Applied Research Project

Final Project Report

Novel Strategies for Enhancing Biodiversity and Ecosystem Function at Northern Ontario Aggregate Pits.

2021-2025

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Project Partners and Team Members

This project was made possible through the collaboration of dedicated partners and team members, each contributing unique expertise and resources. By bringing together diverse perspectives from across institutions and disciplines, the partnership fostered innovation, ensured comprehensive approaches to the research challenges, and strengthened the overall impact of the project's outcomes.

Project Partners:

- The Ontario Aggregate Resources Corporation (TOARC)[2]
- Glencore's Sudbury Integrated Nickel Operations[3]
- Ethier Sand & Gravel[4]
- Pioneer Construction[5]

Research Team[8]:

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Project Summary

There is a pressing need for improved reclamation strategies for end-of-life aggregate pits and unreclaimed legacy sites in Northern Ontario. Soil, climate conditions, and native biodiversity in this region differ significantly from those in Southern Ontario, where The Ontario Aggregate Resources Corporation (TOARC) has led successful reclamation efforts in collaboration with various research partners. While the Management of Abandoned Aggregate Properties (MAAP) program has contributed to the reclamation of legacy sites, it also offers a unique opportunity to test new reclamation strategies for current, permitted sites. Through the MAAP program, TOARC initiated a research partnership with Collège Boréal Laurentian University and Lakehead University to address the limitations of existing reclamation methods in northeastern Ontario. Initial observations suggested that northern sites do not respond as effectively to hydroseeding treatments as southern sites, likely due to harsher climatic conditions and, more critically, the lack of available soil organic matter, a key feature of the region's soil. This project was conducted in two phases: a small-scale greenhouse trial followed by a large-scale field trial. The goal was to develop and test new strategies to improve restoration efforts for former aggregate sites in the region.

Acknowledgement

Project Objectives

The primary objectives of this project were focused on developing effective commercially and operationally viable protocols for the closure and reclamation of aggregate extraction and mining sites. A key goal was to develop methods that could be applied at the time of gradual and permanent site closure, ensuring sustainable rehabilitation. In addition, the project aimed to explore new soil amendments and planting strategies that could improve reclamation efforts in Northern Ontario, specifically addressing challenges such as soil organic matter deficiencies and harsh climatic conditions. Through these efforts, the project also sought to facilitate the restoration of biodiversity and the regeneration of key ecosystem functions, ultimately contributing to the long-term ecological health of former extraction sites.

Research Strategy

The research strategy for this project was implemented in two phases to thoroughly explore reclamation techniques for Northern Ontario sites. The first phase consisted of a small-scale greenhouse trial, aimed at gaining a better understanding of the challenges to plant establishment and growth in the region[10,11]. This phase involved characterizing a range of MAAP-eligible sites, assessing the chemical and physical properties of the substrates, and identifying key limiting factors for plant growth.

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Predictions were made about the conditions and resources that hinder plant establishment, with a particular focus on the region-specific challenges.

In the greenhouse trial, low-cost, novel soil amendments and substrate treatments were tested. These amendments were specifically selected because they are readily available and easy to source within Ontario, making them practical and accessible solutions for reclamation projects in the region. The goal was to identify amendments that could effectively address limiting factors such as soil organic matter deficiencies, while remaining feasible for widespread application.

The second phase of the project involved field-scale reclamation trials, which were implemented at a targeted site based on the findings from the greenhouse trial. The novel amendments and planting strategies that showed promise in the greenhouse were applied to the field site. The field trials focused on monitoring soil development, natural plant recruitment, and the survival and growth of tree, shrub, and herbaceous plant species. The objective was to assess the effectiveness of these strategies on an operational scale and determine their potential for large-scale restoration of aggregate and mining sites in the region.

Phase 1: Greenhouse Trial (2021-2022)

1. Introduction

The greenhouse trial served as a critical first step in assessing the potential effectiveness of various soil amendments for improving plant establishment in Northern Ontario's aggregate reclamation sites. The primary objective was to test these amendments in a controlled environment before committing significant resources, time, and effort to a large-scale field trial. By conducting the trial in the greenhouse, we aimed to evaluate which treatments showed promise, allowing us to exclude ineffective ones and reduce the space required for the subsequent field trial. A greenhouse trial was an excellent first step for several reasons:

- Controlled Environment: It allowed for precise control over environmental variables such as temperature moisture, and light ensuring that plant responses were attributed primarily to the amendments rather than external factors.

- Cost-Effective: Conducting small-scale tests in a greenhouse was far less expensive than field trials, where larger spaces and more resources are required.

- Quick Results: Greenhouse trials typically yield quicker results, enabling researchers to assess the effectiveness of different amendments in a shorter time frame.

- Reduced Risk: By testing amendments in the greenhouse first, we eliminated ineffective treatments early on, thereby reducing the risk of wasting resources on unsuccessful strategies in the field.

- Scalability: Positive outcomes in the greenhouse provided a solid foundation for scaling up the most promising treatments to a larger, more complex field environment.

2. Site Selection and Experimental Design

The greenhouse trial was conducted at Collège Boréal's greenhouse complex in Greater Sudbury, Ontario. The goal was to evaluate the effectiveness of various soil amendments in improving plant establishment and growth under controlled conditions, as a precursor to a larger field trial. The soil for the experiment was sourced from a local pit in Skead, Ontario, which is representative of typical aggregate pit sites in Northern Ontario. This soil was chosen for its medium sandy gravel texture, low

nutrient content, and lack of organic matter, common conditions in disturbed areas such as aggregate pits[12].

Nine soil amendments were selected for testing based on their availability in Northern Ontario and their potential to improve soil conditions for plant growth. The treatments included both organic and inorganic materials and were chosen to address specific soil deficiencies identified in preliminary site assessments. The experimental design followed a randomized block design, using styroblocks because of the availability of a large cavity size and their overall strength. Trembling aspen (Populus tremuloides) and yellow birch (Betula alleghaniensis) were chosen as the plant species for the trial, since aspen is more tolerant to dry and poor nutrient conditions, while yellow birch requires moist, nutrient rich soils. They were also selected   because they are common in the region and have different ecological requirements. Each treatment combination (amendment, plant species, and planting technique) was replicated multiple times across the blocks to ensure statistically reliable results. The experiment aimed to assess the impact of each treatment on plant survival, growth, and root development.

Figure 1. Inside of one of Collège Boréal's greenhouse.

3. Materials and Methods

3.1 Greenhouse Conditions

The greenhouse trial was conducted in a controlled environment at Collège Boréal's greenhouse complex in Greater Sudbury, Ontario, Canada. The growing conditions within the greenhouse were carefully regulated to ensure consistency across all experimental units. The temperature during the daytime ranged from 6°C to 26°C, and light levels were maintained at a constant 28,000 lux, approximately 36,000 lux lower than natural outdoor light levels. Precipitation was managed manually through regular watering (60 minutes/day, which is equivalent to 50 mL/seedling/day) to simulate typical growing conditions. This controlled environment allowed for the isolation of variables, ensuring that plant growth could be primarily attributed to the amendments and treatments rather than fluctuating external factors.

3.2 Soil Preparation and Amendment Application

Soil used for the trial was sourced from an active local borrow pit located on McLennan Drive, Skead, Ontario. The soil was predominantly medium sandy gravel, containing 90% sand, 5% silt, and 5% clay, with a pH of 6.6. It was devoid of organic matter and had low levels of phosphorus (P), potassium (K), and other micronutrients, with undetectable levels of total nitrogen (N). The gravel was sieved using a

metal screen with two centimeters spacing to remove larger stones that could interfere with the planting process.

Prior to adding the amendments, the soil was blended with various materials s using a 60L cement mixer. Each treatment batch was mixed for 60 minutes to ensure homogeneity. After each batch, the mixer was thoroughly rinsed with water to prevent cross-contamination between treatments. The amendments tested in this trial are easily accessible in Northern Ontario, including:

- **Control**
- **SUD - Sudbury Recipe**
- **Limestone and Fertilizer**
- **Nrich – Lime-Stabilized**
- **Municipal Biosolids (LSMB)**
- **Wood Ash + Ammonium Nitrate**
- **Biomass Boiler Fly Ash (BBFA)**
- **Pulp - Pulp Mill Sludge (PMS)**
- **Silty Clay Mineral Soil**

Each treatment was mixed thoroughly with the soil to ensure uniform distribution of the amendments, which were then used to fill the styroblocks for planting.

Table 1. Experimental treatments, their application rate and reasoning

Treatment code	Material	Application Rate	Reasoning
CON	Sand and gravel	N/A	Baseline / Control
SUD	Dolomitic limestone + NPK Fertilizer	10 Mg/ha 400 kg/ha	Applied by VETAC form the CGS to treat acidified soils in the Sudbury mining basin.
AF	Biomass boiler fly ash (BBFA) + NO3- + Urea (1:1)	20 Mg/ha (dry) 74 Kg/ha	Best for promoting growth in local yellow birch field trials. Fertilizer included given absence of N in BBFA. Rate matches SUD N content.
PP	Pulp mill sludge (PMS)	290 Mg/ha (weathered)	To create a 1:1 gravel to residual layer at 7.5 cm depth.
PPA	PMS + BBFA	290 Mg/ha (weathered) 20 Mg/ha (dry)	To create a 1:1 gravel to residual layer at 7.5 cm depth.
PPF	PMS + Forest Floor Inoculation	290 Mg/ha (weathered) 200 Kg/ha (Fresh)	To create a 1:1 gravel to residual layer at 7.5 cm depth.
NRICH	lime-stabilized municipal biosolids (LSMB)	15 Mg/ha (weathered)	Manufacturer's guidelines.
NMC	LSMB + Municipal Compost	15 Mg/ha (weathered) 250 Mg/ha (weathered)	To create a 1:1 gravel to residual layer at 7.5 cm depth.
STOCK	Silty Clay Mineral Soil	N/A	Mineral soil stockpiled by a local aggregate mining company. To be used to cap the area once aggregate operations are completed.

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3.3 Experimental Design

The experiment was conducted using a randomized block design to minimize edge effects and ensure that each treatment was evenly represented across the greenhouse. The experimental unit consisted of 114 styroblocks (Beaver Plastics, Oregon, USA), each containing 24 individual cavities (15 cm deep and 10 cm in diameter). The blocks were arranged in a rectangular configuration within the greenhouse, providing space for 2,736 individual plantings.

