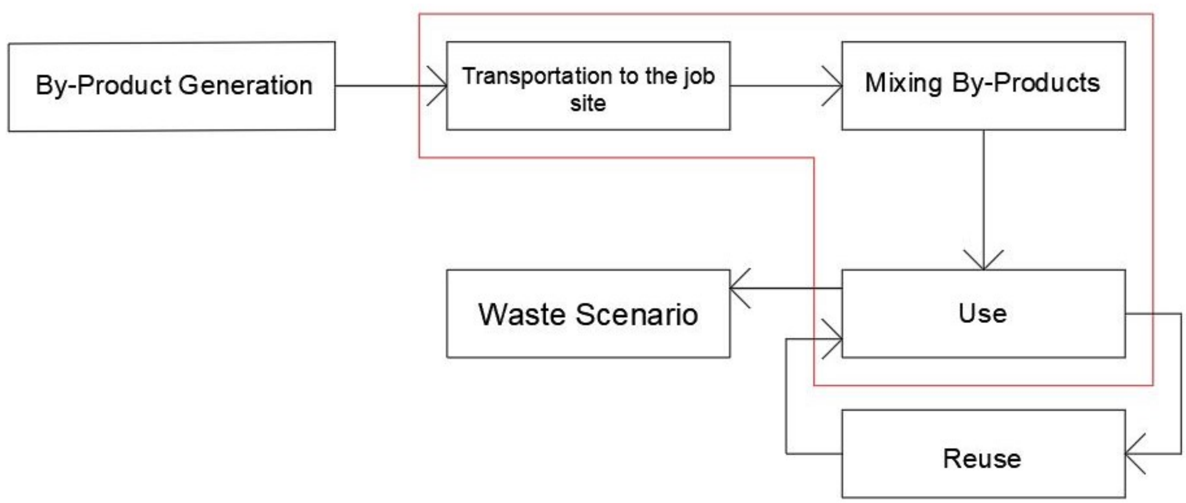

Figure 5.3 Life-Cycle Stage Diagram and System Boundary for this LCA.

The functional unit for this LCA is one ton of by-product material, transported by truck from the site where the material is generated to the project site where the material will be used for 25 years. The project site being analyzed is Eagles Nest, located near Ely, Minnesota on Minnesota State Highway 169. This site was selected due to its use by Saftner et al. (2019) in previous research on a similar topic. The units of this comparison will be ton-miles, as there will be differences in the distances between the generation site and the project site for each by-product and the topsoil. An LCA reference flow is used to show how much of one material is being compared to another material. In this analysis we will be comparing the same amount of material for each of the 16 materials (1:1:1:1:1:1:1:1:1:1:1:1:1:1:1:1).

A reference flow is used to show how much of one material is being compared to another material. In this analysis we will be comparing the same amount of material for each of the 16 materials.

5.3.4.1 Environmental Life-Cycle Analysis

The 17 materials included in the LCA are part of a study on removing contamination from the roadways. Therefore, ecotoxicity is the impact that this LCA will focus on. Climate change is also a concern. The program used in this analysis refers to climate change as “global warming,” so in this report the term “global warming” will be used to avoid confusion between the software results and the analysis. The impacts of the materials on global warming will also be analyzed. This LCA will use the TRACI impact assessment method to analyze and compare the ecotoxicity and global warming impacts of using these by-product materials because the method provides characterization factors that quantify the environmental impacts of the processes being analyzed. The impacts in different categories are reported in common equivalence units and the use of fossil fuels is also included in the method.

5.3.4.2 Economic Life-Cycle Analysis

A Life-Cycle Costing Assessment (LCCA) to compare the life-cycle cost for the different by-products to be used in the engineered topsoil mixes was completed. To complete the LCCA, a spreadsheet was created to help compare the costs associated with each option. The ten by-products and six mixes being studied are being compared to the topsoil material to determine which product is the most economically viable option for use in engineered topsoil. The products are being compared for use in a project located along Minnesota State Highway 169 in Ely, Minnesota. This LCCA was done in constant dollar terms, so it should be noted that inflation was not included as part of this analysis. Comparisons were done in terms of cost per ton-mile, which allowed for normalization of the differing unit weights and transportation distances for each product. Products were also compared for a 25-year life span and for three different replacement scenarios: 100% replacement needed, 50% replacement needed, and 0% replacement needed. The 25-year life span for the soils was used because 25 years is a typical design life for asphalt pavement.

The replacement scenarios represent the effort level needed to replace the topsoil material at the end of the material’s life span. It is possible that the material will still meet project specifications for physical/biological/chemical properties after 25 years. If that is the case, then the soil is said to need 0% replacement. If the soil does not meet project specifications and needs to be completely replaced to meet the specifications, it would need to be 100% replaced. If the soil can be mixed in a 2:1 ratio of old material to new material in order to meet project specifications, it would be said that it is 50% replaced. Future studies are recommended to evaluate material performance over time. The results from those studies can be used to help refine the LCCA that has been completed.

It is important to note that assumptions were made to complete this LCCA. It was assumed that the reconstruction of the road would coincide with the replacement of the roadside topsoil. Because compacted unit weight data was not known for some materials, 0.48 g/cm^3 was assumed for the Floodwood screenings, Cromwell screenings, and Premier Horticulture material, and 0.42 g/cm^3 was assumed for Blandin bark. The average dump truck was assumed to hold 5 cubic meters of material (Masterson Loam, n.d.) and have an average fuel economy of 3.2 mpg (Jackson, 2010). Once the material got to the site, it was estimated that it would take roughly 2 hours to place 1 ton of topsoil material and that it would take about 1 hour to mix one ton of products (M. Straight, pers. comm., 2020). It was assumed that earth work activities cost $115 per hour (HomeGuide, n.d.) and that the materials had a life span of 25 years, with $500 worth of work needed in maintenance every fifth year (M. Straight, pers. comm., 2020). The real discount rate used in this analysis was 0.3% (Vought, 2019).

CHAPTER 6: RESULTS

6.1 INDIVIDUAL BY-PRODUCT CHARACTERIZATION

6.1.1 Biological

6.1.1.1 Chemical Characterization

All peat materials were found to be acidic, having pH values of 4 or below (Table 6.1). The pH of the tree bark was slightly acidic at 6, but all other materials were found to have neutral pH values between 7 and 9. Both coarse and fine tailings have a very low content of organic matter, at 0.2% and lower. Dredge sediment and street sweepings primarily are inorganic materials with organic matter contents of 3% and 2.1%, respectively. Collectively, fine tailings, coarse tailings, dredge sediment, and street sweepings are classified as having a low organic content. Conversely, wood-related materials, including peat and tree bark, tend to be rich in organic matter, typically above 50%. Most materials have a relatively low content of phosphorus and potassium. However, the dredge sediment and peat scrapings have a medium content of phosphorus, and the potassium content in both of the tailings materials are much higher than other materials. High salt content will cause possible salt damage to grass, therefore affecting the plant growth. For all studied materials, the salt contents are lower than 1 mmhos/cm, which is significantly lower than the upper limit for MnDOT grade 2 compost requirements of 10 mmhos/cm.

Table 6.1 Nutrient compositions of the waste materials.

Materials		pH	% Organic Matter	Olsen P, ppm	Bray P, ppm	K, ppm	NO_3-N, ppm	Soluble Salts, mmhos/cm
Dredge Sediment	Erie Pier	7.2	3	NA	13	75	33.1	0.7
Bark	Blandin Bark	6	91.1	NA	6	132	0.3	0.4
Coarse Tailings	MinnTac	8.9	0.1	1	2	287	10.1	0.4
Fine Tailings	MinnTac	8.6	0.2	1	2	300+	5.4	0.5
Peat Scrapings	Cromwell	3.8	59.4	NA	11	12	42.8	0.4
Peat Screenings	Cromwell	3.7	90.6	NA	1	17	0.5	0.1
Peat Screenings	Floodwood	3.6	87.6	NA	2	13	13	0.3
Peat Scrapings	McGregor	4	57.4	NA	17	11	36.2	0.3
Street Sweepings	City of Duluth	8.1	2.1	3	6	61	5.1	0.6
Peat Screenings	Premier Horticulture	3.7	89	NA	3	16	1.2	0.1
Reference	--	6-7, the optimum pH for most plants and soil microorganisms	Low 0-3%, medium 3.1-4.5%, high 4.6-19%, organic soil >19.1%	Low <3, medium 4-7, high 8-18, very high >18	Low <5, medium 6-10, high 11-25, very high >25	Low <50, medium 51-100, high 101-150, very high >150	--	MnDOT Grade 2 compost requirement of ≤10 mmhos/cm

The RCRA requires monitoring of eight metals, including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. Each of these eight metals is extremely toxic at even small concentrations, therefore the measurement of the metal contents in the waste material is crucial to determine if the material should be treated as a hazardous waste. If the metal contents exceed the level set by the MPCA, a Toxicity Characteristic Leaching Procedure (TCLP) is required to test the metal concentrations in the leachate. Both taconite tailings materials were not selected to be tested for the RCRA metal contents because these materials have been characterized by another MnDOT-funded project (Zanko et al., 2012) and the results were copied from that project report and presented in Table 6.2. Overall, the metal contents of the six studied materials are lower than three reference values, including Tier 1 residential soil reference values, soil leaching values, and MPCA-levels at which TCLP is required. Because of the low metal contents, no additional TCLP testing is required.

Table 6.2 The RCRA metal contents. (< DL denotes concentrations below detection limit).

Sample	Description	Arsenic	Barium	Cadmium	Chromium	Lead	Mercury	Selenium	Silver
	Taconite Tailings*	1.42-2.78	5.92-232	<DL	<DL	<DL	<DL	1.46-7.46	<DL
78976-PA-F	Peat Scrapings	<3.4	60.3	<0.51	2.4	2.3	<0.067	<3.4	<1.7
78976-SS-D	Street Sweepings	2.1	22.6	<0.16	16.2	5.4	<0.021	<1.0	<0.52
78976-PA-M	Peat Scrapings	<2.5	56.1	<0.37	5.4	2.7	<0.052	<2.5	<1.2
78976-EP-D	Erie Pier (dredge)	2.7	64.4	0.23	18.7	11.9	0.085	<1.1	<0.56
78976-PA-C	Peat Scrapings	<2.9	54	<0.44	7.3	3.3	<0.055	<2.9	<1.5
Tier 1 Residential Soil Reference Values (SRVs), mg/kg		9	1100	25	87	300	0.5	160	160
Soil Leaching Values (SLVs), mg/kg		5.8	1700	8.81	36.2	2700	3.29	2.64	7.86
MPCA – Levels at which TCLP is required		100	2000	20	100	100	20	100	4

*The tailings were characterized by another project and the results were taken from Zanko et al. (2012).

PAHs, PCBs, and VOCs were measured for selected peat materials, dredge sediment, and street sweepings, but none of these materials have detectable PCBs and VOCs. PAHs were identified for dredge sediment and street sweepings only, but the contents are below 250 µg/kg for every individual PAH component, as shown in Figure 6.1. Based on the MPCA testing criteria, the lowest Soil Reference Values (SRVs) and Soil Leaching Values (SLVs) levels are 1000 µg/kg. The SRVs and SLVs are tools to be used to assist in determining whether further investigation and possible cleanup is needed for a particular exposure area due to potential risks to human health and/or the environment. The SRVs and

SLVs represent contaminant levels in the media, above which unacceptable risks could occur under general exposure conditions. Residential exposure scenarios are assumed for all sites unless more site-specific property use information is available. The PAHs contents of the waste materials do not exceed the minimum MPCA levels.

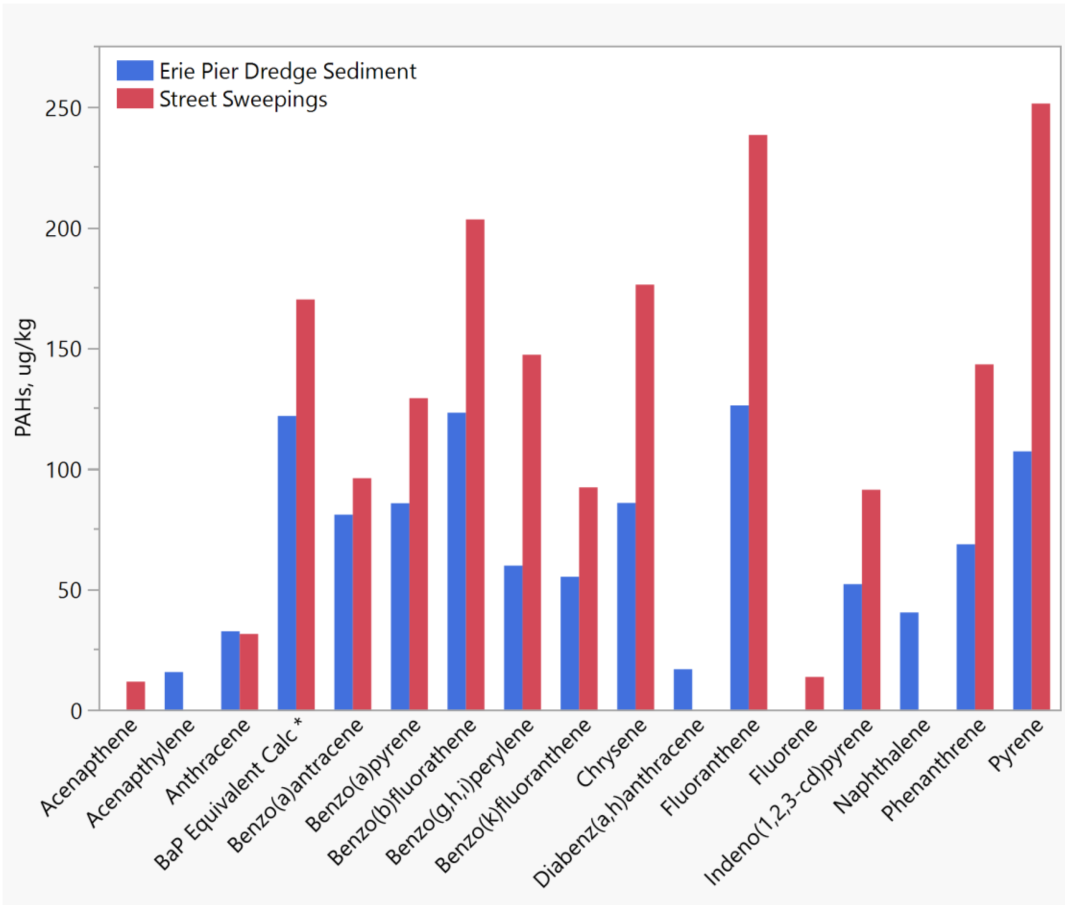

Figure 6.1 PAH content for dredge sediment and street sweepings.