Each block was randomly assigned based on of the following three factors: treatment (one of the nine amendments), species (either trembling aspen or yellow birch), and growing technique (either sowing or planting). The blocks were organized such that species were evenly distributed across the blocks to avoid edge effects. To further minimize variability, the growing technique alternated between blocks, with even-numbered blocks being sown and odd-numbered blocks being planted with pre-germinated seedlings. Each treatment-species-growing technique combination was replicated 76 times, ensuring statistical power for the analysis of results[13].
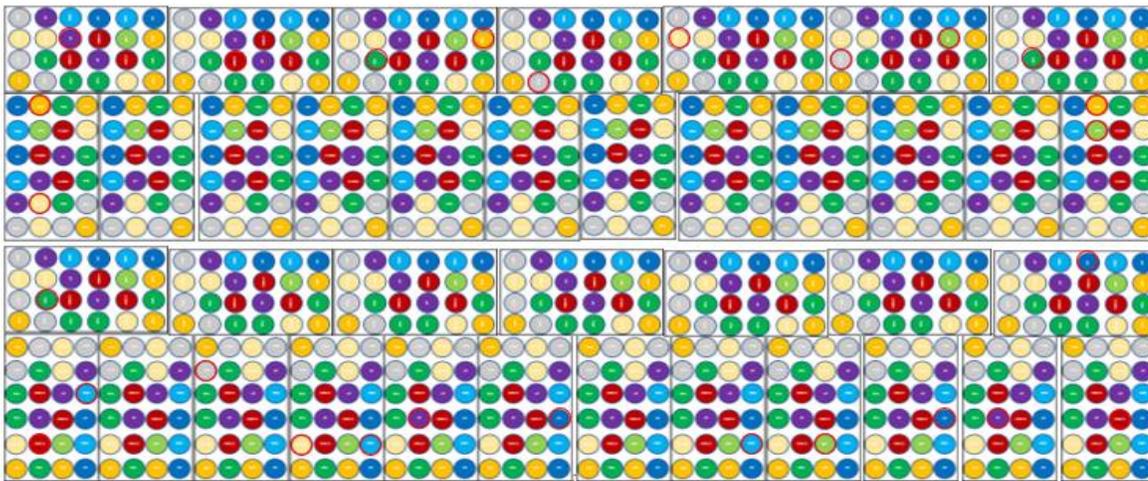
Figure 2. Randomized treatment design per styroblock, and per table.

3.4 Planting and Cultivation Techniques

For the seedling planting technique, Trembling aspen (Populus tremuloides) and yellow birch (Betula alleghaniensis) seedlings were selected because they are common in the region and have different ecological requirements[14,15]. Seedlings for this experiment were grown in-house at Collège Boréal. The seeds were pre-stratified before seeding into Jiffy plugs to germinate, and they were grown for 10 weeks under standard greenhouse conditions The seedlings were kept moist and subjected to a 16-hour light cycle under full-spectrum LED lights. As they grew, they were amended with fertilizer, using a nutrient solution (20-20-20) with concentrations starting at 25 ppm and gradually increasing up to 200 ppm before being planted in the styroblocks.

Seeds of both species were also sown directly into the cavities of the styroblocks. Since trembling aspen seeds are small, they were sown using a mini sampling spoon (0.10 mL volume) to ensure accurate and uniform distribution. After sowing, the blocks were maintained in the greenhouse under the same conditions as the planted seedlings, receiving regular watering to ensure successful germination and establishment.
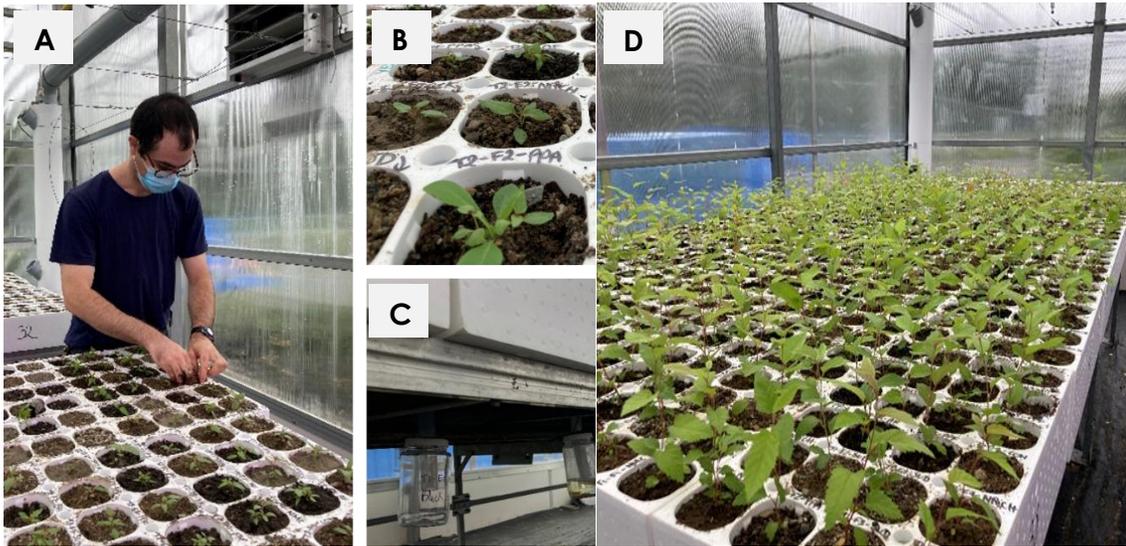
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Figure 3. (A) Collège Boréal student transplanting trembling aspen seedlings. (B) Close up of trembling aspen seedlings. (C) Leachate collection bottle; placed under the table to collect any liquid draining from the substrate. (D) Table with yellow birch seedlings.

3.5 Data Collection and Measurements

To assess plant growth and health, several measurements were taken throughout the greenhouse trial including:

- o Germination Rates: The percentage of seeds that successfully germinated for each species was recorded.
- o Seedling Survival: The survival rate of both seedlings and sown seeds was monitored regularly to determine the success of each treatment in supporting plant establishment.
- o Growth Measurements: Height and stem diameter of seedlings were measured every week to track growth over the duration of the experiment.
- o Root Development: At the end of the trial, the root systems of the seedlings and sown plants were carefully excavated and measured to assess the effectiveness of each treatment in promoting root growth.
- o Visual Health Assessment: Plant health was visually assessed, considering factors such as leaf chlorosis, wilting, or stunted growth, or any other physical symptoms indicating nutrient deficiencies or stress.
- o Chlorophyll Content: In addition to visual health assessments, chlorophyll content in the leaves was measured using a CHL BLUE Chlorophyll Pen (atLEAF). This allowed for an objective evaluation of the plants' photosynthetic capacity and overall health.
- o Pest Assessment: Plants were inspected for any signs of pest infestations, both aboveground and belowground. This was done visually and through tactile examination. Any pests or damage were recorded since pest pressure could influence plant growth and survival, potentially confounding the results of the amendments.
- o Leachate Collection: Leachate, or water that passed through the growing medium, was collected during the experiment to evaluate nutrient leaching. The amount and composition of the leachate provided valuable information about potential nutrient runoff and the environmental impact of using certain amendments.

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Figure 4. College Boreal students filling styroblocks with various treatments and seeding By.

3.6 Statistical Analysis

Before analyzing the data, we first checked if it followed a normal pattern using the Shapiro-Wilk test. If the data didn't follow a normal pattern, we adjusted it using the Box-Cox transformation to make sure our analysis was accurate. To understand the effects of the different soil treatments on seedling growth and chlorophyll (the pigments plants use to convert sunlight into food), we used one-way ANOVA to compare the treatments. We confirmed if the results were significant using Tukey's HSD test, which identifies meaningful distinctions among the groups. We also calculated the effect size using Cohen's d to assess the magnitude of differences between treatments. For germination (the number of seeds that sprouted) and survival rates (the number of plants that remained alive), we used a chi-square test to determine whether the outcomes were influenced by the treatments, and measured the strength of these associations with Cramér's V. We also looked at how the soil treatments affected root growth, seedling size (height and stem diameter), and how healthy the plants were by measuring their chlorophyll. All this data helped us figure out how well the plants were growing under each treatment. To measure how much moisture was lost from the soil over time, we used a special math model called an exponential decay model[14]. We took regular moisture readings with a device called the Accumet TDR 150 to track how much water was left in the soil. The model helped us understand how different treatments affected water retention, which is important for plant growth. Finally, we used graphs and charts to make the data easier to understand, helping us spot patterns and trends in the results.

4. Results

The greenhouse study investigating the use of industrial residuals for borrow pit reclamation yielded several significant findings. The analysis was conducted by Jonathan Lavigne, PhD candidate at Lakehead University. The results provide valuable insights into soil improvements and tree seedling growth, which are crucial for effective land reclamation strategies. It's important to note that the stock amendment (silt clay mineral soil) treatment was not included in the results, as no plants survived in that treatment; therefore, it was removed from the analysis.

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4.1 Soil Property Enhancements
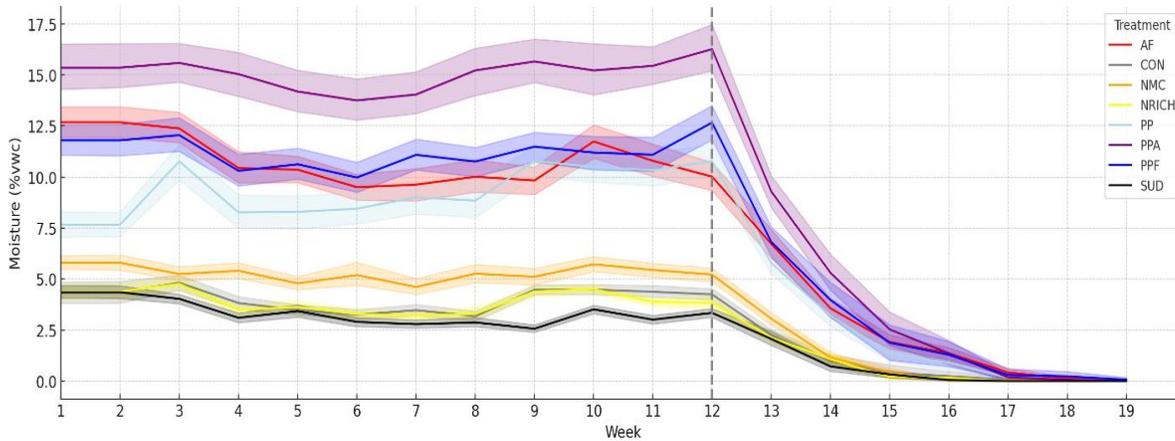
Figure 5. Average Soil Moisture Over Time (with 95% Confidence Intervals).

Treatments such as PPA (purple), PPF (blue), and AF (red) exhibited the highest moisture retention, maintaining values between 10% and 17% VWC. PP (light blue) also showed moderate moisture levels, while treatments such as NMC (yellow), NRICH (orange), CON (gray), and SUD (black) displayed significantly lower moisture retention, with values ranging between 2% and 5% VWC.

At Week 12, all watering ceased (vertical dashed line) to simulate drought conditions which are common in medium sandy gravel sites during the hot summer months. Although there was near-zero soil moisture by week 19, representing an extreme drought condition, the PPA, PPF, and AF treatments, maintained moisture the longest indicating a higher tolerance to periods of low rainfall during the more extreme, hot periods in the summer months.