6.1.1.2 Seed Germination and Plant Growth Test

Among the 11 individual waste materials, fine tailings have the lowest germination rates, plant heights, and biomass for both oats and radishes. The results from the testing are shown in Figure 6.2. Since the nutrient contents for the fine tailings and coarse tailings are similar, the low capacity seen in fine tailings in supporting plant growth could be attributed to the physical properties rather than the chemical properties. The fine tailings have low permeability and porosity values, which results in low infiltration rates, poor drainage, and poor irrigation. All of these factors may have resulted in a low plant growth rate. Other than the fine tailings, the remaining 10 waste materials did not show a significant difference in germination rates or plant growth. Interestingly, the group of organic materials did not exhibit any clear improvement in supporting plant growth in comparison with the group of inorganic materials. This is probably because all waste materials contain nutrients that are sufficient to support six plants in the current 21-day study period.

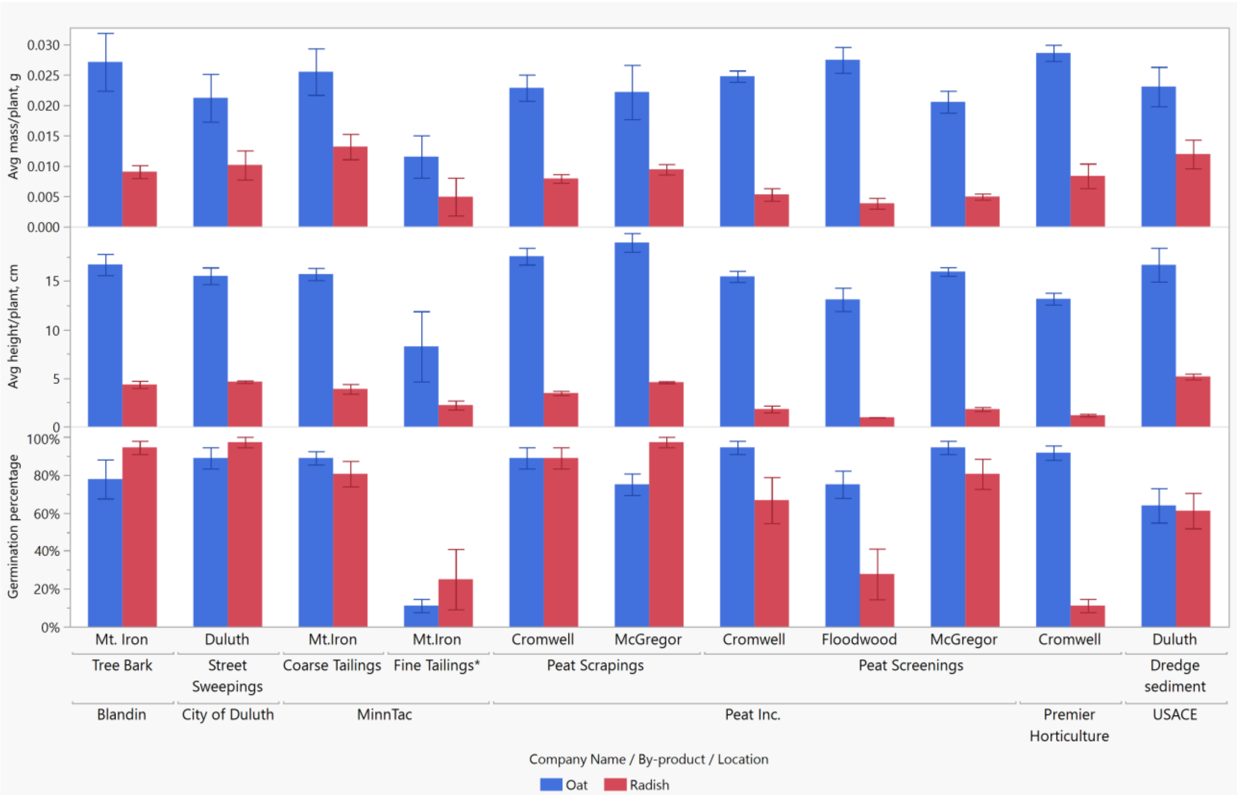

Figure 6.2 Average germination rates, plant heights, and biomass of individual waste materials. Error bars represent the standard error of the replicates.

After the completion of tests done using the individual materials, the three peat materials that had the highest germination rates and plant height were selected to mix with coarse tailings and street sweepings to conduct the plant growth test again. Fine tailings were excluded from this test because this fine-grained material is difficult to mix with other waste materials. Dredge sediment was not included because the plant growth test was performed by USACE through an in-kind contract. The USACE report is attached in Appendix A. The mixture ratios between the peat materials and the inorganic materials were set to be 75% of peat materials + 25% of coarse tailings or street sweepings for the first mixture run, and 25% of peat materials + 75% street sweepings for the second mixture run. Tailings were not included in the second mixture run because the selected ratio of the tailings to organic materials cannot be too high due to the potential leaching of metals from the tailings. Table 6.3 summarizes the plant growth results for the waste mixture from two runs. All organic and inorganic waste mixtures can support plant growth successfully. The plants grown on the mixture of 25% of peat materials and 75% of street sweepings tend to gain slightly more height and biomass.

Table 6.3 The mean (standard deviation) of plant growth data for the mixtures. For each of oat or radish, the height and biomass were compared by Tukey HSD test. Numbers sharing the same letter indicate no significant difference.

Mixture	Germination rate, %	Height, cm	Dry biomass, g
Oat			
75% Cromwell peat scrapings + 25% coarse tailings	72 (31)	14.34 (2.22)^{D}	0.026 (0.007)^{B}
75% Cromwell peat scrapings + 25% street sweepings	94 (9)	18.71 (2.06)^{BC}	0.027 (0.003)^{B}
75% McGregor peat scrapings + 25% coarse tailings	69 (31)	17.28 (2.56)^{BCD}	0.033 (0.005)^{AB}
75% McGregor peat scrapings + 25% street sweepings	78 (25)	18.79 (2.07)^{BC}	0.031 (0.007)^{AB}
75% McGregor peat screenings + 25% coarse tailings	92 (9)	16.53 (1.34)^{CD}	0.028 (0.005)^{B}
75% McGregor peat screenings + 25% street sweepings	89 (14)	18.26 (2.92)^{BCD}	0.026 (0.005)^{B}
25% Cromwell peat scrapings + 75% street sweeping	75 (12)	22.71 (0.06)^{AB}	0.037 (0)^{AB}
25% McGregor peat scrapings + 75% street sweeping	78 (19)	16.97 (2.28)^{BCD}	0.029 (0.003)^{AB}
25% McGregor peat screenings + 75% street sweeping	83 (24)	25.29 (0.69)^{A}	0.043 (0.002)^{A}
Radish			
75% Cromwell peat scrapings + 25% coarse tailings	100 (0)	4.95 (0.64)^{A}	0.011 (0.002)^{BC}
75% Cromwell peat scrapings + 25% street sweepings	100 (0)	4.78 (0.45)^{A}	0.011 (0.001)^{BC}
75% McGregor peat scrapings + 25% coarse tailings	89 (9)	4.07 (0.78)^{AB}	0.010 (0.002)^{BC}
75% McGregor peat scrapings + 25% street sweepings	97 (7)	4.97 (0.93)^{A}	0.011 (0.005)^{BC}
75% McGregor peat screenings + 25% coarse tailings	89 (9)	3.99 (0.63)^{AB}	0.009 (0.003)^{C}
75% McGregor peat screenings + 25% street sweepings	100 (0)	5.13 (0.70)^{A}	0.010 (0.002)^{BC}
25% Cromwell peat scrapings + 75% street sweeping	100 (0)	3.86 (0.25)^{AB}	0.019 (0.001)^{A}
25% McGregor peat scrapings + 75% street sweeping	100 (0)	2.77 (0.23)^{B}	0.014 (0.002)^{ABC}
25% McGregor peat screenings + 75% street sweeping	92 (12)	4.04 (0.28)^{AB}	0.017 (0.003)^{AB}

6.1.2 Environmental

6.1.2.1 Environmental Characterization

DI water contains minimal chemicals, usually under detectable limits (1 µg/L). Any chemicals measured from the DI mixture were released from the waste materials as shown in Figure 6.3. Due to the acidic properties of the peat materials, the solution mixture with peat scrapings or screenings had pH values below 6. These peat materials also released metals (usually below 10 ppb) and phosphorus (below 100 ppb). The observed values were particularly higher for peat scrapings than peat screenings. Besides the peat materials, tree bark, coarse tailing, and dredge sediment released one or two chemicals. For example, tree bark released copper and phosphorus, coarse tailing and dredge sediment leached zinc, and phosphorus was also released from dredge sediment. Street sweepings and fine tailings were the only two materials without detectable amounts of released copper, zinc, and phosphorus.

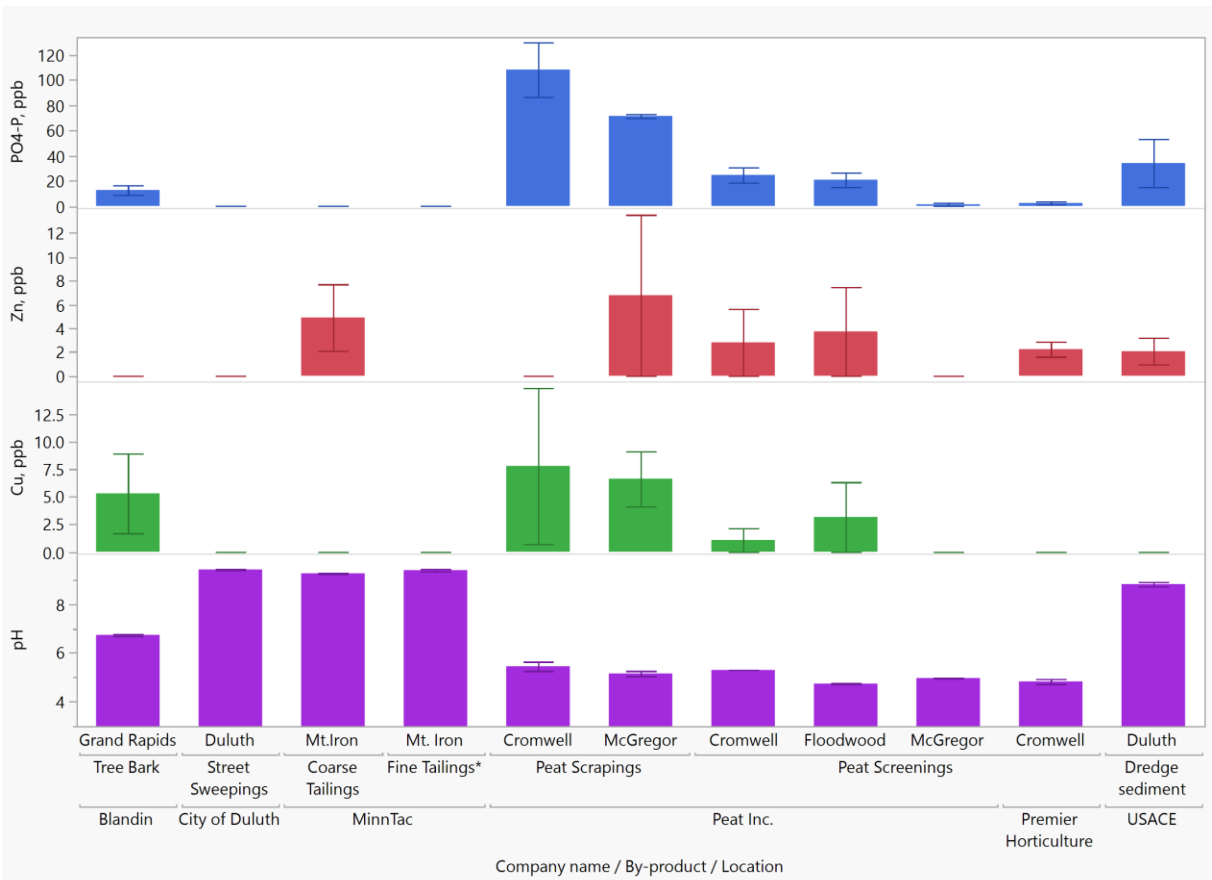

Figure 6.3 pH, copper, zinc and PO4-P concentrations of DI and waste material solution after shaken for 24 hours.

When the waste materials were mixed with synthesized stormwater, all materials showed the capacity to retain metals and phosphorus, as shown in Figure 6.4. The peat materials were particularly efficient in removing metals by reducing zinc from 1,000 ppb to below 100 ppb and in removing more than half of influent copper. However, these peat materials were not as efficient as other inorganic materials in phosphorus removal. This is true even though the peat reduced phosphorus concentrations from 4,668 ppb to below 2,000 ppb. The relatively lower phosphorus removal efficiencies probably were attributed to the release of phosphorus from the peat materials. Even though street sweepings are classified as inorganic, their performance in metal removal was similar to the peat materials, but a higher phosphorus removal capacity was observed.

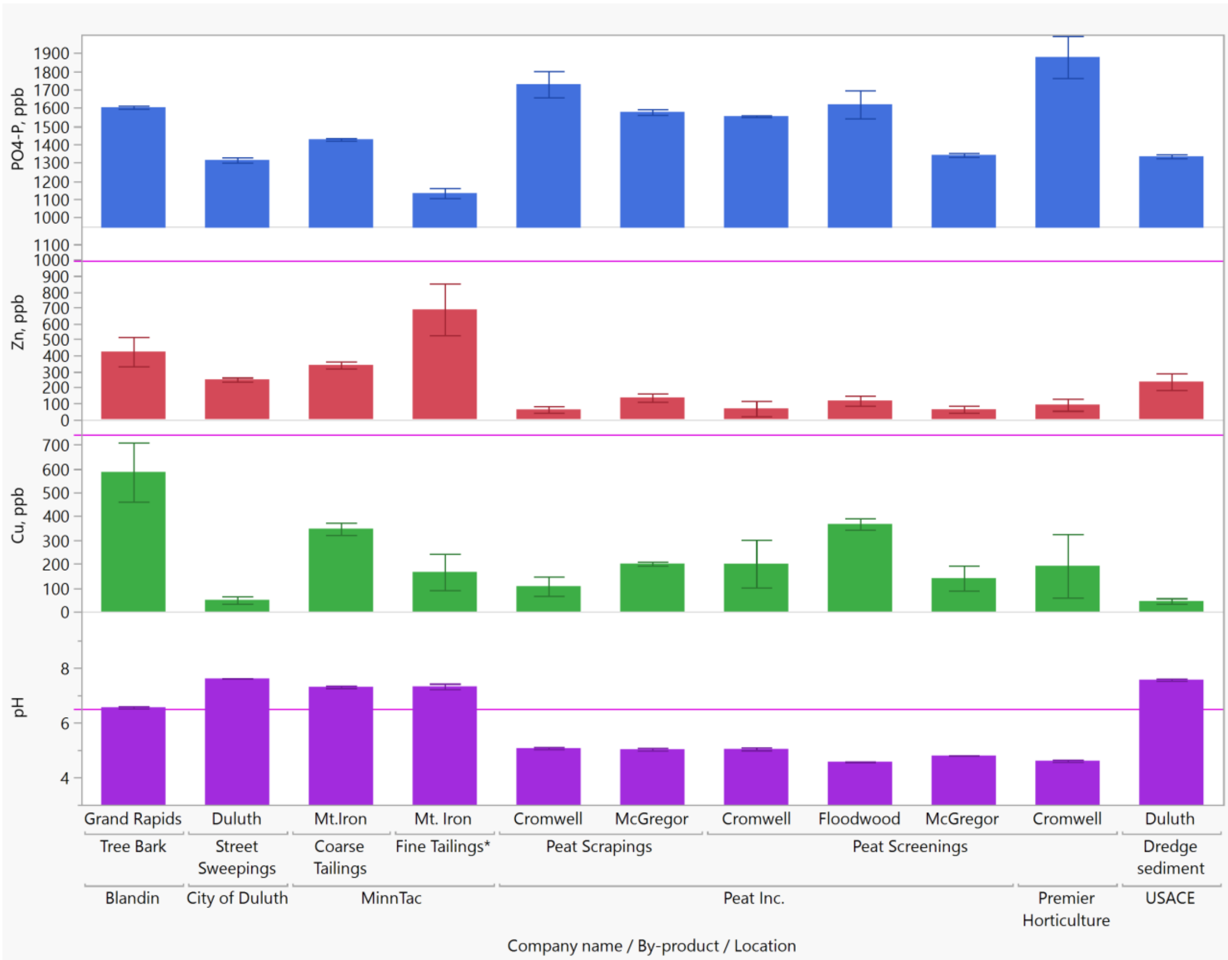

Figure 6.4 Metal and phosphorus concentrations of the mixture with synthesized stormwater. Pink line represents the influent chemical concentrations. The influent concentration of phosphorus was 4,668 ppb.

6.1.3 Civil Engineering

The test results obtained from the laboratory testing align with Johnson et al.'s (2017) predictions. Coarser materials had a larger hydraulic conductivity than the finer materials. Peat scrapings and peat screenings had very similar hydraulic conductivities and tested similarly to the coarse tailings and street sweepings. Dredge material and fine tailings both had low hydraulic conductivities. Based on the results from the hydraulic conductivity testing and combined with the results of the biology and environmental testing, materials will be selected for blending and further testing.

6.1.3.1 Physical Characterization

The physical characterization assists in determining other properties of the materials, including the hydraulic conductivity. If the physical characterization of two different materials is similar, then it is expected that the two materials will have similar hydraulic conductivities, so these tests were done to help determine if other materials can be substituted for materials studied in this report. The test results obtained can be found in the following sections.

6.1.3.1.1 ORGANIC/MOISTURE CONTENT TEST

The results from these tests align closely with the results found during the biology testing. Varying test results are expected, as there is natural variation as a result of sampling methods. Although the values vary, the materials did not vary between being classified as either organic or inorganic. The results obtained from the organic and moisture content tests can be found in Table 6.4.

Table 6.4 Organic and moisture content test results.

Material	Moisture Content (%)	Organic Content (%)
Dredge Sediment	20.1	4.6
Coarse Tailings	7.3	0.5
Fine Tailings	34.9	3.3
Street Sweepings	8.6	2.7
Cromwell Peat Scrapings	201.8	59.4
McGregor Peat Scrapings	177.7	61.5
Premier Horticulture Peat Screenings	129.7	99.2
Floodwood Peat Screenings	269.5	92.4
Blandin Bark	164.3	88.6
Cromwell Peat Screenings	190.6	75.3

6.1.3.1.2 GRADATION, HYDROMETER, AND SPECIFIC GRAVITY TEST

Gradation tests are not applicable for fibrous materials such as the peat and bark materials in this study. Gradation testing was only completed for the tailings materials, dredge sediment, and street sweepings. The results of the gradation testing were as expected based on visual classification; coarse tailings had larger grain sizes compared to the other materials. Fine tailings had the smallest grain size, and street sweepings and dredge material fell between the two tailings samples. After the gradation tests, hydrometer tests and specific gravity tests were completed. The results from these tests can be found in Figure 6.5 and Table 6.5.

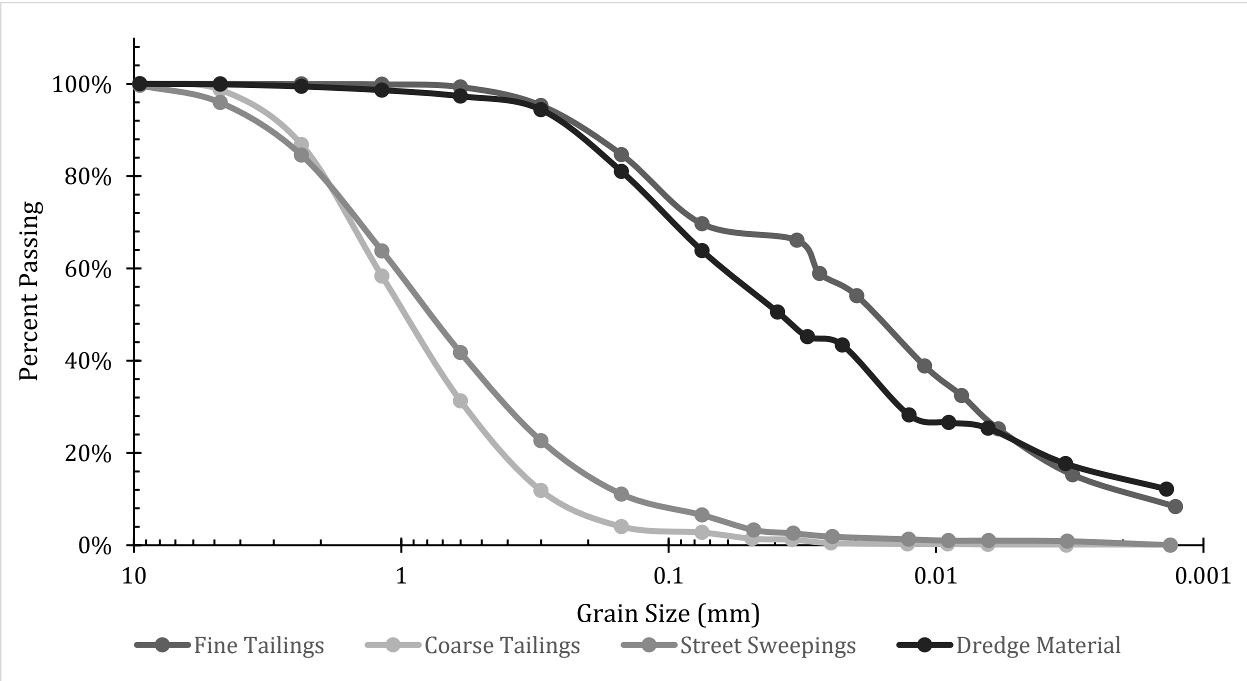

Figure 6.5 Graphical gradation and hydrometer test results for four inorganic materials.

Table 6.5 Specific gravity test results for four inorganic materials.

Material	Specific Gravity
Dredge Sediment	2.55
Coarse Tailings	2.91
Fine Tailings	2.86
Street Sweepings	2.63

6.1.3.1.3 ATTERBERG LIMIT TEST

The results of the Atterberg limits tests show that coarse tailings, fine tailings, and street sweepings were all non-plastic. The dredge material was found to have a liquid limit of 30%, a plastic limit of 23.3%, and a plasticity index of 6.6%. The liquid limit results are shown in Figure 6.6.

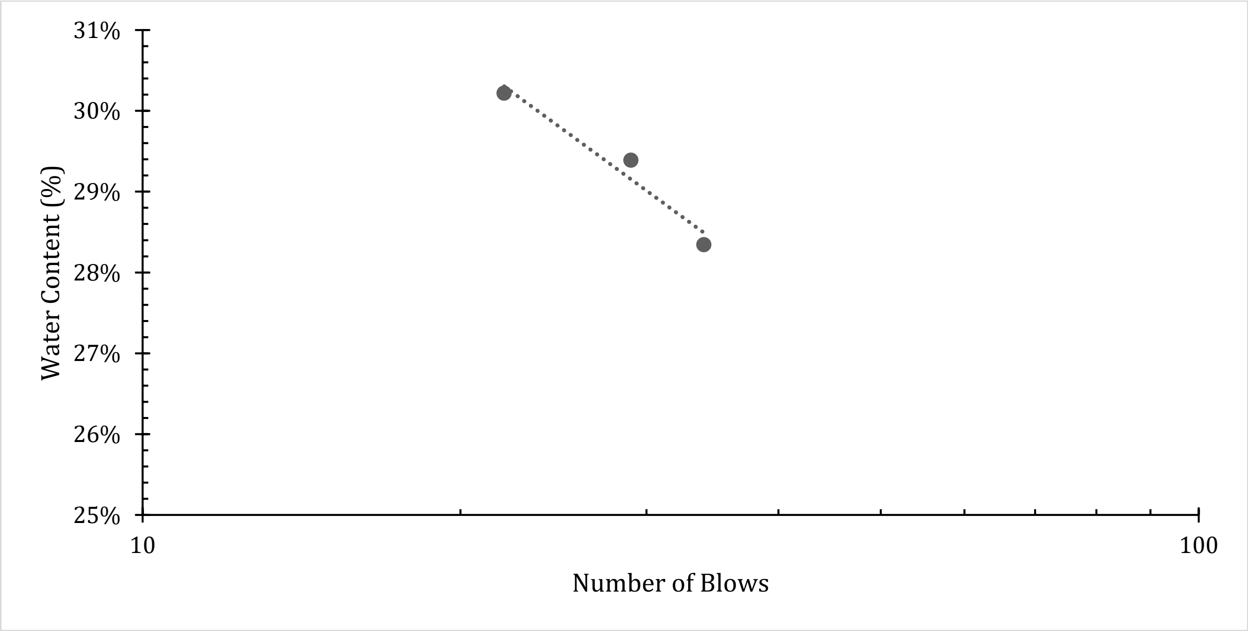

Figure 6.6 Atterberg limit test results for dredge material.

6.1.3.2 Compaction Characterization

The Proctor testing revealed that the peat scraping materials had a low max dry unit weight. This was expected due to the material being relatively light and highly absorptive. The finer-grained inorganic materials (fine tailings and street sweepings) had a higher max dry unit weight than the other two inorganic materials. This was also expected because fine-grained materials can compact tighter and have fewer air voids. The test results from the Proctor tests are shown in Table 6.6.

Table 6.6 Proctor test results.

Material	Max Dry Unit Weight (pcf)	Optimum Moisture Content (%)
Dredge Sediment	103.1	17.3
Coarse Tailings	118.2	12.6
Fine Tailings	120.2	13.3
Street Sweepings	124.1	11.3
Cromwell Peat Scrapings	33.6	106.1
McGregor Peat Scrapings	34.9	83.0

6.1.3.3 Hydraulic Conductivity Testing

The values obtained during the hydraulic conductivity testing were all within the expected range. The fibrous and coarse materials both had a higher hydraulic conductivity. This is because these materials have a large amount of air voids due to the large grain size. Conversely, the smaller grain size materials, which can pack together tighter, have fewer air voids and, as a result, a lower hydraulic conductivity. Dredge sediment and fine tailings had the lowest hydraulic conductivities, while Blandin bark had the highest. The results from the failing and constant head tests are shown in Table 6.7.

Table 6.7 Falling and constant head test results for each by-product material.