Overall, the results indicate that PMS-based amendments, particularly PPA, PPF, PP, and AF, significantly improved soil moisture retention before Week 12. In contrast, BBFA-based treatments (NMC, NRICH) and unamended controls (CON, SUD) retained far less moisture. When irrigation ceased, all soils dried out, but those treated with PMS amendments delayed moisture loss, demonstrating their potential to support plant growth on dry sites such as gravel aggregate sites.
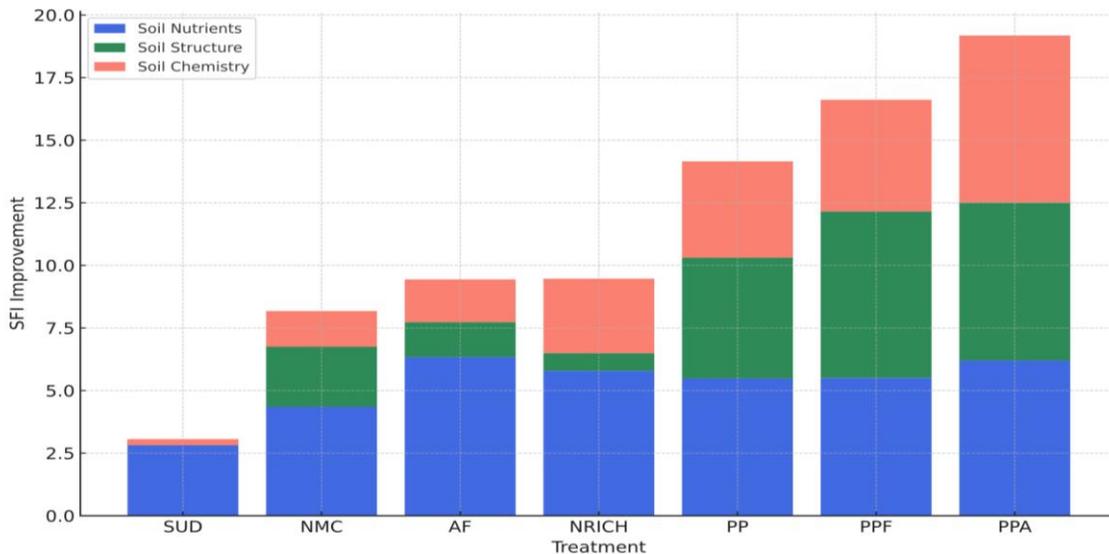
Figure 6. Improvement to Gravel Soil Following Incorporation of Industrial Residuals.

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The bar graph illustrates the Soil Fertility Index (SFI) improvement across different treatments, with contributions from soil nutrients (blue), soil structure (green), and soil chemistry (red). Among all treatments, PPA shows the highest overall improvement, followed closely by PPF and PP, indicating significant enhancements in soil fertility. These treatments exhibit strong gains in all three components, particularly soil chemistry.

In contrast, SUD demonstrates the lowest SFI improvement, suggesting minimal impact on soil quality. Treatments such as AF, NRICH, and NMC show moderate improvements, primarily driven by increases in soil nutrients and structure. The results highlight the effectiveness of PMS-based amendments (PP, PPF, PPA) in improving multiple soil properties, making them the most beneficial for soil enhancement in this study.

Table 2. Results of a comparative analysis of nutrients enrichment in soil treated with various industrial residuals (t=20 weeks).

| Parameters	CON	AF	NMC	NRICH	PP	PPA	PPF	SUD
pH	6.6	8.7	8.8	8.8	6.8	7.7	6.6	7.4
Organic Matter (%)	0.4	1.4	3.6	1.3	11.1	10.9	11.2	1.0
Sand-Silt-Clay (%)	91-4-5	88-4-8	80-8-12	88-4-8	88-8-10	80-9-11	74-11-15	88-4-8
Nitrate (ppm)	0.3	33.6	15.4	5.2	353	311.5	71	7.7
Phosphorus (ppm)	7	14	27	22	66	69	91	23
Potassium (ppm)	34	395	177	208	86	788	99	126
Magnesium (ppm)	41	177	170	107	118	308	156	81
Calcium (ppm)	251	3990	3360	6010	3030	4790	3780	1230
CEC (meq/100g)	2.9	23.6	19.9	32.7	17.6	29.7	21.7	8.3

The table presents key soil parameters across different treatments, highlighting variations in pH, organic matter, texture, nutrient content, and cation exchange capacity (CEC). Control (CON) soil has the lowest nutrient levels and organic matter content, with a pH of 6.6, indicating acidic conditions. In contrast, treatments like AF, NMC, and NRICH significantly increase pH (above 8.7), suggesting strong alkalinity, which could impact nutrient availability.

Organic matter content is highest in PMS-based amendments (PP, PPA, and PPF), reaching around 11%, which enhances soil fertility and moisture retention. These treatments also exhibit the highest nitrate concentrations, particularly PP and PPA, with over 300 ppm, supporting plant growth. In contrast, nitrate levels remain low in SUD and CON, indicating limited nitrogen availability. Phosphorus levels are highest in PPF (91 ppm), followed by PPA and PP, suggesting improved soil fertility. Potassium, magnesium, and calcium levels are also significantly elevated in PPA, with potassium reaching 788 ppm, the highest among all treatments. The CEC, a measure of soil nutrient-holding capacity, is notably higher in AF, NRICH, and PPA, indicating improved soil chemistry and nutrient retention. Overall, PMS-based amendments (PP, PPA, PPF) exhibit the most significant improvements in soil fertility, particularly in organic matter content, nutrient availability, and CEC, while alkaline treatments (AF, NMC, NRICH) may require pH management to optimize nutrient uptake.

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4.2 Tree Seedling Performance

The study focused on two tree species: yellow birch (*Betula allegheniensis*) and trembling aspen (*Populus tremuloides*). These species were chosen to represent different forest succession stages, with yellow birch typical of mature forests and trembling aspen representing earlier seral stages. Both species were either seeded directly into the styroblocks, or 10-week-old seedlings were transplanted in their original Jiffy pellets.

Survival and Germination Rate

Trembling aspen seeds sown directly into gravel had a 40.7% germination rate, but this significantly increased with soil amendments. The highest improvement was seen in PPA-amended soil (80.8%), followed by NMC (75.9%), AF (75.4%), and PPF (72.4%), all showing strong positive effects (p<0.001). NRICH (57.1%), SUD (49.1%), and PP (44.4%) had moderate but significant improvements (p<0.05). In unamended gravel (CON), only 18.2% of seedlings covered more than 20% of the soil surface, whereas PPA-amended soils had 74.4% of individuals exceeding this threshold. Other amendments such as NMC, AF, PP, and PPF also increased plant cover (>35%) (p<0.01), while SUD and NRICH had limited effects.

Transplanted seedling, survival rates varied by treatment. In control conditions, 85.7% of seedlings survived the first phase of the trial. BBFA significantly improved survival (93.0%) (p<0.05), while PPA and SUD decreased it (61.9% and 78.6%). Other treatments had no significant effects. Among planted trembling aspen seedlings, CON had an 80.3% survival rate, with AF, NRICH, and PPA increasing survival by over 10% (p<0.01). PP and NRICH also improved survival slightly (p<0.05), while SUD and PPF had negligible effects.

Nearly all seeded yellow birch seeds germinated in gravel (96.0%). Industrial amendments slightly reduced germination, but rates remained above 84% for all treatments. SUD (84.7%) and NMC (84.4%) showed significant decreases (p<0.05). However, all transplanted yellow birch seedlings survived to the end of the trial, indicating strong resilience.

Vegetative Growth

Leaf chlorophyll content (LCC) was lowest in CON soils (0.11 g/m²). PMS amendments significantly improved LCC, with PP, PPA, and PPF increasing levels to 0.45, 0.40, and 0.38 g/m², respectively (p<0.001). NMC also improved chlorophyll content (0.28 g/m²), while AF and SUD had minor effects (p<0.05). NRICH had no significant impact.

Seedlings grown in PMS-amended soil showed the best overall performance among all treatments. This superior growth can be attributed to the balanced improvement in soil properties provided by PMS, including better nutrient availability, improved soil structure, and enhanced moisture retention. Both trembling aspen and yellow birch seedlings benefited from PMS application, suggesting its broad applicability in forest restoration efforts.

Seedlings in LSMB and BBFA treatments faced challenges, primarily due to the elevated soil pH resulting from these amendments. High pH can interfere with nutrient uptake and potentially stress young seedlings, highlighting the need for careful management of application rates for these materials. Under simulated drought conditions, a critical test for reclamation in areas prone to water stress, seedlings in PMS-amended soil exhibited the longest survival times. This resilience can be directly linked to the improved moisture retention capabilities and increased organic matter content provided by PMS, underlining its potential for enhancing drought resistance in reclaimed areas.

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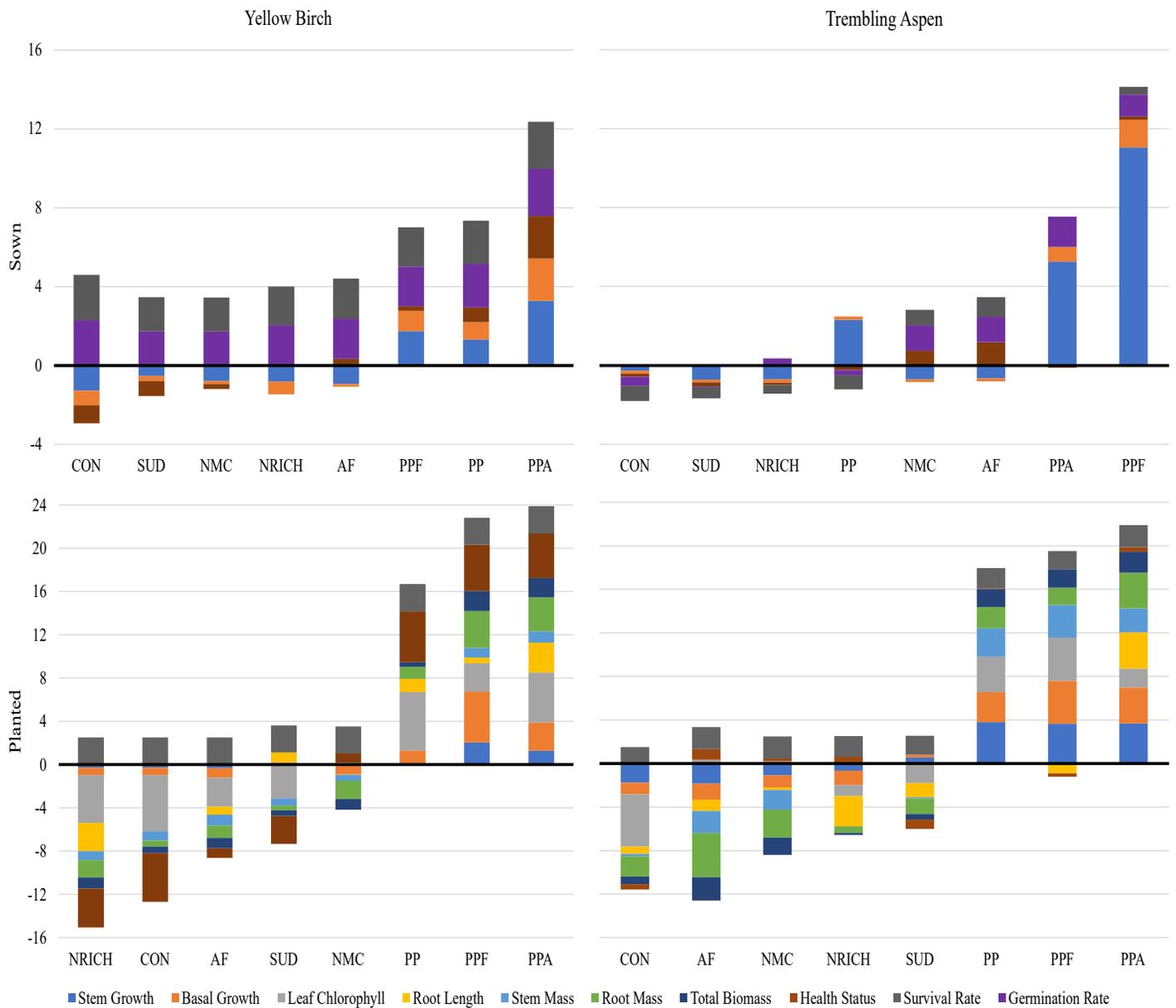
Figure 7. Comparative Plant Performance Index (PPI) of standardized growth and health responses of seedlings grown in industrial residuals (t= 12 weeks). Each coloured bar segment of the stacked column represents its weighted contribution. Any values above 0 are considered greater than the overall mean. Bar sizes indicate distance from the overall mean multiplied by inverse of covariance of the treatment. Larger cumulative values indicate greater seedling performance.

4.3 Leachate Composition

Nutrient and DOC Leachate Concentration in Soils Amended with Industrial Residuals at 15 Weeks
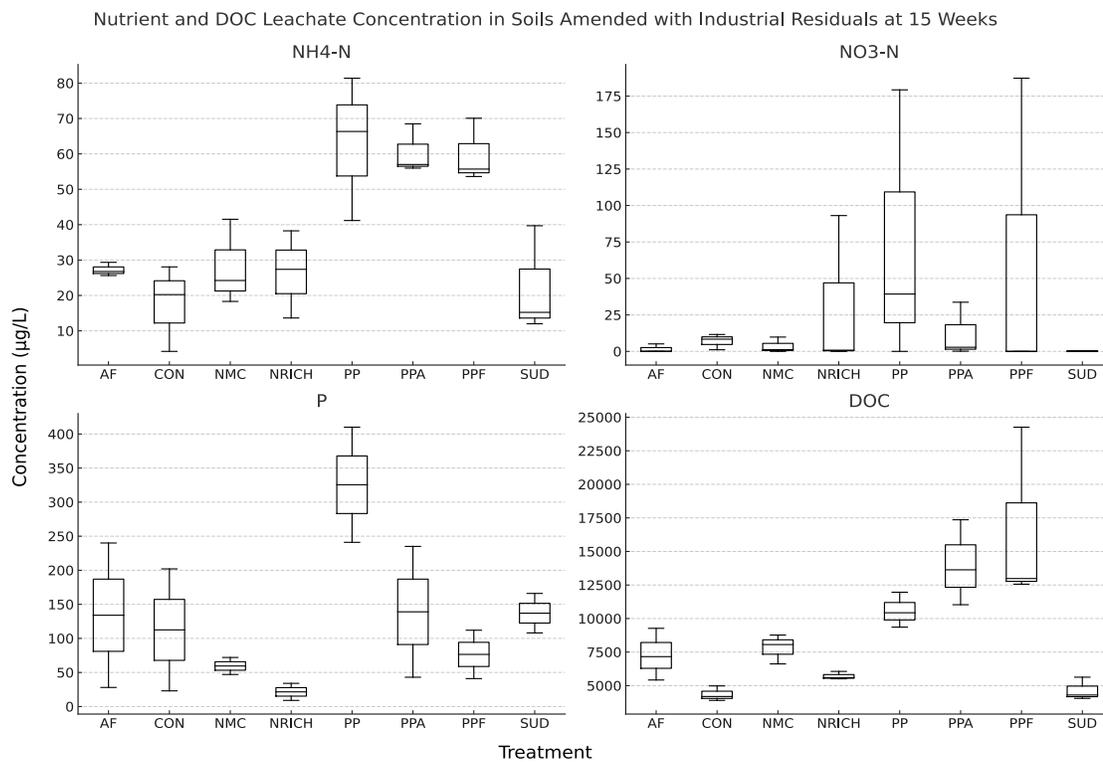
Figure 8. Box plots of nutrient (NH4-N, NO3-N, and P) and dissolved organic carbon (DOC) leachate concentrations in soils amended with industrial residuals at 15 weeks. The treatments are compared to evaluate the impact on soil leachate composition. Concentrations are presented in $\mu g/L$, highlighting variations among different soil amendments.

This graph presents the nutrient and dissolved organic carbon (DOC) leachate concentrations in soils amended with industrial residuals at 15 weeks. The four box plots show the variation in ammonium nitrogen (NH4-N), nitrate nitrogen (NO3-N), phosphorus (P), and DOC across different treatments.

In the NH4-N panel, PP and NRICH treatments exhibit the highest ammonium concentrations, with NRICH showing a wider range of values. In contrast, AF, CON, and NMC have the lowest NH4-N levels, suggesting limited nitrogen retention in these treatments.

For NO3-N, treatments PP, PPA, and PPF display significantly higher variability and elevated nitrate concentrations, with some extreme values reaching above 175 µg/L. The control (CON) and SUD treatments show the lowest NO3-N levels, indicating minimal nitrogen leaching.

The phosphorus panel highlights that PP treatment has the highest phosphorus leachate concentration, exceeding 400 µg/L, while NMC and NRICH show the lowest levels. Other treatments, including PPA and PPF, exhibit moderate phosphorus leaching.

Finally, in the DOC panel, PPF and PPA treatments show the highest dissolved organic carbon concentrations, with PPF reaching values close to 25,000 µg/L. CON and NRICH treatments have the lowest DOC concentrations, suggesting limited organic matter mobilization in these soils.

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Overall, the results indicate that PMS-based amendments (PP, PPA, PPF) contribute to higher nitrogen, phosphorus, and DOC leaching, while control (CON) and unamended soils (SUD) show the lowest levels of nutrient loss. These findings highlight the potential for nutrient-rich amendments to enhance soil fertility but also raise concerns about nutrient leaching risks.

4.4 Environmental Considerations

The study also addressed potential environmental impacts of using these industrial residuals. LSMB and BBFA treatments showed higher risks of nutrient leaching, particularly for calcium and potassium. This leaching potential raises concerns about possible impacts on groundwater quality and emphasizes the need for careful application strategies.

An important observation was the initial spike in nutrient loss immediately after applying the amendments. However, this spike decreased over time, suggesting that with proper management, the long-term environmental impact could be minimized. This finding aligns with previous research indicating that aligning application rates with anticipated plant productivity can mitigate excessive nutrient loss.

Regarding heavy metal concerns, PMS and LSMB introduced trace amounts of heavy metals, but the levels were within acceptable limits for soil amendments. BBFA showed potential for introducing higher levels of certain trace metals, necessitating careful monitoring and potentially limiting its application in sensitive areas.

5. Discussion

5.1 Soil Structure and Nutritional Response

The application of different industrial residuals led to varying degrees of improvement in soil properties. Pulp mill sludge (PMS) emerged as the most effective amendment, demonstrating substantial enhancements in soil quality. PMS significantly increased the soil organic matter content, which is a critical factor in improving overall soil structure and fertility. This increase in organic matter directly contributed to better moisture retention capabilities in PMS-amended soil, addressing one of the key challenges in borrow pit reclamation – the tendency for rapid drainage and drought susceptibility in sandy soils.

In contrast, lime-stabilized municipal biosolids (LSMB) and biomass boiler fly ash (BBFA) showed less favorable outcomes in terms of soil improvement. While these amendments did offer some benefits, they also presented challenges, particularly regarding soil pH. The elevated pH levels associated with LSMB and BBFA applications could potentially lead to nutrient imbalances, affecting the availability of certain micronutrients essential for plant growth.

In terms of nutrient availability, PMS demonstrated the most balanced improvement across various essential nutrients. The organic-rich composition of PMS contributed to a gradual release of nutrients, enhancing overall soil fertility without causing dramatic spikes in specific elements. LSMB, while effective in increasing nitrogen and phosphorus levels, raised concerns about excessive pH elevation. BBFA was notably effective in improving potassium content but, like LSMB, its application needed careful management to avoid adverse effects on soil pH.

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The gravel substrate used in this study is highly deficient in essential nutrients, organic matter, and moisture retention, making natural revegetation extremely difficult. To improve soil conditions, industrial residuals were tested as amendments, with promising results.

Pulp mill sludge (PMS) significantly improved nutrient availability, particularly nitrogen, due to its composition and the presence of active nitrifying bacteria. However, when PMS was mixed with biomass boiler fly ash (BBFA), nitrate levels dropped due to increased soil pH, which likely disrupted bacterial activity. BBFA is highly alkaline, and while it can help neutralize acidic soils, excessive alkalinity can inhibit nitrogen cycling, leading to reduced plant-available nitrogen. Similar studies have shown mixed effects of BBFA on soil microbial communities, with some indicating improved nitrogen mineralization and others showing declines due to pH stress.

Lime-stabilized municipal biosolids (LSMB) primarily contained organic nitrogen and ammonia, requiring microbial transformation to become plant-available. However, due to its high pH (often exceeding 12), nitrification was slow, limiting its effectiveness as a nitrogen source. PMS-treated soils had a significant increase in soil organic matter (SOM) from 0% to 11%, improving soil structure, moisture retention, and microbial activity. By contrast, BBFA and LSMB did not meaningfully increase SOM, limiting their ability to enhance soil water retention. Despite this, BBFA did improve moisture retention in gravel soils, though plants had difficulty accessing the stored water, potentially due to soil pore clogging.

5.2 Plant Response

Trembling aspen and yellow birch seedlings showed the strongest growth in PMS-treated soils. The increase in SOM significantly improved moisture and nutrient availability, which directly enhanced root and shoot development. Roots in PMS-amended soil formed dense aggregates, maximizing nutrient absorption. Above-ground, leaf chlorophyll content was highest in PMS soils, indicating better photosynthetic efficiency and overall seedling health. In contrast, BBFA and LSMB treatments did not lead to significant improvements in plant growth, likely due to poor moisture retention and nutrient imbalances. High soil pH in BBFA and LSMB soils also appeared to limit phosphate availability, leading to deficiencies despite elevated phosphorus content in the amendments.

Seed germination rates varied by species and treatment. Trembling aspen seeds showed higher germination in industrially amended soils, particularly in BBFA-treated substrates, while yellow birch had slightly lower germination rates with amendments. However, seedling survival was not strongly influenced by amendments, possibly due to controlled moisture conditions in the experiment. When drought conditions were simulated, PMS and BBFA soils delayed drought stress symptoms, highlighting their benefits in moisture retention.

5.3 Soil Leachate and Environmental Considerations

One key concern was the potential leaching of heavy metals from industrial residuals. While minor increases in chromium and lead (from LSMB) were detected, overall metal leaching remained below environmental safety thresholds. Additionally, nutrient losses, particularly nitrate, were minimal, reducing concerns of water contamination. However, phosphorus leaching remained high across all treatments, including the control, indicating a potential risk of eutrophication in nearby water bodies.

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6. Conclusion

This greenhouse study explored the potential of using industrial residuals – pulp mill sludge (PMS), lime-stabilized municipal biosolids (LSMB), and biomass boiler fly ash (BBFA) – to reclaim borrow pits, which are characterized by nutrient-poor, sandy soils that are inhospitable to plant growth. The research assessed how these residuals affected both soil properties and the growth of trembling aspen and yellow birch seedlings, two tree species commonly found in Northeastern Ontario forests.

The results clearly indicated that PMS was the most promising amendment. It significantly improved soil organic matter content and moisture retention, leading to enhanced seedling performance overall. In contrast, LSMB and BBFA presented challenges related to elevated soil pH and, in some cases, limited moisture retention. The standard treatment (dolomitic limestone and synthetic fertilizer) was ineffective as no plants survived.