Material	Hydraulic Conductivity (in/hr)
Dredge Sediment (falling head)	0.009
Coarse Tailings (constant head)	6.902
Fine Tailings (falling head)	0.033
Street Sweepings (constant head)	7.200
Cromwell Peat Scrapings (constant head)	3.430
McGregor Peat Scrapings (constant head)	5.584
Premier Horticulture Peat Screenings (constant head)	94.110
Floodwood Peat Screenings (constant head)	13.550
Blandin Bark (constant head)	49.748
Cromwell Screenings (constant head)	5.811

6.2 BLENDED BY-PRODUCT CHARACTERIZATION

After the completion of the individual by-product characterizations, materials were chosen for blending. It was determined that the blends needed to consist of one of the inorganic materials and one of the organic materials. Fine tailings were eliminated for blend testing due to the poor workability of the materials and the poor chemical test results. Blandin tree bark, along with the peat screening materials, are not recommended due to the large nominal particle diameter size of the materials. The large chunks of organic materials in these by-products results in a high hydraulic conductivity value. After materials were eliminated, it was determined that the blends found in Table 6.8 would be tested. The soil blends were made by mixing different amounts by weight of materials in small batches in the lab.

Table 6.8 Blend tests compositions.

Soil Blends
80% Street Sweepings + 20% Cromwell Peat Scrapings
80% Street Sweepings + 20% Cromwell Peat Screenings
80% Street Sweepings + 20% McGregor Peat Scrapings
80% Dredge Material + 20% Cromwell Peat Scrapings
80% Dredge Material + 20% Cromwell Peat Screenings
80% Dredge Material + 20% McGregor Peat Scrapings

6.2.1 Hydraulic Conductivity Testing

Hydraulic conductivity tests were the only tests that were run on the blended materials. This was due to the limited amount of materials remaining. Because Proctor tests were not run on the blended materials, reaching 85% relative compaction for the hydraulic conductivity testing was not achievable. For conservancy, the materials were packed into the molds with high effort. This was done by placing the material into the mold in five lifts of roughly equal volume and then placing a heavy weight on top of the material to compact it. The results from the hydraulic conductivity tests on the blended materials can be found in Table 6.9.

Table 6.9 Falling and constant head test results for blended soils.

Material	Hydraulic Conductivity (in/hr)
80% Street Sweepings + 20% Cromwell Peat Scrapings (constant head)	6.321
80% Dredge Sediment + 20% Cromwell Peat Scrapings (falling head)	0.193
80% Street Sweepings + 20% McGregor Peat Scrapings (constant head)	6.066
80% Dredge Sediment + 20% McGregor Peat Scrapings (falling head)	0.097
80% Street Sweepings + 20% Cromwell Peat Screenings (constant head)	4.139
80% Dredge Sediment + 20% Cromwell Peat Screenings (constant head)	1.743

6.3 LIFE-CYCLE ANALYSIS

6.3.1 GIS Map

In total, there were 21 by-products that were identified as potential materials for this project. Of these 21 by-products, only 15 were sampled, and of the 15 sampled materials only 10 were characterized. There was concern among the businesses that generate some of the by-products that the possible benefits of re-use will not outweigh the future liability from characterization data discovered in this study. Figure 6.7 shows the GIS map product that was produced using the information found in Table 3.1.

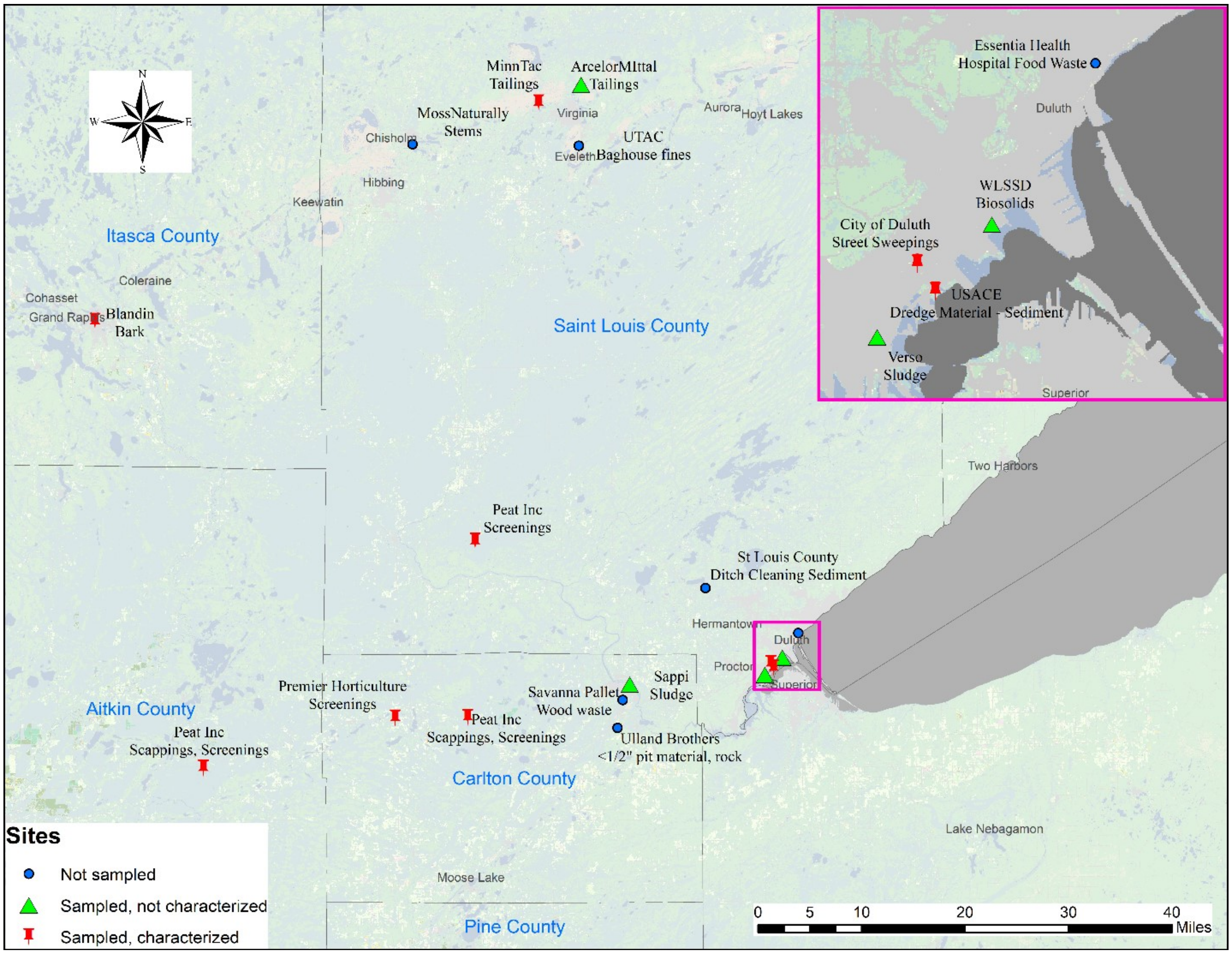

Figure 6.7 GIS map of material locations.

6.3.2 Environmental Life-Cycle Analysis

The transportation of materials was shown to have the largest contribution to the overall environmental impact. The energy needed to mix the materials was assumed to be the same for each material. The total distance between the project site used and the material location can be found in Table 6.10. It was assumed that the materials would be mixed at a temporary on-site mixing plant to create the sustainably designed soils and then would be placed alongside the road per project specifications. The unit weights that were used to convert the volume of material being transported into weight can also be found in Table 6.10. The mixed material will be used for 25 years at the project site. The life span of the material is assumed to be the same as the design life of the road. The ten individual materials and the six materials selected for mix characterization were included in the LCA.

Table 6.10 Distances and Unit Weights used in the LCA for each material.

	Distance (mi)	Unit Weight (pcf)
Dredge Sediment	101	103.1
Street Sweepings	95	124.1
Coarse Tailings	39	118.2
Fine Tailings	39	120.2
McGregor Scrapings	119	34.9
Premier Horticulture	109	30.0*
Cromwell Scrapings	113	33.6
Cromwell Screenings	113	30.0*
Floodwood	83	30.0*
Blandin Bark	91	26.0*
Kunst Excavation	101	40.0*

*Values were assumed because proctor lab testing was not able to be performed on these materials.

The impacts of using these materials were calculated using the TRACI 2.1 V1.05 / US 2008 method in SimaPro. The results of the analysis are shown in Figure 6.8. These results were also compared in importing topsoil from Kunst Excavation and Dirt Delivery in Duluth, Minnesota.

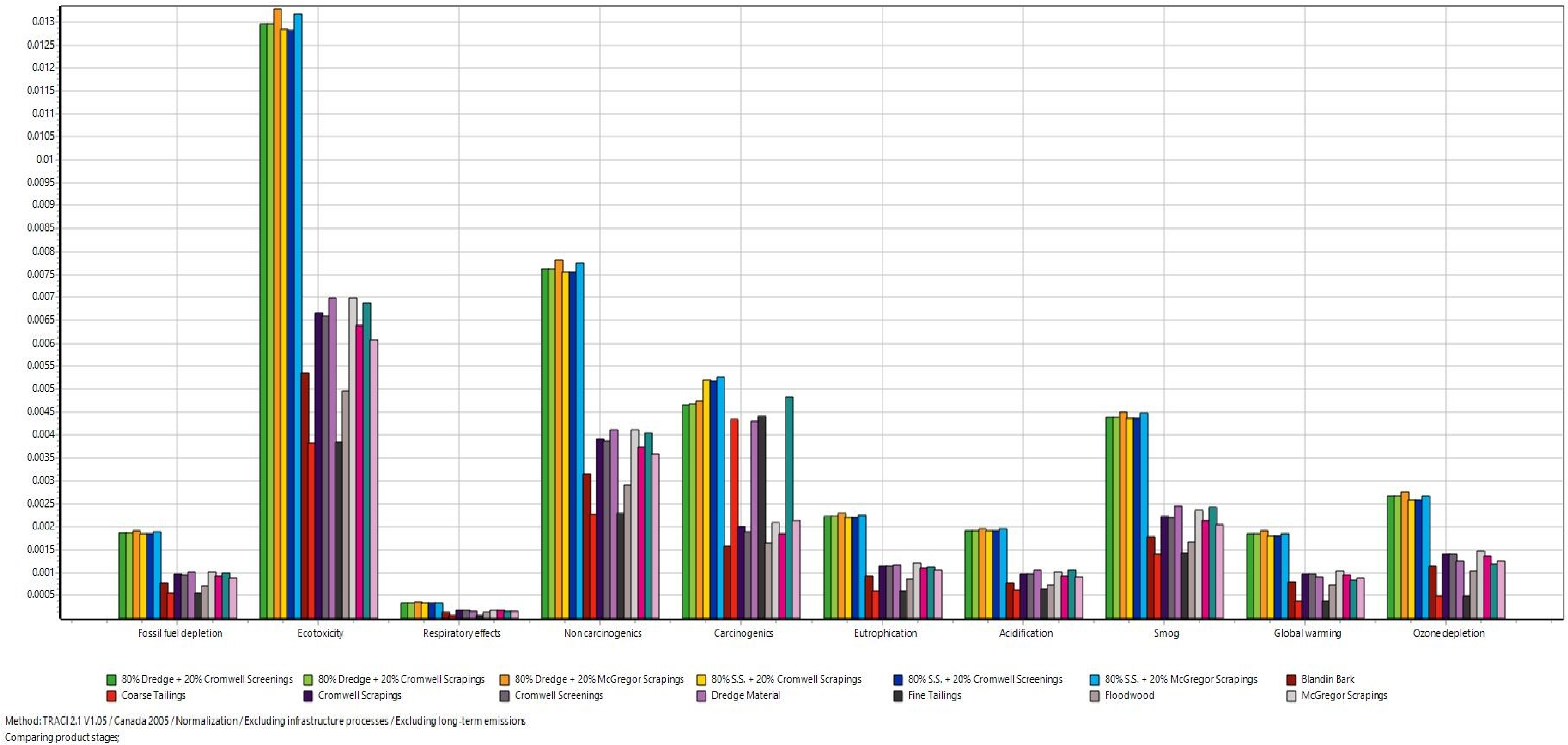

Figure 6.8 Full results from the Environmental LCA.

The LCA demonstrated that the mixed materials have a larger impact in every category. This is because the mixed materials contain two by-products, which means that the mileage traveled to get the site is higher than it is for the individual materials. The by-products cannot be used individually but can be used as part of the mixtures, so each by-product was analyzed individually. The values for the ecotoxicity of the materials and mixtures can be found in Table 6.11. Ecotoxicity is measured in CTUe units. A CTUe is a unit of comparative aquatic ecotoxicity and is defined as "the estimated potentially affected fraction of species (PAF) integrated over time and the volume of the freshwater compartment, per unit of mass of the chemical emitted" (Golstein, 2014). The impacts to global warming are shown in Table 6.12 and are reported in CO_2 eq units. A kg CO_2 eq. is a unit that compares the impact of a process on global warming in terms of the amount of carbon dioxide that would need to be released to achieve the same effect. Graphical representations of the impacts of the by-products on both ecotoxicity and global warming are shown in Figure 6.9 and Figure 6.10.

Table 6.11 Ecotoxicity impact values.