Specifically, the study demonstrated that PMS effectively addresses the key limitations of borrow pit soils, namely the lack of organic matter and poor water-holding capacity. This resulted in healthier seedlings with better survival rates, particularly under simulated drought conditions. While LSMB and BBFA offered some benefits in terms of nutrient addition, their potential to raise soil pH to undesirable levels necessitates careful management of application rates to avoid detrimental effects on plant growth and microbial activity.

These findings suggest that PMS should be prioritized in reclamation efforts targeting nutrient-poor, sandy soils in borrow pits. Furthermore, the study emphasizes the need for customized application protocols for LSMB and BBFA to prevent adverse effects on soil pH and microbial activity. Incorporating organic-rich amendments like PMS can markedly improve the survival and growth rates of tree seedlings, which is crucial for the successful revegetation of disturbed sites. The study underscores the importance of balancing nutrient enhancement with physical soil improvements to achieve effective revegetation and sustainable land reclamation in these challenging environments. Further research in field settings is warranted to validate these greenhouse findings and optimize application strategies for these industrial residuals.

7. Challenges and Recommendations for next steps

The greenhouse trial faced several challenges that may have impacted the experimental process and plant growth. Preparing the soil was particularly labor-intensive, as sieving and mixing amendments with gravel required significant time and effort to achieve uniformity. Moisture retention was another major issue, as gravel-based substrates struggling to hold water, necessitating frequent irrigation to prevent seedling desiccation. Additionally, space constraints in the greenhouse limited the number of replicates and species that could be tested simultaneously, reducing the scope of the study. Root growth was also restricted by the use of pots, which prevented natural root expansion and may have influenced plant responses to the soil amendments. These challenges highlight the complexities of testing soil treatments in a controlled environment before transitioning to larger-scale applications.

However, building on the positive outcomes observed with pulp mill sludge (PMS) and the challenges associated with borrow pit reclamation, the next logical step is to conduct a pilot-scale field trial exploring different soil amendment strategies for long-term stability. Since the

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silty clay soil amendment from the greenhouse trial proved unsuitable for plant growth, it will be excluded from further testing.

Additionally, the limestone + fertilizer (SUD) treatment shall not be included in the field trial, as pre-treatment soil analysis indicated a near-neutral pH. Given the high susceptibility of borrow pits to erosion due to their coarse-textured soils and uneven terrain, the study should incorporate different surface configurations. This could include comparisons between flat plots and plots featuring pit-and-mound microtopography to enhance water retention and minimize soil displacement.

Long-term monitoring of key soil parameters such as pH, organic matter content, nutrient availability, and moisture levels will be essential. Additionally, the survival, growth, and health of various tree and shrub seedlings should be closely tracked. Expanding the range of tested tree species would help determine the broader applicability of these amendments for revegetation. The findings from this study will identify the most effective amendment types, surface designs, and material combinations for ensuring the sustainable restoration of gravel pit ecosystems.

Phase 2 : Field Trial (2022-2025)

1. Introduction

The second phase of the project was to conduct field trials which represented a crucial phase in evaluating the effectiveness of soil amendments for improving plant establishment in Northern Ontario's aggregate reclamation sites. Building on insights gained from the greenhouse study, this large-scale trial tested selected amendments in real-world conditions, where environmental factors such as weather, soil variability, and erosion come into play. The primary objective was to assess how well the amendments performed outside the controlled greenhouse environment, ensuring they can support long-term vegetation growth and ecosystem recovery. A field trial was essential for several reasons:

o   Real-World Conditions: Unlike a greenhouse, a field trial exposes amendments to natural environmental challenges, including fluctuating moisture levels, temperature extremes, and precipitation patterns, providing a more accurate measure of their long-term viability.
o   Scalability and Practical Application: While greenhouse trials provide preliminary data, only a field trial could confirm how amendments behaved at the scale required for actual operational reclamation projects.
o   Soil Stability and Erosion Control: Borrow pits and aggregate sites are prone to erosion due to their coarse soils and disrupted landscapes. Testing amendments in the field allows for the evaluation of their ability to retain moisture, support soil structure, and prevent sediment loss.
o   Plant Performance in Uncontrolled Conditions: Tree and shrub seedlings are monitored to assess survival, growth, and overall health in conditions that could not be simulated in a greenhouse.

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o   Long-Term Monitoring: Unlike the short duration of a greenhouse trial, the field study enables multi-seasonal tracking of soil and plant responses, providing critical data on amendment effectiveness over time.

2.   Site Selection and Experimental Design

The field trial was conducted at an aggregate pit in Skead, Ontario, to evaluate the effectiveness of various soil amendments in improving plant establishment and growth under real-world conditions. Unlike the greenhouse trial, where environmental variables were controlled, the field experiment exposed amendments to natural weather fluctuations, soil erosion, and moisture variability, providing a more comprehensive assessment of their long-term viability.

Figure 9. Field trial location map.

The trial consisted of twenty-eight plots, each measuring approximately one hundred and forty square meters (seven by twenty meters). There were seven treatment groups, including a control (untreated soil), PPA, AF, Nrich, Nrich and compost, pulp, and compost. Each treatment was replicated four times, with two plots on flat terrain and two on a pit-and-mound microtopography. While treatments were randomly assigned to plots, the pit-and-mound design remained consistent across all designated plots to ensure comparability.

A diverse selection of plant species was tested to assess amendment effectiveness across different functional groups. Tree species included red pine, red oak, red maple and jack pine,

while smooth serviceberry served as a woody shrub component. These species were chosen for their ecological importance, resilience in disturbed environments, and potential to contribute to long-term site revegetation. Their varying growth requirements also allow for a comprehensive evaluation of amendment effectiveness across different functional plant groups. Additionally, seedlings were planted at appropriate depths to prevent desiccation and ensure stability, particularly in erosion-prone plots. The mix of tree, shrub, and herbaceous species is expected to contribute to soil stabilization, organic matter accumulation, and long-term ecosystem recovery in the disturbed site.

To assess the impact of the amendments, several key parameters were monitored. Vegetative growth was assessed by through stem height, basal diameter, canopy cover, and overall plant vigor.

- o *Survival rates were tracked to determine the percentage of successfully established plants per species and treatment.*
- o *Soil nutrient analysis included periodic sampling to measure nitrogen, phosphorus, potassium, organic matter content, and cation exchange capacity.*
- o *Soil moisture retention was evaluated to assess how amendments influenced water availability, particularly in erosion-prone areas.*
- o *Microbial activity was also monitored through soil microbial biomass and enzyme activity, providing insight into soil biological health.*
- o *Erosion and soil stability were observed to determine changes in soil structure, including sediment loss and compaction differences between treatments.*
- o *Leaf chlorophyll content was measured as an indicator of nutrient uptake and overall plant health.*
- o *Additionally, biodiversity and natural regeneration were tracked to assess spontaneous plant recruitment from surrounding areas, indicating whether amendments encouraged broader ecosystem recovery.*

By integrating these monitoring strategies, the field trial generated a robust dataset to evaluate which amendments, and site designs best support long-term ecological restoration in aggregate pit environments.

3. Materials and Methods

3.1 Field Conditions

The field trial was conducted under natural environmental conditions at the Skead, Ontario aggregate pit. Unlike the controlled greenhouse setting, no artificial watering or environmental modifications were implemented, ensuring that plant establishment and growth reflected real-world conditions. This approach was chosen to align with potential large-scale applications, where post-planting maintenance such as irrigation would not be feasible.

3.2 Site Preparation and Amendment Application

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Prior to planting, the site underwent preparatory work to optimize safety and experimental consistency. Site preparation included the removal of debris and litter, the sloping of terrain to a 3:1 slope to minimize erosion and fall hazards.

Once the site was cleared, plots were delineated, and the college's farm tractor was used to create the pit-and-mound microtopography in each of the designated plots. This work was completed in the fall of 2022. In June 2023, a plant inventory of the forest adjacent to the site prepared site was conducted to assess pre-existing vegetation and evaluate natural recruitment potential within study plots (Annex A).

Figure 10. Pioneer Construction staff sloping the pits before the research team began activities.

In the spring and summer of 2023, soil amendments were applied directly to the surface of the plots rather than being mixed into the substrate, due to logistical constraints such as time limitations and the absence of appropriate mixing equipment.

To improve efficiency and reduce the physical workload for the research team, the college's farm tractor was used to spread amendments on the flat plots. This mechanized application helped ensure a more uniform distribution while addressing the labor-intensive nature of manual amendment spreading.

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Figure 11. From left to right: Boréal's Technologist spreading wood ash; center: pit-and-mound microtopography; right: a technologist applying compost using the Collège's tractor.

The selected treatments were based on the results of the greenhouse trial, and followed the same application rates as those used in the greenhouse trial and included:

- Control (CON)

- Pulp - Pulp Mill Sludge (PMS) (PP)

- Pulp - Pulp Mill Sludge (PMS) + Biomass Boiler Fly Ash (BBFA) (PPA)

- Nrich – Lime-Stabilized (NRICH)

- Nrich + Municipal Compost (NMC)

- Municipal Compost (C)

- Wood Ash + Ammonium Nitrate (AF)

Table 3. Experimental treatments, their application rate and reasoning

Treatment code	Material	Application Rate	Reasoning
CON	Sand and gravel	N/A	Baseline / Control
PP	Pulp mill sludge (PMS)	290 Mg/ha (weathered)	To create a 1:1 gravel to residual layer at 7.5 cm depth.
PPA	PMS + BBFA	290 Mg/ha (weathered) 20 Mg/ha (dry)	To create a 1:1 gravel to residual layer at 7.5 cm depth.
AF	Biomass boiler fly ash (BBFA) + NO_3^- + Urea (1:1)	20 Mg/ha (dry) 74 Kg/ha	Best promoted growth in local yellow birch field trials). Fertilizer included to given absence of N in BBFA. Rate matches SUD N content.
NRICH	lime-stabilized municipal biosolids (LSMB)	15 Mg/ha (weathered)	Manufacturer's guidelines.

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| NMC | LSMB + Municipal Compost | 15 Mg/ha (weathered) 250 Mg/ha (weathered) | To create a 1:1 gravel to residual layer at 7.5 cm depth. |
| C | Municipal Compost | 250 Mg/ha (weathered) | To create a 1:1 gravel to residual layer at 7.5 cm depth. |

3.3 Experimental Design

The study employed a randomized block design with twenty-eight experimental plots, each measuring approximately 140 m² (7 × 20 m). Each treatment was replicated four times: two plots were established on flat terrain, while two incorporated a pit-and-mound microtopography.

Figure 12. Experimental plot disposition.

The placement of treatments within the plots was randomized; however, the pit-and-mound layout remained consistent across all designated plots to ensure comparability.

The microtopography plots were located on the edges of the sloped pit and generally have a slight slope. The flat plots were positioned at the bottom of the pit on the flat surface. A 1.5-meter buffer was maintained between plots to minimize edge effects while accommodating site space restrictions.
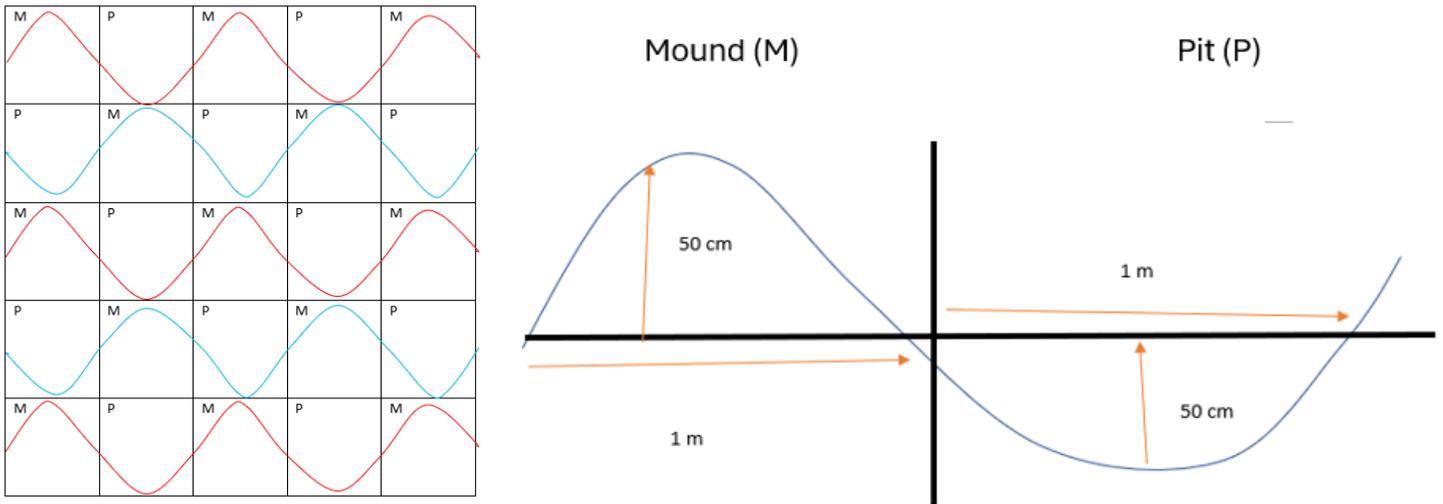
Figure 13. Pits and mounds microtopography design.

Figure 14. Study site prior to planting.

3.4 Cultivation and Planting

Red Maple and Red Oak seeds were collected by the research team, while Serviceberry seeds were sourced from a commercial supplier. All seeds underwent species-specific stratification protocols to break dormancy and promote germination. Seedlings were cultivated under controlled conditions in Collège Boréal's greenhouse throughout 2023 to ensure uniform growth and establishment.

In parallel, Jack Pine and Red Pine seedlings, representing the current year's crop, were overwintered in storage boxes kept in the college's freezer to preserve viability for spring planting. Prior to transplanting, all seedlings were gradually acclimatized outdoors over several days to reduce transplant shock.

Following the application of soil amendments, seedlings were planted in their designated plots using a randomized but systematic layout: a random configuration of seedlings was first generated to fill a single 140 m² plot, and this same layout was then replicated across all other plots to maintain consistency while minimizing spatial bias within plots. Transplanting into the field plots took place in the spring of 2024 and spanned approximately four weeks.

Figure 15. From left to right, serviceberry, red maple and red oak seedling at Collège Boréal's greenhouse.

Seedlings were planted by hand to ensure proper root placement and mineral soil contact, which is critical for early establishment. Planting holes were created using planting shovels, and care was taken to avoid excessive root disturbance.

Figure 16. Collège Boréal's Student Research Assistant transplanting red pine seedlings.

3.5 Data Collection and Measurements

To evaluate the effectiveness of soil amendments, multiple parameters were monitored throughout the trial period. Vegetative growth assessments included measurements of stem height, basal diameter, and overall plant health.

Survival rates were tracked for each species to determine establishment success under different treatments. The initial round of vegetative data collection was conducted in the summer of 2024 to establish baseline (T0) measurements of seedling survival, growth, and overall plot conditions prior to further monitoring.

Each data collection period typically requires approximately three to four weeks to complete, due to the number of plots and parameters assessed. Subsequent rounds of data collection were carried out in October 2024 to capture end-of-season conditions, and again in the summer of 2025 to evaluate overwinter survival and early second-year growth. Vegetative data will continue to be collected annually to monitor long-term trends in seedling performance and site recovery throughout new project ending in 2028.

Figure 17. Red maple seedlings in the fall of 2024

Soil samples were collected periodically for nutrient analysis, including nitrogen, phosphorus, potassium, organic matter content, and cation exchange capacity. Unlike the greenhouse trial, root extractions were not conducted, as plants were left to grow for long-term monitoring.

Figure 18. Olivia Baudet measuring vegetative growth and collecting soil samples.

4. Results

4.1 Soil Property Enhancements (Appendix C)

Table 4: Soil Property.

Treatment	Microtopography	pH	Moisture (%)	Total Carbon (%)	P	K	Ca (µg/g)	Mg	Na	Total Kjeldahl Nitrogen (mg/kg)	Chloride
Control	Pit & Mounds										
	Flat										
Ash + Urea	Pit & Mounds										
	Flat										
Pulp + Ash	Pit & Mounds										
	Flat										
Pulp	Pit & Mounds										
	Flat										
NRICH	Pit & Mounds										
	Flat										
Compost	Pit & Mounds										
	Flat										
NRICH + Compost	Pit & Mounds										
	Flat										

Element	Typical Range
pH	5.5-7
Moisture	10-40%
Total Carbon (%)	0.5-3%
Phosphorus (P)	10-30 ppm
Potassium (K)	100-250 ppm
Calcium (Ca)	600-2500 ppm
Magnesium (Mg)	100-300 ppm
Sodium (Na)	<200 ppm
Nitrogen	<2000 ppm
Chloride	8-15 ppm

(red)	Above Range
(green)	Within Range
(tan)	Under Range

The control treatment across both "Pit & Mounds" and "Flat" microtopographies displayed the most balanced profile, with all properties—pH, moisture, total carbon, nutrients, sodium, total Kjeldahl nitrogen, and chloride—falling within the typical natural range. This suggests your unamended soils are chemically steady and suitable for supporting natural vegetation without nutrient imbalances or contamination concerns.

With the Ash + Urea treatment, both microtopographies remained well within normal ranges for pH, moisture, carbon, sodium, nitrogen, and chloride, but showed levels above the typical range for core nutrients like phosphorus, potassium, calcium, and magnesium. This over-enrichment, indicated by red, reflects significant nutrient additions from amendments—potentially offering fertility benefits but also posing risks of nutrient leaching and imbalance if not managed carefully.

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The Pulp + Ash treatment led to a similar pattern, with natural soil chemical properties largely maintained—except for elevated concentrations of phosphorus, potassium, calcium, and magnesium, which exceeded typical background levels. This could aid rapid plant establishment and boost overall fertility, but the consistently surplus nutrient supply (multiple reds) warrants monitoring for possible ecological consequences, such as the vulnerability of less-competitive native species or the risk of nutrient run-off.

For the Pulp treatment alone, the trend continued. Both microtopographical conditions featured natural values for pH, moisture, sodium, nitrogen, and chloride, but excessive phosphorus, potassium, calcium, and magnesium were observed. The magnitude of this effect is somewhat less dramatic than with the pulp and ash mixture, yet still notable and universal above the typical range.

The NRICH amendment produced a similar nutrient profile: regular soil moisture and chemistry remained unaffected, but phosphorus, potassium, calcium, and magnesium concentrations rose well beyond natural norms. Again, this signals aggressive amendment-driven enrichment that may be advantageous for plant growth in the short term but could alter ecological balances if nutrient surpluses persist.

The application of Compost likewise elevated phosphorus, potassium, calcium, and magnesium in both microtopographical settings, with the remainder of soil properties staying normal. This suggests compost offers substantial fertility enhancement while generally preserving favorable physical and chemical soil conditions.

In the NRICH + Compost treatments, the outcomes mirrored those of the single NRICH and compost amendments: strong increases in key nutrients (above range), with all other factors stable and within normal boundaries. This could generate especially fertile conditions for revegetation but also raises concerns of over-supplying nutrients compared to the local ecological baseline.

Across all treatments and microtopographies, pH, soil moisture, total Kjeldahl nitrogen, sodium, and chloride remained within or close to the optimal range regardless of amendment type, indicating that none of the applied materials triggered pH or salinity problems, nor excessive nitrogen supply.

In summary, the data demonstrate that while the control soils maintain original, balanced chemistry, all amendment treatments—especially those containing ash, pulp, NRICH, or compost—reliably raise the concentrations of plant-essential nutrients well above local natural background. This increases fertility and would likely stimulate plant growth and restoration success, but the degree of surplus means there may be long-term risks to natural ecosystem function, native species competition, or water quality. The consistency of responses between "Pit & Mounds" and "Flat" surfaces indicates that nutrient effects are driven more by the amendment than microtopography.

The detailed laboratory analysis with all actual numerical values will be provided in Annex C at the end of this report.

4.2 Seedling Performance

Due to a limited availability of red maple seeds, not all plots received red maple plantings, which may have influenced species-specific comparisons across treatments.

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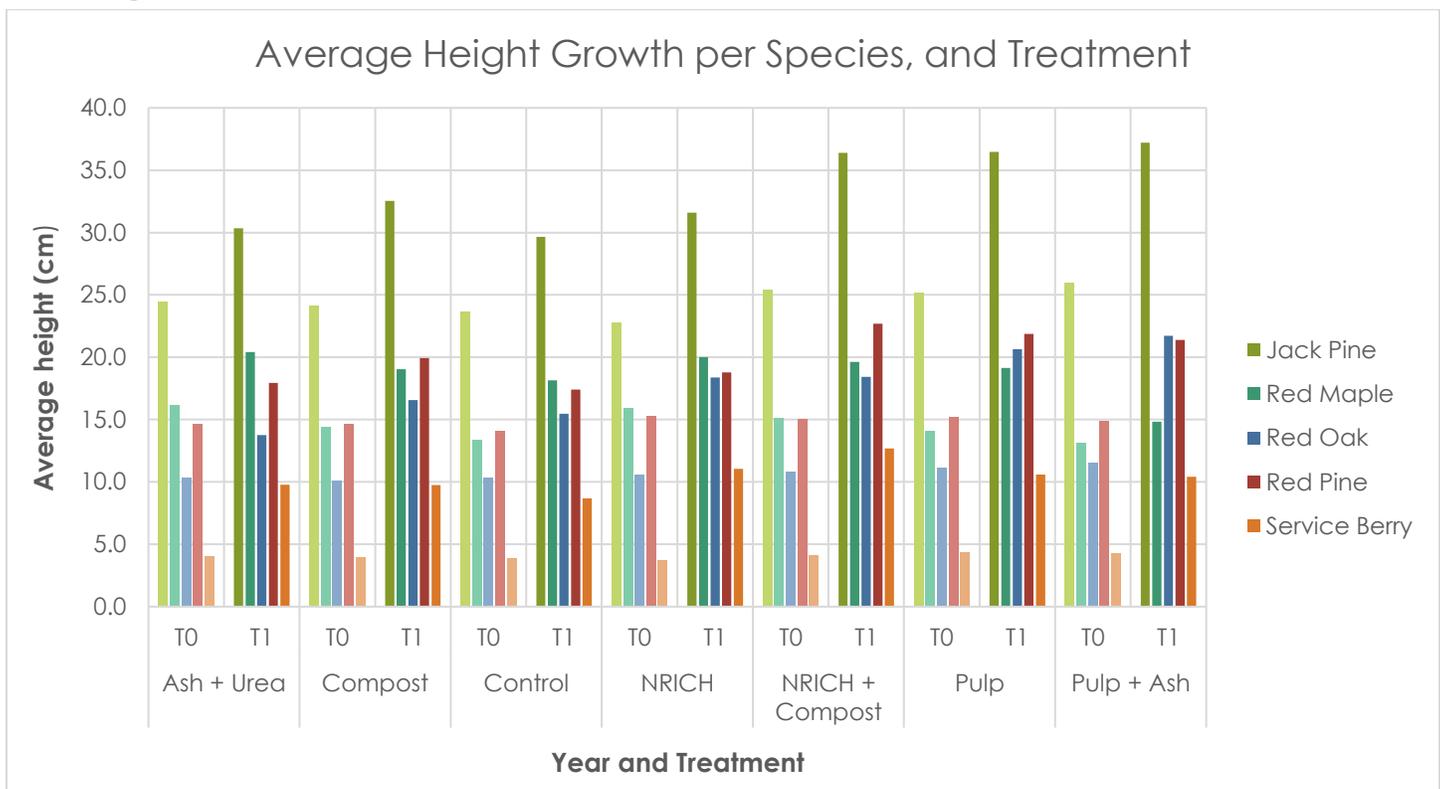
Figure 19. Average seedling height growth per species and treatment.