Material	Ecotoxicity Impact (CTUe)
Dredge Sediment	72.70
Street Sweepings	71.59
Coarse Tailings	39.85
Fine Tailings	40.16
McGregor Scrapings	72.83
Premier Horticulture	66.43
Cromwell Scrapings	69.23
Cromwell Screenings	68.70
Floodwood	51.53
Blandin Bark	55.66
Kunst Excavation	63.36
80% Dredge + 20% Cromwell Screenings	134.80
80% Dredge + 20% Cromwell Scrapings	134.90
80% Dredge + 20% McGregor Scrapings	138.35
80% S.S. + 20% Cromwell Scrapings	133.75
80% S.S. + 20% Cromwell Screenings	133.64
80% S.S. + 20% McGregor Scrapings	137.20

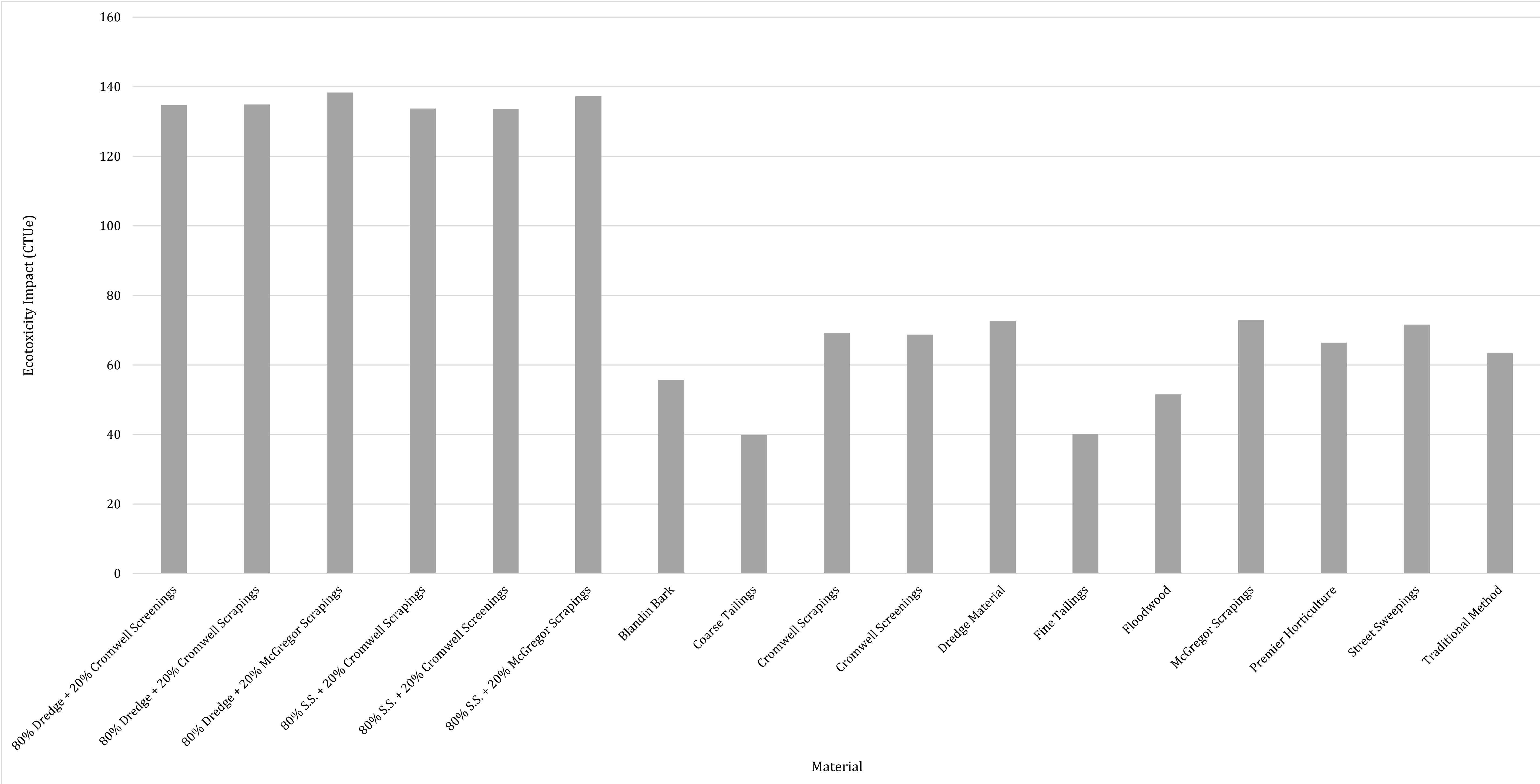

Figure 6.9 Ecotoxicity impact values.

Table 6.12 Global warming impact values.

Material	Global Warming Impact (kg CO_2 eq)
Dredge Sediment	21.08
Street Sweepings	19.92
Coarse Tailings	8.80
Fine Tailings	8.81
McGregor Scrapings	24.17
Premier Horticulture	22.13
Cromwell Scrapings	22.96
Cromwell Screenings	22.93
Floodwood	16.86
Blandin Bark	18.50
Kunst Excavation	20.60
80% Dredge + 20% Cromwell Screenings	43.67
80% Dredge + 20% Cromwell Scrapings	43.67
80% Dredge + 20% McGregor Scrapings	44.88
80% S.S. + 20% Cromwell Scrapings	42.52
80% S.S. + 20% Cromwell Screenings	42.51
80% S.S. + 20% McGregor Scrapings	43.72

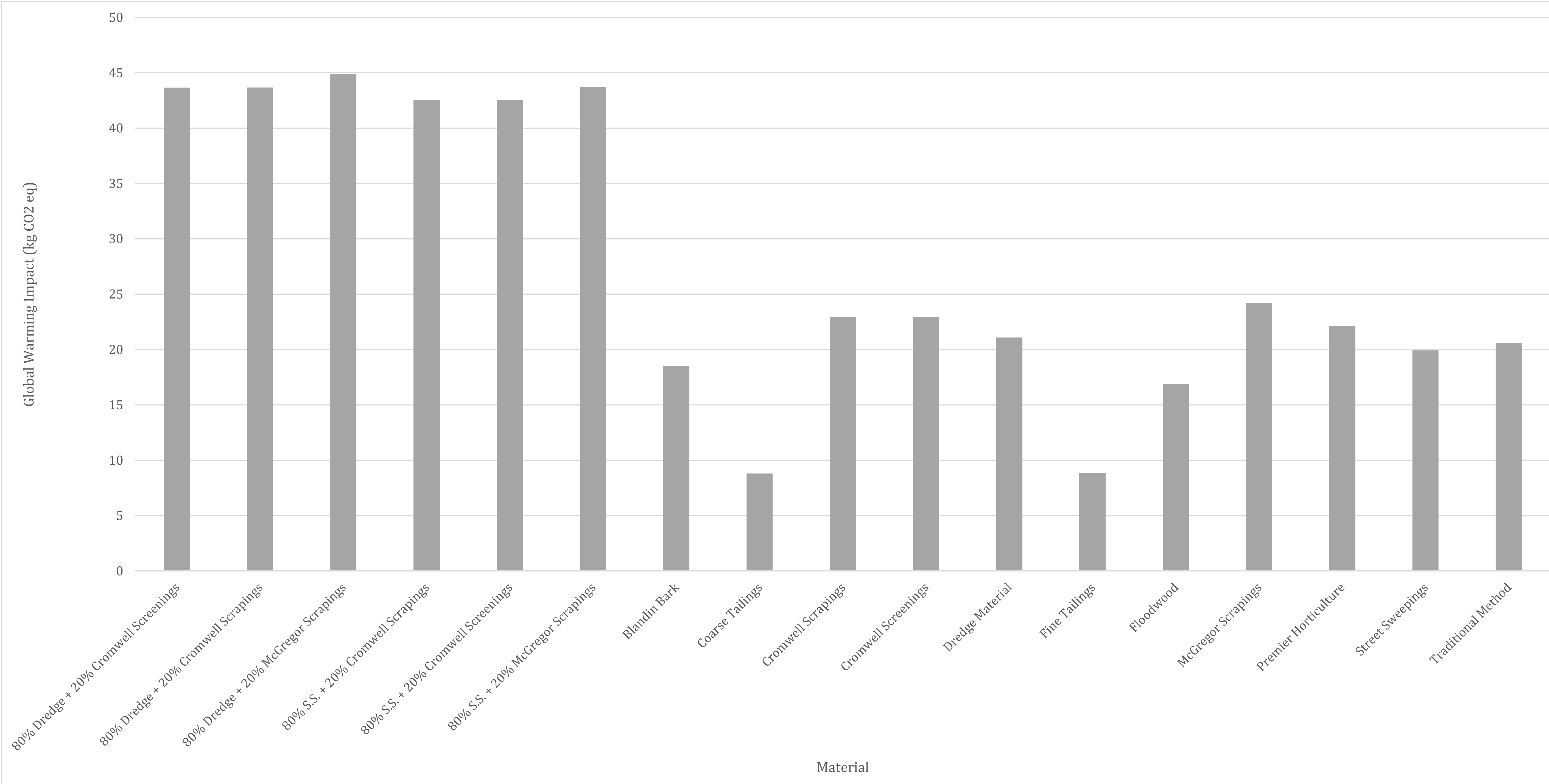

Figure 6.10 Global warming impacts.

6.3.3 Economic Life-Cycle Analysis

The parameters used for the analysis are shown in Table 6.13. Table 6.14 contains the costs that were calculated during the analysis. It is important to note that the values shown in Table 6.14 show consistent results for maintenance costs. This is because it was assumed that the maintenance schedule for each material would be the same. The values in Table 6.14 are normalized for mileage traveled, so it is also important to note that materials that are closer to the project site are shown in this analysis as being more expensive.

Table 6.13 Parameters used for each material in the LCCA.

	Options																
	Dredge Material	Street Sweeping	Fine Tailings	Coarse Tailings	McGregor Scrapings	Premier Horticulture	Cromwell Scrapings	Cromwell Screenings	Floodwood Screenings	Blandin Bark	80%SS 20%CWSCRAPE	80%SS 20%CWSCREEN	80%SS 20%McG	80%Dredge 20%CWSCRAPE	80%Dredge 20%CWSCREEN	80%Dredge 20%McG	Topsoil Material
Unit Weight of Material (gram/cm^3)	1.3	1.6	1.5	1.5	0.5	0.4	0.4	0.4	0.4	0.3	1.4	1.4	1.4	1.1	1.1	1.1	0.5
Volume of 1 ton of Material (m^3/ton)	0.69	0.57	0.59	0.60	2.02	2.36	2.10	2.36	2.36	2.70	0.67	0.67	0.67	0.79	0.80	0.79	1.77
Tons Per Truck Load (tons)	7.28	8.76	8.49	8.32	2.47	2.12	2.38	2.12	2.12	1.85	7.50	7.45	7.50	6.31	6.26	6.31	2.82
Initial Cost to Purchase Products	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$150
Cost of Construction per Truck	$2510	$3,023	$2,928	$2,871	$852	$730	$821	$730	$730	$639	$2,586	$2,571	$2,586	$2,175	$2,160	$2,175	$649
Maintenance Costs (Every 5th year)	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500	$500
Distance from Production Site to Project Site (miles)	101	95	39	39	119	109	113	113	83	91	208	208	214	214	214	220	101
Fuel Efficiency of Truck (mpg)	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20	3.20
Salvage Value - 100% Salvageable (% increase to cost at end of life)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Salvage Value - 50% Salvageable (% increase to cost at end of life)	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Salvage Value - 0% Salvageable (% increase to cost at end of life)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Lifetime (years)	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

Real discount rate (%)	0.3
Dump Truck Capacity (m^3)	5
2021 Price of Diesel (Costs/Gallon)	$3.39
Time Period (years)	25

Table 6.14 Results from the LCCA.

Material	Present Costs	Maintenance Costs	100% Salvageable Material Cost per Ton-Mile	50% Salvageable Material Cost per Ton-Mile	0% Salvageable Material Cost per Ton-Mile
Dredge Sediment	$2616.96	$1926.77	$6.18	$7.84	$9.49
Street Sweepings	$3123.58	$1926.77	$6.09	$7.84	$9.59
Coarse Tailings	$2912.88	$1926.77	$14.80	$18.93	$23.06
Fine Tailings	$2969.92	$1926.77	$14.68	$18.81	$22.94
McGregor Scrapings	$977.93	$1926.77	$9.89	$11.43	$12.97
Premier Horticulture	$845.64	$1926.77	$12.02	$13.72	$15.42
Cromwell Scrapings	$941.15	$1926.77	$10.66	$12.28	$13.90
Cromwell Screenings	$849.88	$1926.77	$11.61	$13.26	$14.91
Floodwood Screenings	$817.89	$1926.77	$15.66	$17.83	$19.99
Blandin Bark	$735.41	$1926.77	$15.78	$17.80	$19.82
Kunst Excavation	$756.36	$1926.77	$9.39	$10.61	$11.84
80% Dredge + 20% Cromwell Screenings	$2386.80	$1926.77	$3.22	$4.05	$4.87
80% Dredge + 20% Cromwell Scrapings	$2402.01	$1926.77	$3.21	$4.03	$4.86
80% Dredge + 20% McGregor Scrapings	$2408.36	$1926.77	$3.13	$3.93	$4.74
80% S.S. + 20% Cromwell Scrapings	$2805.95	$1926.77	$3.04	$3.88	$4.71
80% S.S. + 20% Cromwell Screenings	$2790.74	$1926.77	$3.05	$3.89	$4.72
80% S.S. + 20% McGregor Scrapings	$2812.30	$1926.77	$2.96	$3.77	$4.59

CHAPTER 7: CONCLUSION

This project demonstrates that there is great potential for using blended by-products as biofiltration media. The results show that using a mixture of inorganic and organic materials works well to support plant growth, aid in contaminant removal, and capture stormwater runoff. The following sections detail the conclusions that were made based off the laboratory testing and analysis.

7.1 BIOLOGICAL CONCLUSIONS

The studied waste materials/by-products were characterized to contain minimal or undetectable RCRA metals, PAHs, PCBs, or VOCs, implying these materials are not hazardous to be used as soil amendment. All materials except fine tailings could successfully support the growth of radish and oat even though dredge sediment, street sweeping, and tailings contain low organic matters, probably because the tests were performed with six plants in 28 days only. Fine tailings have similar chemical properties as coarse tailings but fine tailings have very low permeability, which leads to low infiltration and prevents plant growth.

7.2 ENVIRONMENTAL CONCLUSIONS

The lab batch tests show the studied waste materials/by-products could release a small amount of metals (copper and zinc) and phosphorus (mostly <100 ppb) when mixing with deionized water but were able to retain the chemicals when mixing with synthesized stormwater. Without plant uptake, all materials can remove more than 50% of the phosphorus. Peat screenings/scraping were particularly more efficient in removing zinc than inorganic materials or tree bark but released acidic effluent (pH 4-5). Street sweeping and dredge sediment showed the largest capacity to adsorb copper than all other materials. Based on the lab test results, a blend with peat materials and other inorganic materials could reduce the effluent acidity but enhance metal removal.