The bar graph presents the average height growth (in cm) of five plant species—Jack Pine, Red Maple, Red Oak, Red Pine, and Service Berry—under seven different soil amendment treatments: Ash + Urea, Compost, Control, NRICH, NRICH + Compost, Pulp, and Pulp + Ash. For each treatment, plant height is presented at T0 (2024), representing the initial height after planting, and T1 (2025), reflecting growth after one year.

Jack Pine consistently exhibits significant height growth across all treatments from T0 to T1. Its height at T0 is already substantial, generally above 20 cm in most treatments. By T1, Jack Pine showed remarkable gains, particularly in the **Pulp** and **Pulp + Ash** treatments, where its average height exceeded 35 cm. Even in the Control and less impactful treatments like Ash + Urea and Compost, Jack Pine demonstrates healthy growth, consistently reaching or surpassing 25 cm by T1. The most pronounced growth for Jack Pine is seen in the Pulp and Pulp + Ash treatments.

Red Maple showed consistent positive growth from T0 to T1 across all treatments, with initial heights at T0 generally ranging from 10 to 15 cm. By T1, Red Maple's average height typically falls between 15 cm and 20 cm. The greatest height for Red Maple at T1 is observed in the **Pulp**, **NRICH + Compost**, and **NRICH** treatments, where it reached around 20 cm. Even in the Control and Compost treatments, Red Maple showed steady, albeit more modest, growth.

Red Oak also experienced growth from T0 to T1 in all treatments. Its initial height at T0 is generally between 10 cm and 15 cm. By T1, Red Oak's height typically ranged from 15 cm to just over 20 cm. The most favorable growth for Red Oak is noted in the **Pulp** and **NRICH + Compost** treatments, both of which resulted in heights nearing 20 cm at T1. In treatments like Ash + Urea and Compost, Red Oak's growth was less pronounced but still consistent.

Red Pine exhibited moderate but consistent height growth from T0 to T1 across all treatments. Its T0 heights generally ranged from 12 cm to 15 cm. By T1, Red Pine typically reached between 14 cm and

18 cm. The treatments yielding the slightly higher growth for Red Pine are **NRICH + Compost** and **Pulp**, though the differences across treatments were not as dramatic as for Jack Pine. In all cases, Red Pine showed a clear increase in height over the year.

Service Berry demonstrated consistent growth between T0 and T1 in every treatment, even though its overall height remains modest compared to the other species. The greatest increase for Service Berry was observed in the **Pulp** and **Pulp + Ash** treatments, where average height approaches 10 cm by T1. Treatments such as NRICH and NRICH + Compost also yielded noticeable gains, with T1 averages around 8–9 cm. In contrast, the Control, Ash + Urea, and Compost treatments resulted in more limited growth, with T1 heights generally remaining at or just above 5 cm. Despite finishing as the shortest species after one year, Service Berry nonetheless showed measurable improvement in every amendment scenario, especially where amendments like Pulp are utilized.

When considering the overall growth across all species from T0 to T1, the Pulp and Pulp + Ash treatments appeared to provide the most significant positive impact. These treatments consistently lead to the largest height gains for Jack Pine and Service Berry and also supported robust growth in Red Maple and Red Oak. The NRICH and NRICH + Compost treatments also generally promoted strong growth, particularly for Red Maple and Red Oak. In contrast, the Control, Ash + Urea, and Compost treatments generally showed lower overall height increases across the species, indicating less enhancement of growth. The data clearly show that the most effective treatments lead to substantial increases in height across the board, even for species that start very small.

4.2.2 Diameter
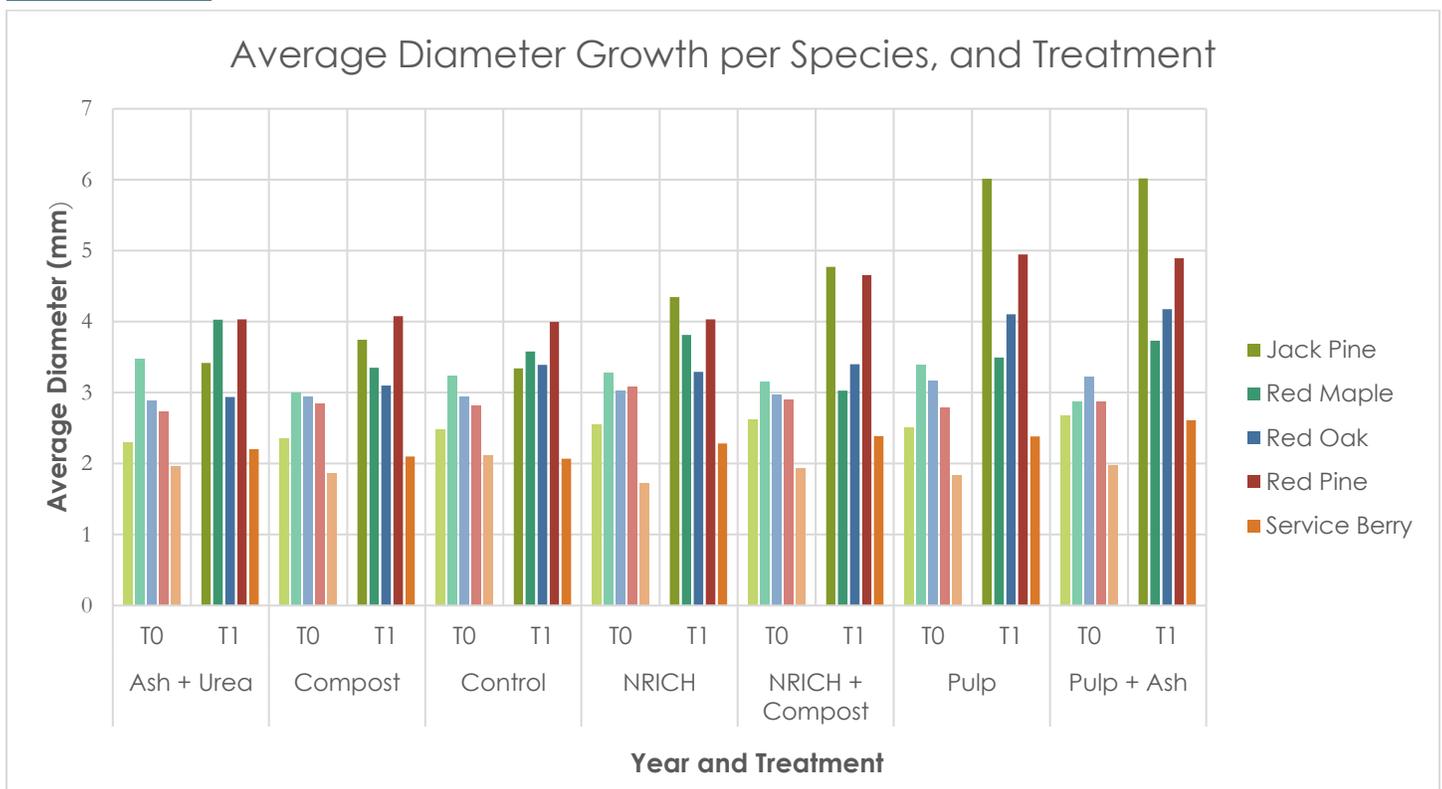
Figure 20. Average seedling diameter per species, treatment and microtopography.

The bar graph presents the average diameter growth (in mm) of five plant species—Jack Pine, Red Maple, Red Oak, Red Pine, and Service Berry—across the seven soil treatments. For each treatment, average diameter is presented at T0 (2024), representing the initial stem diameter after planting, and at T1 (2025), reflecting growth after one year.

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Jack Pine consistently demonstrated substantial diameter growth across all treatments from T0 to T1. At T0, its average diameter often exceeds 3 mm and, notably, Jack Pine experienced its most marked increases in the **Pulp** and **Pulp + Ash** treatments by T1, where its diameter reached approximately 6 mm—the highest observed across all species and treatments. Even in less impactful treatments such as Ash + Urea, Compost, and Control, Jack Pine's diameter growth remained healthy, consistently surpassing 4 mm by T1.

Red Maple showed steady, positive diameter growth across all treatments from T0 to T1. Its average diameters at T0 were generally around 3 mm, with the most pronounced growth occurring in the **Pulp + Ash** and **Pulp** amendments, reaching nearly 4 mm by T1. For Red Maple, the NRICH-based treatments also promoted solid diameter gains, while Ash + Urea, Control and Compost yielded smaller, but consistent, increases.

Red Oak followed a similar trend of moderate growth from T0 to T1 in all treatments. Initial diameters hover just below 3 mm, with the greatest increases seen in **Pulp + Ash** and **Pulp**, where T1 diameters climb to around 4 mm. Treatments such as NRICH and NRICH + Compost also produced steady year-over-year gains. In contrast, Control, Ash + Urea, and Compost had the least impact on Red Oak's diameter expansion, with T1 values remaining below 4 mm.

Red Pine exhibits robust and consistent diameter growth from T0 to T1 in every amendment scenario. Of particular note, Red Pine achieved the largest T1 diameters in **Pulp** and **Pulp + Ash**, approaching 5 mm. In other treatments—including NRICH, NRICH + Compost, and even Control—Red Pine's diameter at T1 consistently ranged from 4 mm to just over 4.5 mm, reflecting sound performance across the board, with particularly strong gains from the more enhanced soil amendments.

Service Berry began with the smallest diameters at T0, generally just above 2 mm. It nonetheless demonstrated measurable increases in all treatments from T0 to T1. The best diameter gains for Service Berry are observed in the **Pulp** and **Pulp + Ash** treatments, where T1 diameters approach 2.5 mm. In NRICH and NRICH + Compost, Service Berry's diameter also increases marginally. However, in the Control, Compost, and Ash + Urea treatments, Service Berry's diameter remained relatively low—typically just above 2 mm at T1—making it the most limited responder among the five species.

When considering overall diameter growth from T0 to T1, the **Pulp** and **Pulp + Ash** amendments clearly provided the most significant increases across nearly all species, regularly resulting in the largest average stem diameters after one year. The NRICH and NRICH + Compost treatments also produced above-average gains, especially in Red Pine, Red Oak, and Red Maple. By contrast, the Control, Compost, and Ash + Urea treatments yielded the smallest increases in diameter for most species.