7.3 CIVIL ENGINEERING CONCLUSIONS

As the saturated case represents the worst case for infiltration, saturated hydraulic conductivity was used to characterize materials and mixes in this project. The lab testing of the by-products showed the hydraulic conductivity was controlled by the finest material. The organic materials had high hydraulic conductivities, and the coarser materials generally had higher hydraulic conductivities than the finer materials. The results showed that Blandin bark had the highest hydraulic conductivity, while the dredge sediment had the lowest hydraulic conductivity. The blended materials showed hydraulic conductivity values that were between the highest and lowest observed individual material hydraulic conductivity, with the lower hydraulic conductivity material controlling the blend hydraulic conductivity.

7.4 LIFE-CYCLE ANALYSIS CONCLUSIONS

The results from the LCA and LCCA show the results for a specific project site. It is important to note that the results shown in these analyses may change depending on where the project for which these materials are being analyzed is located. The results from this analysis are heavily influenced by where the material is generated and how far the material must be transported. This report can be used as a template for further analyses, but from this analysis, it is clear that the farther a material has to be transported, the more environmental impact it will have. This conclusion reinforces the importance of the current research. Using local waste material to meet federal and state requirements, decrease costs, and improve sustainability presents great potential for future projects.

7.5 WASTE MATERIAL RECOMMENDATIONS

Our lab study found that the materials of peat screenings, peat scrapings, tree bark, dredge sediment, street sweepings, coarse and fine tailings were not hazardous to be re-used. Based on the physical, chemical, and biological properties of the studied materials, we recommend not using dredge sediment or fine tailings as a soil amendment. The former material was found to grow the plant of invasive species, and the latter had extremely low permeability, which led to difficulty in supporting plant growth and mixing with other materials. Coarse tailing and street sweeping are not recommended to be used as a single media because the content of the organic matter is lower than 3%, which may be not sufficient to support continuous plant growth. Tree bark is weak in removing metals. It is not recommended unless the other materials in the blend could remove metals efficiently. The peat materials are typically acidic, with a pH below 5. Instead, the drain pHs of taconite tailings and street sweepings are typically above 9. Because of this, the mixture of peat materials with taconite tailings or street sweepings could change the pHs to neutral. From another MnDOT project (Johnson et al., 2017), we noticed that the mixture ratio of peat materials must be controlled to below 50% to get a neutral effluent with low phosphorus.

7.6 IMPLEMENTATION AND FUTURE WORK

7.6.1 Implementation

This research shows that there is great potential for beneficial re-use of byproducts in sustainably designed soil. This could be accomplished by two different methods: creating soil using byproducts, or blending on-site soils with byproducts. Both methods would result in a beneficial re-use of byproducts in Minnesota. All materials studied in this project were tested to be safe to be re-used as a soil amendment. To get a balanced nutrient supply and chemical adsorption, the blend of peat by-products with inorganic materials (tailings, street sweeping, and dredge sediment) is highly recommended.

Through the work of previous (Johnson et al., 2017; Saftner et al., 2019; Cai et al., 2021) and present projects, our research team has developed a suite of test methods to evaluate a waste product. New material should be first identified if it is hazardous and not by the chemical properties following EPA and MPCA's regulations. Only the non-hazardous material could be defined as having a potential for beneficial re-use. The non-hazardous waste needs to be further evaluated for water infiltration capacity, pollutant release/retention, and plant growth before being used as a soil amendment.

Once the properties of the new material are characterized through laboratory tests, the soil conditions of the applied sites should be assessed. Based on this research, the sustainably designed soils used should vary on a per-project basis. The soil blends used in the construction of bioslopes and bioswales will need to vary due to varying on-site soil conditions. The results from the LCA and LCCA also showed that the environmental and economic impacts depend heavily on project location. Therefore, the soil blends will need to be customized for each project to ensure that the blends are optimized to reduce impacts to the environment, reduce costs, and meet performance criteria.

When designing a sustainably designed soil, it is always best to conduct lab testing to get an accurate idea of how the designed soils will perform. However, it is not always within a project's budget to conduct an intensive laboratory investigation. Previous research regarding bioslope and bioswale design in Minnesota has shown relatively good correlation between the Kozeny-Carmen and Mouton equations for predicting the hydraulic conductivity of designed soils (Johnson et al., 2017). These equations will provide a close estimate for the hydraulic conductivity of the material, which will provide an estimate for how the soil will perform from a civil engineering perspective. Biological and environmental engineering performance are harder to predict and therefore will require some form of laboratory investigation.

7.6.2 Future Work

This research focused solely on the laboratory testing of by-product material for use as a filtration media. The number of mixes that were tested was also limited due to the COVID-19 pandemic. Future work should test other by-product mixtures to determine their potential for use as filtration media. Since this research was limited to lab testing, future work should also investigate the *in-situ* performance of these soil mixtures. This could be done by constructing a full size biofiltration system using these by-products. Long-term monitoring should also be completed on constructed biofiltration systems to analyze how well these materials perform over time. It is not anticipated that water retention capacity or plant growth potential will change with time, but the contaminant removal efficiency could vary with age.

To apply the waste materials in the field, a design manual needs to be developed to list the potential materials, material characterization requirements, mixing ratios and mixing technology, design and construction specifications, and post-construction monitoring requirements. This instruction manual will be created based on research outputs, information collected from agencies such as MPCA and MnDOT, and field applications. To make people aware of the beneficial re-use of waste materials, the research outputs will be disseminated to the target audience by conference or meeting presentations, journal publications, and workshops.

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APPENDIX A: Dredge Material Soil Blend Test

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Feasibility of Dredged and Recycled Material from Duluth Harbor for Use as a Plant Growth Medium

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Abstract

In recent years, the beneficial use of recycled materials has been widely studied in a myriad of environmental applications. In this study, the ca-pacity of a recycled substrate (comprised primarily of Duluth Harbor sediment) was investigated for its application as a plant growth medium. This investigation included seedbank characterization and plant growth studies. The seedbank characterization was performed by way of a plant emergence study simulating both saturated and upland soils. The plant species that emerged from both simulations were identified as common nettle (*Urtica dioica*), smartweed (*Polygonum sp*.), dogfennel (*Eupatorium capillifolium*), wild geranium (*Geranium molle*), wild lettuce (*Lactuca serriola*), and an unidentified gramineous species. In plant growth studies, the recycled substrate was evaluated singly and in combination with peat material to determine the impact of the existing seedbank on the growth of 4 test species: Kentucky bluegrass (*Poa pratensis*), little bluestem (*Schizachyrium scoparium*), side-oats grama (*Bouteloua curtipendula*), and switchgrass (*Panicum virgatum*) for 42 days. Plant growth studies were conducted in batches and evaluated under laboratory conditions. Test plants were notably impacted by plants from the existing seedbank in experimental substrate. Plants grown in control substrate were evaluated to establish a baseline for plant growth, density, and biomass. Root and shoot biomasses of Kentucky bluegrass and switchgrass were significantly lower in experimental substrate, whereas little bluestem and sideoats grama showed no differences in root or shoot biomasses compared to the control. Shoot lengths, however, were greater for Kentucky bluegrass in the control substrate. Experiments evaluating plant growth in the recycled substrate amended with peat material revealed shoot heights and biomasses for each species to be considerably less than those observed in unamended substrates; an outcome that was likely attributed to the physicochemical differences of the combined substrates. Thus, it is concluded that the plant species of the existing seedbank moderately im-pacted growth of the desired plant species during the evaluation period.

Introduction

Background

The reuse of waste materials is gaining increased attention nationwide as a means to reduce pollution and conserve natural resources (Krause and McDonnell, 2000). Characteristics such as the material lifecycle and its transfer from organic to inorganic states are important factors in deter-mining the most appropriate applications of the recycled materials. The study herein supports the Re-use of Regional Waste in Sustainably Designed Soils study (2019), with the overarching goal of identifying, selecting, characterizing, and combining regional waste and by-product materials to create a designed soil to meet MnDOT's topsoil specifications and needs in Northeastern Minnesota. If feasible, the reuse of these materials can reduce disposal and/or storage of solid wastes while providing a site-specific designed soil or soil amendment through beneficial use.

An additional component of this investigation is the study of dredged sediment from Duluth Harbor with which the recycled materials were combined. In previous years, dredged materials have been successfully amended with other residuals to produce manufactured soils for wider applications such as gardening and landscaping (Lee 2001). Although physical and chemical properties of dredged sediment are the typical characteristics considered before beneficial use application, here, the seedbank is characterized to further assess its feasibility in developing a modified soil. It is noteworthy that soil embedded seeds are beneficial for planting and restoration purposes, however, the soil or sediment media may also be an avenue for introducing invasive species (Ribeiro et al. 2017). Thus, seedbank characterizations are conducted to predict the introduction of invasive plant species (Forcella et al.1997). Previous studies of unamended, native sediment indicate the presence of invasive species such as, Purple Loosestrife (*Lythrum salicaria*), Common Reed (*Phragmites australis*), and Spotted Knapweed (*Centaurea stoebe*), among others around the Duluth Superior Harbor (Valpur 2007; 2010). As detailed by Patelke et al. (2019), the media of interest for this investigation is an aggregate of wood waste from timber and paper industry, mineral tailings from iron mining, dredge sediment from Duluth-Superior Harbor and Mississippi River, compost, and sewage sludge from water treatment plants.

Purpose and Objective

The purpose of this effort was to assess the feasibility of the Duluth Harbor recycled substrate to be employed as a beneficially usable material. The goal was to conduct a plant emergence study, plant growth studies, and examine bioavailable nutrients in the recycled medium. Specifically, we aimed to (1) determine if existing seeds of native and invasive plants were present in the medium and capable of germination, (2) determine the capacity of the medium to support and sustain plant growth, and (3) determine the native to invasive species ratio.

Technical Approach

Chemical Characterization

The test media used in the study, herein referred to as recycled substrate, was comprised of aggregates of wood waste from timber and paper industry, mineral tailings from iron mining, dredge sediment from Duluth-Superior Harbor, and compost from water treatment plants. Background levels of organic and inorganic compounds present in the recycled substrate and peat materials were determined by the NRRI -University of MN. Subsequent chemical characterization of the test media was conducted at ERDC-EL to determine plant available nutrients (nitrate, ammonia, phosphorus, and iron) to compare pre- and post-media concentrations.

Emergence Study

The recycled substrate was evaluated to determine the composition of the existing seedbank composition by way of an emergence study. The medium was prepared and maintained under greenhouse conditions, as well as controlled, laboratory conditions with soil moisture contents adjusted to simulate both wet (saturated) and dry (upland) soil conditions. A total of 6 containers were prepared; 3 containers simulated upland soil conditions, and 3 containers simulated saturated soil conditions (Figure A1).

Figure A11. Recycled substrate placed in plant growth containers simulating saturated soil conditions (top containers) with sand amendments, and up-land conditions (bottom containers) with no amendments.

Soil preparation for saturated conditions entailed the mixing of the recycled substrate with thermally treated (oven-dried) sand at a 1.5:1 sand to soil ratio (by volume). Thermal treatment of the sand was performed to inactivate any seeds or propagules that may be present in the media. One liter of deionized (DI) water was added to each replicated. In containers simulating upland conditions, 250 mL of DI water were added to each replicate via spray application. No sand amendments were added to the upland simulation containers. Water content in each mesocosm was maintained weekly. Emergence studies began in January 2021 and was maintained for 20 weeks under laboratory conditions. At Day 84 (at the onset of the spring season), the replicates of the upland simulation were combined and placed under greenhouse conditions where plants would be subjected to natural light intensities and photoperiods. The combination of the mesocosm replicates, in which the emerged plants were carefully transplanted, provided a greater soil depth for plant roots to support continued plant growth. At termination of the study, the genera and/or species of the emerged plants were identified.

Growth Study

The recycled substrate and peat material were evaluated to determine their ability to support seed germination and growth of 4 plant species. These plant species included Kentucky bluegrass (Poa pratensis), little bluestem (Schizachyrium scoparium), side-oats grama (Bouteloua curti-pendula), and Switchgrass (Panicum virgatum). Two batches of growth experiments were investigated under controlled laboratory conditions and evaluated for shoot height and density. Test batch #1 assessed plant growth in dried and undried recycled substrate under laboratory conditions, and test batch #2 assessed plant growth in undried recycled substrate amended with peat material under laboratory conditions. For each test batch, unplanted controls were prepared.

Approximately 150 g of recycled substrate was deposited into planting cones, and seeds of each plant species of interest were sown into each. Six seeds of Kentucky bluegrass, little bluestem, and switchgrass; and 3 seeds of sideoats grama were sown into each microcosm in replicates of 7. Plant growth was evaluated over a period of 42 days. In microcosms with undried recycled substrate with peat amendments (test batch #2), the media was prepared at 4:2 and 3:2 soil amendment ratios. The combined media was prepared in accordance with the sediment/amendment ratios shown in Table A1. Due to the low germination and growth rates of Little Bluestem observed in test batches #1, only Kentucky bluegrass, sideoats grama, and switchgrass were evaluated in test batch #2.

Table A15. Media identifications and corresponding composition.

Substrate ID	Composition
A	*80% Duluth Harbor Recycled substrate* *20% Cromwell Peat Screenings*
B	*60% Duluth Harbor Recycled substrate* *40% Cromwell Peat Screenings*
C	*80% Duluth Harbor Recycled substrate* *20% Cromwell Peat Scrapings*
D	*60% Duluth Harbor Recycled substrate* *40% Cromwell Peat Scrapings*
E	*80% Duluth Harbor Recycled substrate* *20% McGregor Yard Scrap*
F	*60% Duluth Harbor Recycled substrate* *40% McGregor Yard Scrap*

Results and Discussion

Chemical Characterization

Background concentrations of ammonium (NH_4^+), nitrate (NO_3), and orthophosphate (PO_4^{3-}) in the sediment were reported to be within normal range sufficient for plant growth (Table A2). Pollutant levels did not appear to be present in concentrations high enough to adversely affect plant growth. All chemical characterization of the sediment and recycled material can be found in the Supplemental Material section.

Table A16. Background measurements of the recycled substrate including soil moisture content (MC), soil organic matter (SOM), ammonium (NH_4^+), nitrate (NO_3), and orthophosphate (PO_4^{3-}).

		Exchangeable Nutrients (Bioavailable)		
MC (%)	SOM (%)	NH_4^+ (mg/kg)	NO_3 (mg/kg)	PO_4^{3-} (mg/kg)
17.25	*4.29*	*4.01*	*18.65*	*1.98*

Emergence Study

The saturated soil simulations conducted over 12 weeks yielded a total of 3 different plant species with 8-16 plants per mesocosm. The species identified in the mesocosms were wild lettuce (*Lactuca serriola*), smartweed (*Polygonum sp.*), and an unidentified gramineous species. The mesocosms were maintained under greenhouse conditions until day 49, when low overnight temperatures caused considerable diebacks to occur. Thereafter, the mesocosms were maintained under controlled laboratory conditions. Plants began emerging from both simulations between Days 7 and 14. Growth from the existing seedbank reestablished under laboratory conditions after Day 63. However, plant lengths measured in 7-day intervals thereafter revealed that plant growth and development rates were considerably lower than those observed in upland mesocosms. It is important to note that the same species were observed in both saturated and upland soil simulations. After Day 84, the saturated soil simulation was terminated.

Figure A12. Replicates #2 and 3 of the saturated soil simulations at Day 42 before the occurrence of plant diebacks around day 46 of the evaluation.

The upland simulation yielded plants with comparatively greater development relative to those observed in the saturated soil simulation with longer shoot lengths. At Day 84, the plants in the upland simulation began to emerge from the soil and demonstrated continuous growth and development throughout the remainder of the evaluation. At Day 140, the plant genera/species present in the mesocosm included common nettle (*Urtica dioica*), smartweed (*Polygonum sp.*), dogfennel (*Eupatorium capillifolium*), wild geranium (*Geranium molle*), wild lettuce (*Lactuca serriola*), and an unidentified gramineous species. Although each of the identified species are classified by the USDA as weedy and invasive species, their degrees of invasiveness over time would be contingent on soil conditions, species abundance, and anthropogenic activities as weedy species employ a number of methods to establish and spread (Zhang, 2014).

Figure A13. Upland simulation with the recycled substrate after 49 days (replicates 1-3). Plants shown above are the plants that survived the low temperatures.

Figure A14. Plants emerging from the recycled substrate (upland simulation) at Day 84 in greenhouse.

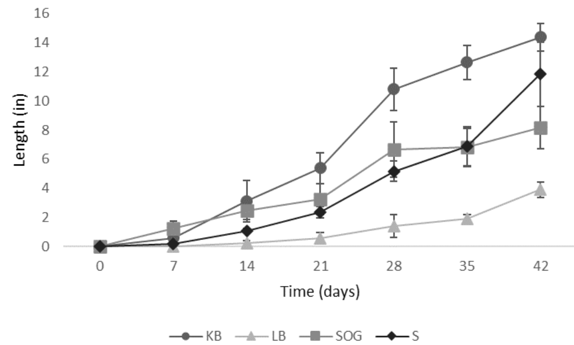
Figure A15. Recycled substrate with plants growing from the existing seedbank at Day 140.

Growth Study

Test Batch #1: Plant Growth in Recycled Substrate

Seeds sown in oven-dried recycled substrate were evaluated over time to determine the maximum growth of each plant species under optimal growth conditions as any potential interference from the existing seedbank were eliminated through the drying process. This evaluation was conducted to establish a baseline for plant growth in subsequent batch experiments. Plant growth was first observed after 5 days in microcosms of Kentucky bluegrass and sideoats grama. At Day 42, shoot lengths for Kentucky bluegrass, little bluestem, sideoats grama, and switchgrass in dried sediment were 14.5, 0.75, 10.25, and 8.5 inches, respectively (Figure A6). Little bluestem exhibited slow growth in the sediment compared to the other species and appeared to be a result of reduced seed viability based upon subsequent seed germination tests. Kentucky Bluegrass grew at the fastest rate and to the tallest height in both dried and undried media. Although sideoats grama and switchgrass grew at comparable rates, switchgrass reach an overall height approximately 2.25 in taller than sideoats grama. Plant densities in each microcosm were calculated based on the number of shoots sprouted from the seeds planted, with germination percentages for each test species between 86-100%. Healthy plants harvested from the substrate yielded baseline root and shoot biomasses by which the results from subsequent test batches were compared. Root and shoot biomasses (dry wt.) are shown in Table 4.

In the experimental substrate, plants from the existing seedbank resulted in taller shoot lengths in each plant species except for Kentucky bluegrass. Maximum shoot lengths for Kentucky bluegrass, little bluestem, sideoats grama, and switchgrass in the undried sediment were 13.0, 4.0, 11.5 and 8.75 inches, respectively (Figure A6).



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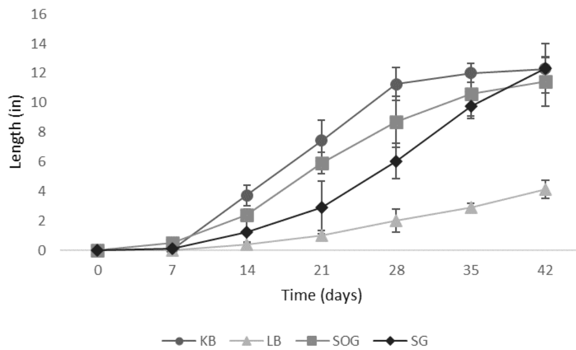

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Figure A6. Plant growth rates for each plant species in dried (a) and undried (b) substrate.

Table A3. Post substrate measurements of nutrients ammonium (NH_4^+), nitrate (NO_3), and orthophosphate (PO_4^{3-}).

Exchangeable Nutrients (Bioavailable)		
NH_4^+ (mg/kg)	NO_3 (mg/kg)	PO_4^{3-} (mg/kg)
4.17	*20.04*	*1.12*

Figure A7. Plants growing in control (left) and experimental (right) recycled substrate. Plants from the existing seedbank are observed in experimental substrate.

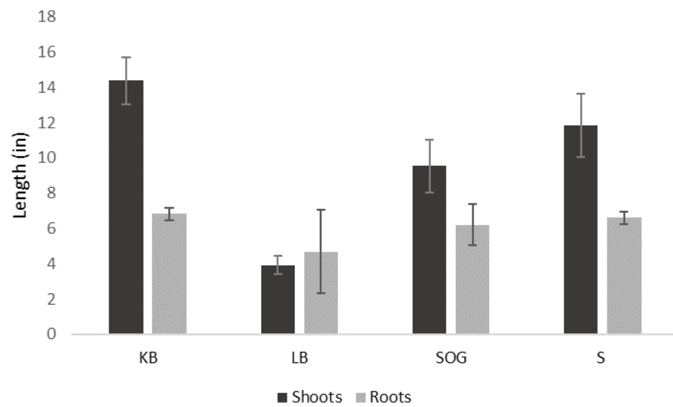
Smartweeds, wild lettuce, and other unidentified species were observed growing from the mesocosms (Figure A7). A 10% reduction in shoot heights was observed in the Kentucky bluegrass microcosms. Taller shoot lengths were observed for the other 3 species over the 42-day evaluation period. Weeds were present in 68% of the plant microcosms. The root and shoot biomasses of Kentucky bluegrass and switchgrass evaluated at harvest were significantly less that those harvested from dried, control sediment. Kentucky bluegrass, little bluestem, and switchgrass all yielded significantly greater shoot biomasses (α=0.05) in the dried, control substrate. Although the averages of sideoats grama root lengths were comparable, a statistical difference (α=0.05) was observed between the two samples sets; indicating that the shoot masses were produced in the dried, control substrate were significantly greater. Higher root masses were also observed for little bluestem, sideoats grama, and switchgrass in the dried, control substrate. Kentucky Bluegrass, on the other hand, produced its highest root biomass (P= 0.011; α=0.05) in the undried, experimental substrate.

Although modest, the trend of longer plant shoots for plants in the experimental substrate demonstrated that the existing seedbank of the sediment does not exhibit a high degree of invasiveness at this point in the study. It is likely that the presence of the weed species altered the hydrology or the nutrient availability in the microcosm, thereby affecting the growth of the plant species of interest. Ericsson (1995) suggests that root growth is favored when nitrogen (N), phosphorus (P), or sulfur (S) is sufficient, and potassium (K), magnesium (Mg), and manganese (Mn) are limiting, and vice versa for shoot growth; thus, altering the root-to-shoot ratio in various plant species. This phenomenon is supported by findings from Samuelson et al. (1992) when root proliferation and development was observed to respond sharply to N distribution in soil. Pre- and post- nutrient concentrations in the substrate did not implicate nutrient competition with the existing plant species as the definite factor attributing to the varying root-to-shoot ratios. However, the plant growth date suggest that some form of competition occurred.

Table A4. Day 42 plant heights and biomasses for each plant species evaluated in dried and undried recycled substrate under laboratory conditions.

Plant Species	Shoots		Roots	
Dried Media	**Height (in)**	**Biomass (g)**	**Length (in)**	**Biomass (g)**
Kentucky Bluegrass	*14.4*	*0.12*	*6.8*	*0.04*
Little Bluestem	*3.9*	*0.01*	*4.7*	*0.00**
Side Oats Grama	*9.5*	*0.06*	*6.2*	*0.03*
Switchgrass	*11.8*	*0.10*	*6.6*	*0.04*
Undried Media				
Kentucky Bluegrass	*12.3*	*0.07*	*6.4*	*0.03*
Little Bluestem	*4.1*	*0.00**	*3*	*0.00**
Side Oats Grama	*11.4*	*0.06*	*6.0*	*0.02*
Switchgrass	*12.3*	*0.03*	*6.0*	*0.02*

**Denotes biomasses too small to register on balance*



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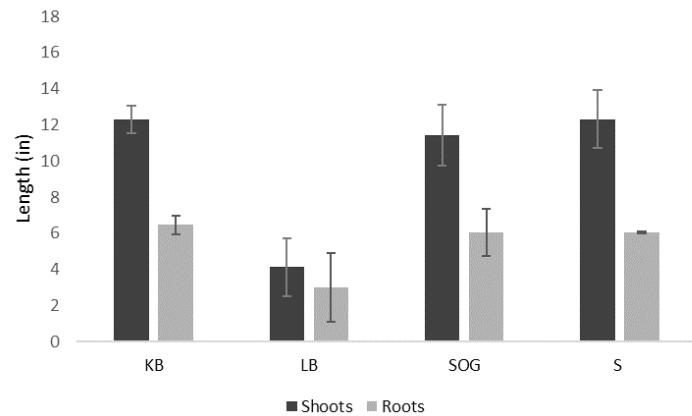

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Figure A8. Average shoot and root lengths of each plant species harvested from dried (a) and undried (b) substrates.

Test Batch #2: Plant Growth in Recycled Substrate with Peat Amendments

Based on the plant yields observed in test batches #1, little bluestem was not evaluated in test batch #2 due to its slow growth. Thus, only Kentucky bluegrass, sideoats grama, and switchgrass were evaluated. The recycled substrate amended with peat material demonstrated its effect on plant growth as maximum shoot heights at Day 42 were considerably less than those observed in test batch #1. Sideoats grama exhibited the most productive growth in each of the 6 substrate combinations (reference Table 1 for details of the media composition). Substrate E, containing 20% of McGregor Yard scarp, yielded no plant growth for Kentucky bluegrass nor switchgrass (Figure A9). Sideoats grama growth, however, was observed to be least in Substrate E compared to the other media combinations. Substrate A contained 20% of Cromwell peat screenings and seemed to have yielded the greatest plant growth for Kentucky bluegrass and switchgrass. Switchgrass germination percentages were between 75 and 100% in each of the substrates evaluated. With the exception of Substrate A, plant densities (determined by number of shoots relative to number of seeds planted) for Kentucky Bluegrass were very low. Interestingly, very little plant growth from the existing seedbank was observed. It is likely that the recycled sediment employed in this evaluation differed chemically from that employed in the previous (batch #1) evaluation. A more comprehensive analysis of soil characteristics could elucidate the differences in soil conditions that affect plant growth.

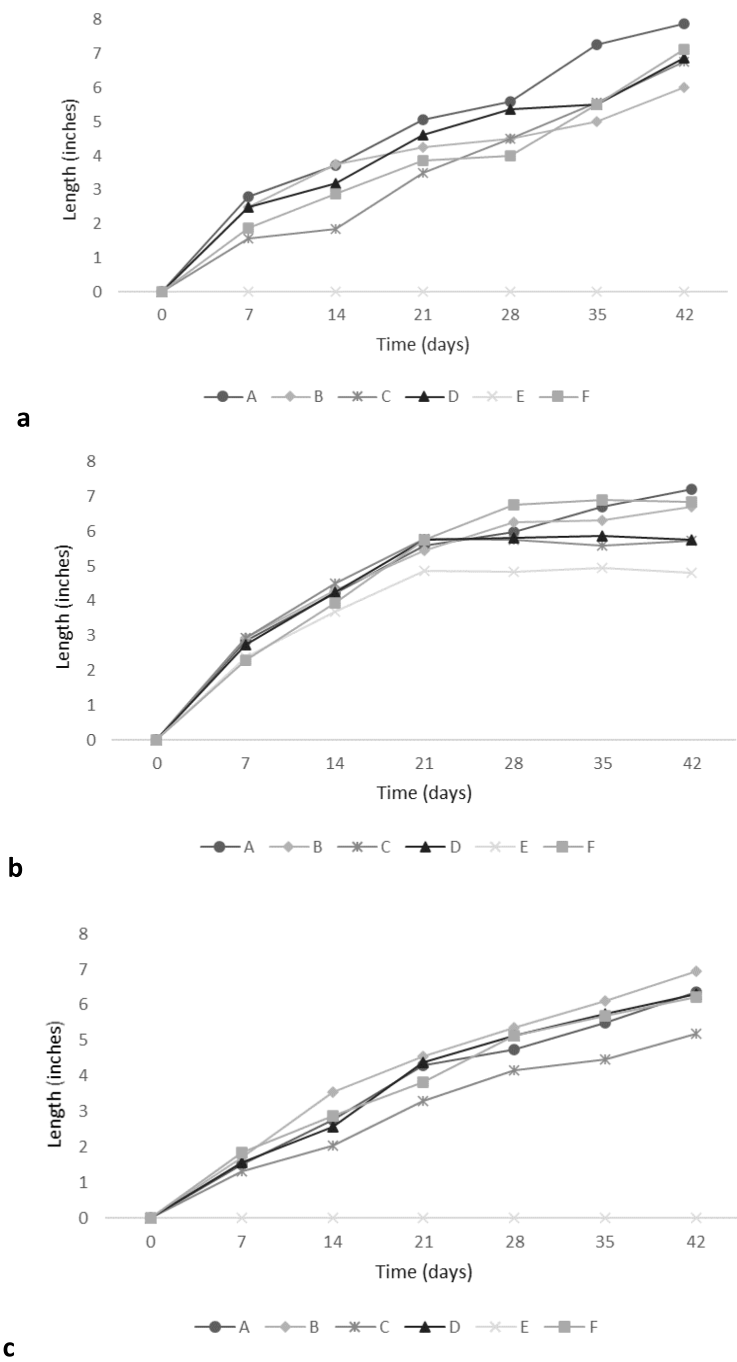

Figure A9. Plant growth rates for Kentucky bluegrass (a), sideoats grama (b), and switchgrass (c) in amended substrates.

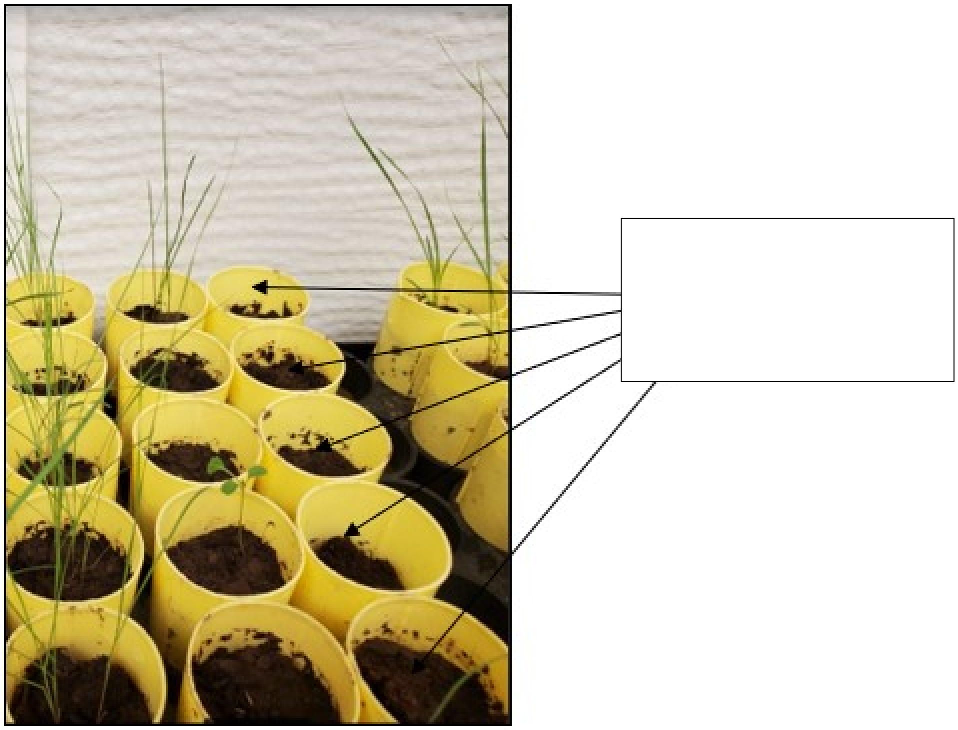

Figure A10. Example of the limited plant (Kentucky Bluegrass) growth observed in Substrate B with little interference from weed growth.

Overall, no discernable growth trends were determined for either plant species in either substrate combination. For this reason, factors including soil conditions, interference from weeds, and soil chemistry must be comprehensively considered before determining a rationale for the current observations. In an effort to explicate the results of the study, test plants (Kentucky bluegrass, sideoats grama, and switchgrass) were grown in the unamended recycled substrate used to prepare the combination media, repeating the batch #1 evaluation. It is worthy to note that the unamended, undried sediment did not yield comparable growth results over 42 days. At Day 42, maximum shoot lengths recorded for Kentucky bluegrass, sideoats grama, and switchgrass were 7.75, 8.75, and 8.5, respectively. Similar to observations from the planted microcosms with amended substrates, very few weeds were observed. Taking into account the unexpectedly low growth rates observed in the unamended substrate, it is likely that the media, although collected from the same site could have been collected at a different location and/or soil depth.

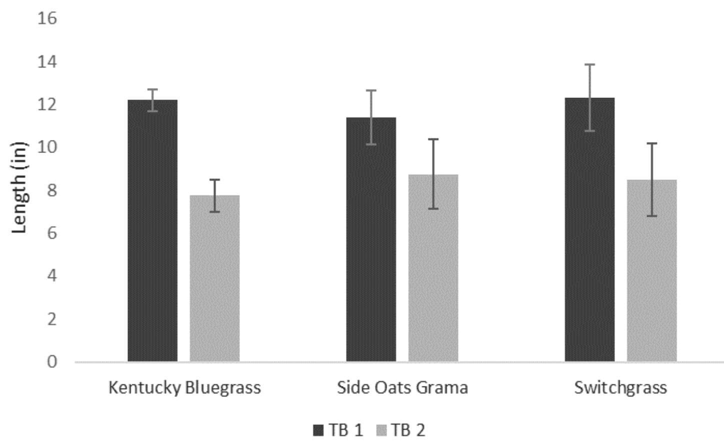

Figure A11. Comparison of maximum shoot lengths reached by plants of in the undmended recycled substrate from test batches #1 and 2.

Figure A12. Test plants grown in the unamended substrate.

Plants grown in the unamended substrate reached maximum heights that were 23-37% shorter than plants grown in test batch #1 after 42 days. Whole plant masses (dry weight) ranged from 0.01 to 0.16 g across the entire study (Figure A12).

Table A5. Average of whole plant biomasses (dry wt) and germination percentages observed in each substrate combination.

Plant Species	A	B	C	D	E	F
			Biomass (g)			
Kentucky Bluegrass	*0.163*	*0.027*	*0.038*	*0.021*	*n.a.*	*0.034*
Side Oats Grama	*0.124*	*0.091*	*0.064*	*0.040*	*0.064*	*0.061*
Switchgrass	*0.0435*	*0.057*	*0.048*	*0.029*	*0.004*	*0.068*
			Germination (%)			
Kentucky Bluegrass	*0.47*	*0.13*	*0.20*	*0.10*	*0.00*	*0.10*
Side Oats Grama	*0.87*	*0.70*	*0.60*	*0.37*	*0.47*	*0.70*
Switchgrass	*0.47*	*0.73*	*0.60*	*0.30*	*0.00*	*0.60*

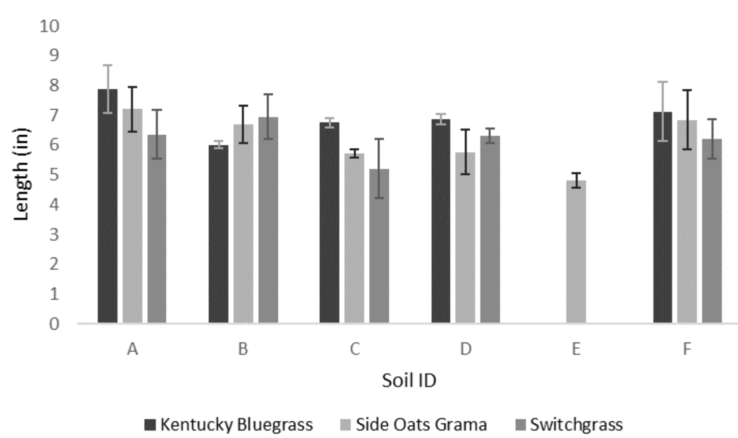

Figure A13. Shoot lengths of each plant species evaluated in amended substrates (A–F).

Seed germination was less than 50% in all 6 soils composites for Kentucky Bluegrass. In 3 of the 6 soil mixtures, germination rates were 60% and above for Side Oats Grama; and for Switchgrass, germination percentages were greater than 50% in 2 or the 6 soils tested. Moreover, a seed viability test with tetrazolium chloride indicated that 90-100% of the seeds for each species were viable. In the absence of the subsequent assessment of the unamended substrate, it would appear as if the composition of the peat amendments was limiting growth in both the plant species of interest, as well as the existing seedbank.

Conclusions

This study has demonstrated that the existing seedbank of the Duluth Harbor sediment exhibits a moderate degree of invasiveness due to its observed hindrances in the growth, particularly biomass, of each plant species evaluated over 42 days. Taking into account the 3 phases of invasiveness (introduction, establishment, and distribution), additional studies are required over an extended period to accurately assess the full extent of invasiveness of plants from the existing seedbank. The identified plant species were common nettle, smartweed, dogfennel, wild geranium, and wild lettuce in addition to an unidentified gramineous species. The planted species grown in the unamended, experimental substrate (test batch #1) demonstrated their ability to establish and grow in the presence of the existing seedbank. However, long-term evaluations are required to obtain conclusive results regarding the continued growth and distribution of the desired species.

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Supplemental Material

Table S-1. Chemical analyses of Duluth Harbor recycled substrate.

Type	Parameters	Duluth Harbor Recycled Substrate
Nutrient analysis	pH	7.2
	%OM	3
	Olsen P, ppm	na
	Bray P, ppm	13
	K, ppm	*75*
	NO3_N, ppm	33.1
	Soluble Salts, mmhos/cm	0.7
CHEMICAL ANALYSES RCRA METALS RESULTS REPORTED IN MG/KG, DRY WEIGHT	Arsenic	2.7
	Barium	64.4
	Cadmium	0.23
	Chromium	18.7
	Lead	11.9
	Mercury	0.085
	Selenium	<1.1
	Silver	<0.56
MG/KG, DRY WEIGHT	Phosphorous	171
	Nitrate	29
PAHs, ug/kg, DRY WEIGHT	Acenapthene	<11.8
	Acenapthylene	15.6
	Anthracene	32.5
	Benzo(a)antracene	80.8
	Benzo(a)pyrene	85.5

	Benzo(b)fluorathene	123
	Benzo(g,h,i)perylene	59.7
	Benzo(k)fluoranthene	55.1
	Chrysene	85.6
	Diabenz(a,h)anthracene	16.8
	BaP Equivalent Calc *	121.682
	Fluoranthene	126
	Fluorene	<11.8
	Indeno(1,2,3-cd)pyrene	52
	Naphthalene	40.3
	Phenanthrene	68.5
	Pyrene	107
PCBs		No detections above the reporting limits
VOCs		No detections above the reporting limits

Table S-2. Chemical analyses of Duluth Harbor recycled substrate.

Type	Parameters	Duluth Harbor Recycled Substrate	Peat Scrappings Cromwell	Peat Screenings Cromwell	Peat Scrappings McGregor
Nutrient analysis	pH	7.2	3.8	3.7	4
	%OM	3	59.4	90.6	57.4
	Olsen P, ppm	na	na	na	na
	Bray P, ppm	13	11	1	17
	K, ppm	*75*	12	17	11
	NO3_N, ppm	33.1	42.8	0.5	36.2
	Soluble Salts, mmhos/cm	0.7	0.4	0.1	0.3
CHEMICAL ANALYSES RCRA METALS RESULTS REPORTED IN MG/KG, DRY WEIGHT	Arsenic	2.7	<2.9		<2.5
	Barium	64.4	54		56.1
	Cadmium	0.23	<0.44		<0.37
	Chromium	18.7	7.3		5.4
	Lead	11.9	3.3		2.7
	Mercury	0.085	<0.055		<0.052
	Selenium	<1.1	<2.9		<2.5
	Silver	<0.56	<1.5		<1.2
MG/KG, DRY WEIGHT	Phosphorous	171	151		206
	Nitrate	29	93.8		87.3
PAHs, ug/kg, DRY WEIGHT	Acenapthene	<11.8	NA		NA
	Acenapthylene	15.6	NA		NA
	Anthracene	32.5	NA		NA
	Benzo(a)antracene	80.8	NA		NA
	Benzo(a)pyrene	85.5	NA		NA
	Benzo(b)fluorathene	123	NA		NA

	Benzo(g,h,i)perylene	59.7	NA		NA
	Benzo(k)fluoranthene	55.1	NA		NA
	Chrysene	85.6	NA		NA
	Diabenz(a,h)anthracene	16.8	NA		NA
	BaP Equivalent Calc *	121.682			
	Fluoranthene	126	NA		NA
	Fluorene	<11.8	NA		NA
	Indeno(1,2,3-cd)pyrene	52	NA		NA
	Naphthalene	40.3	NA		NA
	Phenanthrene	68.5	NA		NA
	Pyrene	107	NA		NA
PCBs		<DL	<DL		<DL
VOCs		<DL	<DL		<DL