The data indicates that the treatments which strongly enhanced stem diameter are the same as those that benefited height growth, further supporting the value of targeted organic amendments—especially Pulp-based strategies—in maximizing early plant establishment and vigor. Even species that start small, such as Service Berry, show measurable improvement with more intensive amendments, highlighting the role of soil enhancement in promoting overall plant development.

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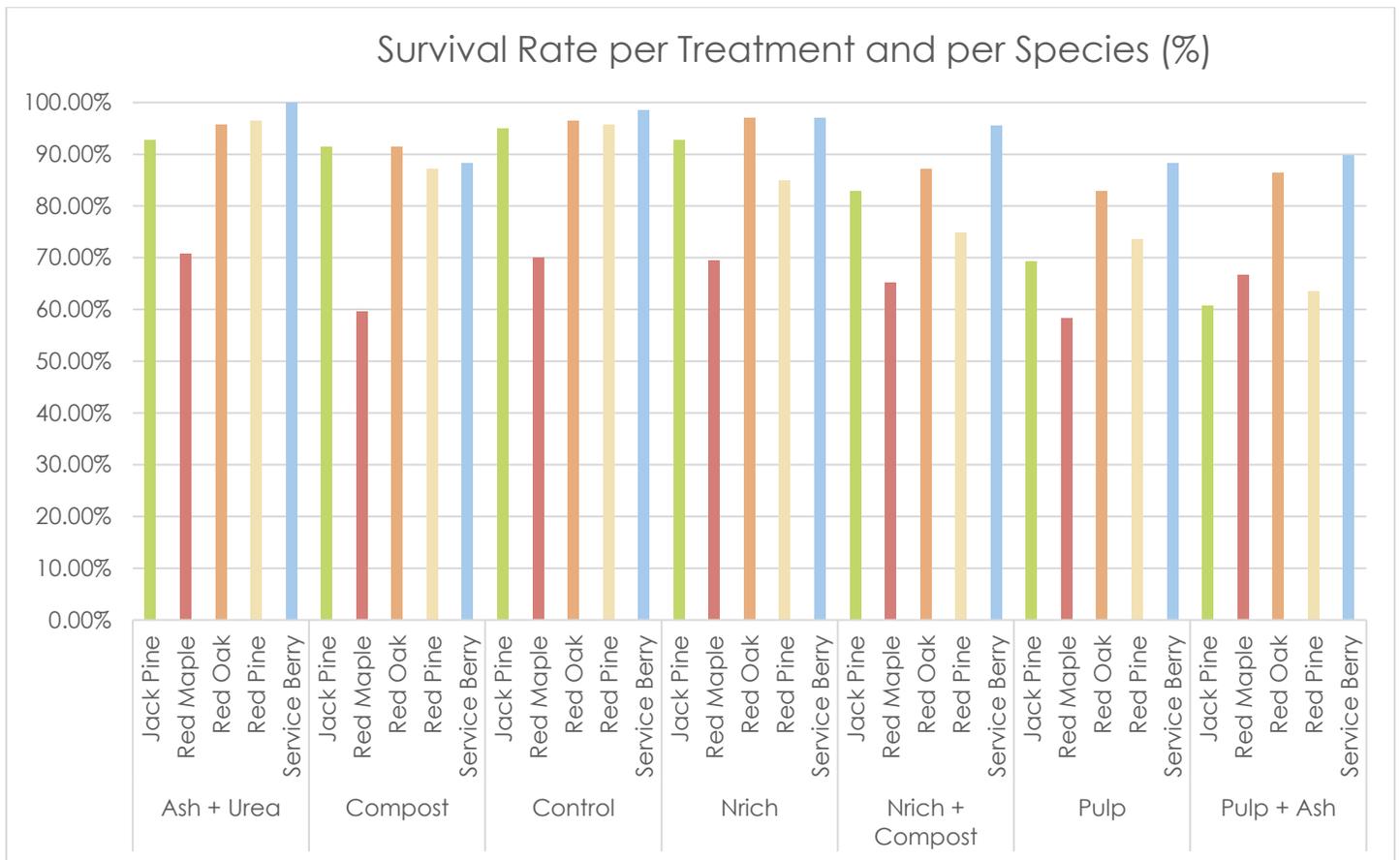
Figure 21: Average seedling survival per species and treatment.
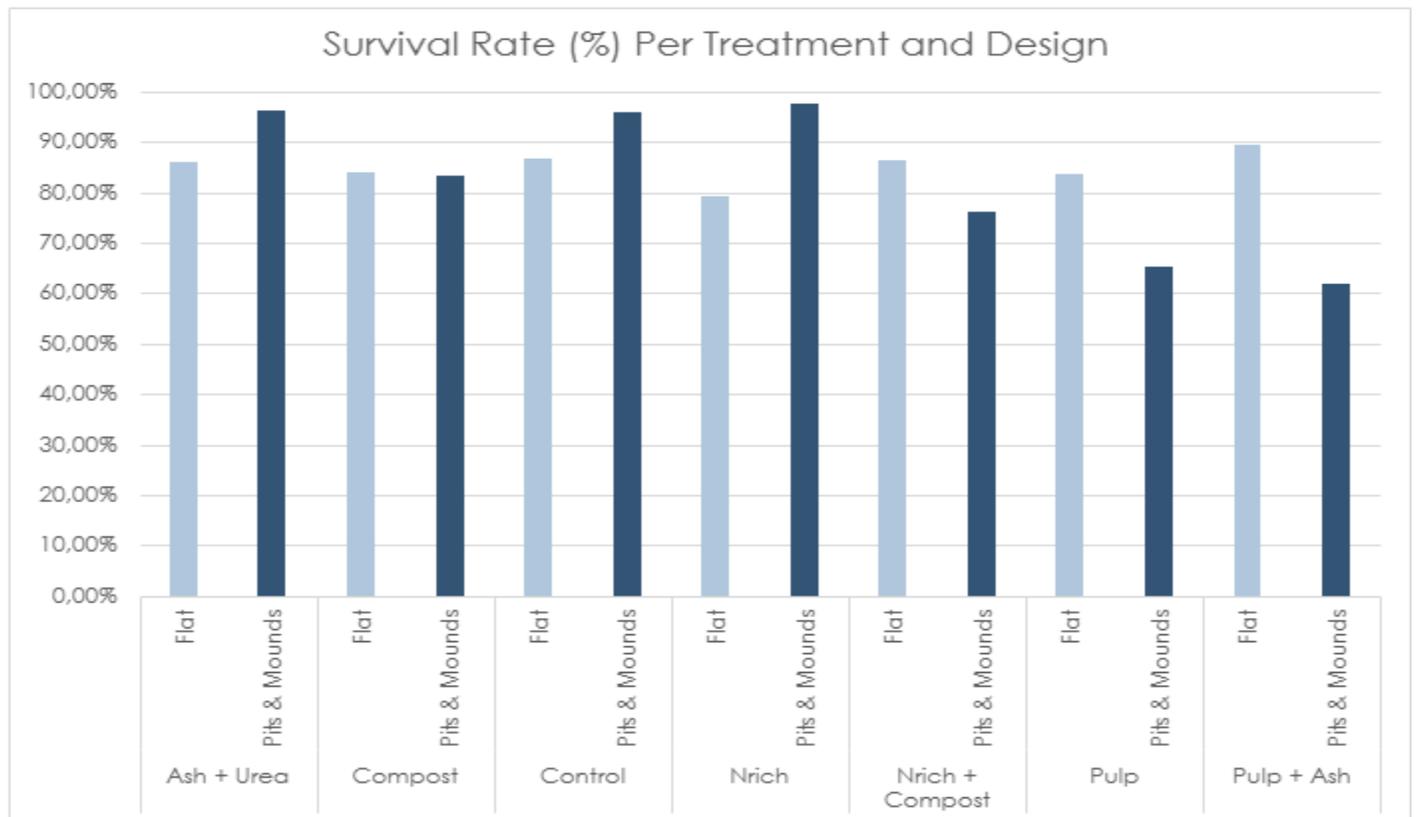
Figure 22: Average seedling survival per treatment and microtopography.

Analysis of seedling mortality across treatments and microtopography revealed clear trends in both overall survival rates and species-specific responses. In most treatments, mortality was generally low, reflecting effective amendment strategies for aggregate pit rehabilitation. Specifically, the Ash + Urea treatment exhibited consistently low mortality across all species in both flat and pits & mounds designs. The number of dead seedlings per species remained below five in almost every instance within this treatment, indicating high overall survival rates likely exceeding 90% for each species. This outcome suggests that Ash + Urea creates a favorable soil environment for a broad range of species, regardless of microtopography.

Compost-treated plots also showed strong performance, particularly in the flat design, where mortality rates were low and similar to those observed for Ash + Urea. In the pits & mounds configuration, however, Red Pine in particular exhibited higher mortality, with the number of dead seedlings reaching around thirteen, while other species were less affected. This indicates that although Compost improves soil conditions overall, certain species—such as Red Pine—may still face site-specific challenges in microtopographically complex settings.

Interestingly, control plots with no amendments showed low mortality across all species and designs, somewhat unexpectedly given the poor nutrient profile of these soils. This result could possibly be attributed to either initial seedling vigor or a limited duration of observation. NRICH treatments (T1) reflected a similarly positive trend, with all species showing high survival and only minimal losses, demonstrating this amendment's utility for supporting plant establishment.

In contrast, significant patterns of higher mortality emerged for certain amendment and microtopography combinations. The NRICH + Compost blend, despite being one of the most effective at improving soil chemistry, resulted in elevated mortality rates for Red Pine and, to a lesser extent, for Jack Pine in the pits & mounds design.

Red Pine mortality was particularly pronounced, exceeding thirty dead individuals out of fifty-six, suggesting that this species may be sensitive to specific conditions created by this amendment blend or by increased soil moisture and variation in these microsites.

Jack Pine also suffered notably in pits & mounds when combined with Pulp or Pulp + Ash treatments, with mortality approaching forty out of fifty-six planted seedlings. These high rates of mortality correspond to survival rates below thirty percent for these pine species, highlighting a strong negative interaction between amendment and microtopography for species with lower tolerance for such soil conditions.

On the other hand, broadleaf species such as Red Maple, Red Oak, and Serviceberry consistently displayed low mortality across all treatments and designs. Their capacity to thrive regardless of amendment or microtopographic variation makes them promising candidates for aggregate pit revegetation, especially in challenging or nutrient-variable environments.

Overall, these results demonstrate that amendment choice and site design (microtopography) both have profound influences not only on soil chemistry but also on the survival of plantings, especially for more sensitive species such as pines.

Amendments like Ash + Urea, Compost, and NRICH are generally effective, supporting high survival rates for most species, particularly in flat microtopographic designs. Conversely, Pulp and Pulp + Ash treatments, especially when combined with pits & mounds, should be avoided for pine-dominated plantings due to their sharply higher mortality rates.

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For diverse or broadleaf-dominated plantings, most amendment and microtopography combinations will support good early survival, but careful matching of amendment, species, and site design will be critical to maximize the establishment success of more sensitive species in aggregate pit rehabilitation projects.

4.2.4 Natural Regeneration

Coverage of Natural Vegetation per Treatment & Design
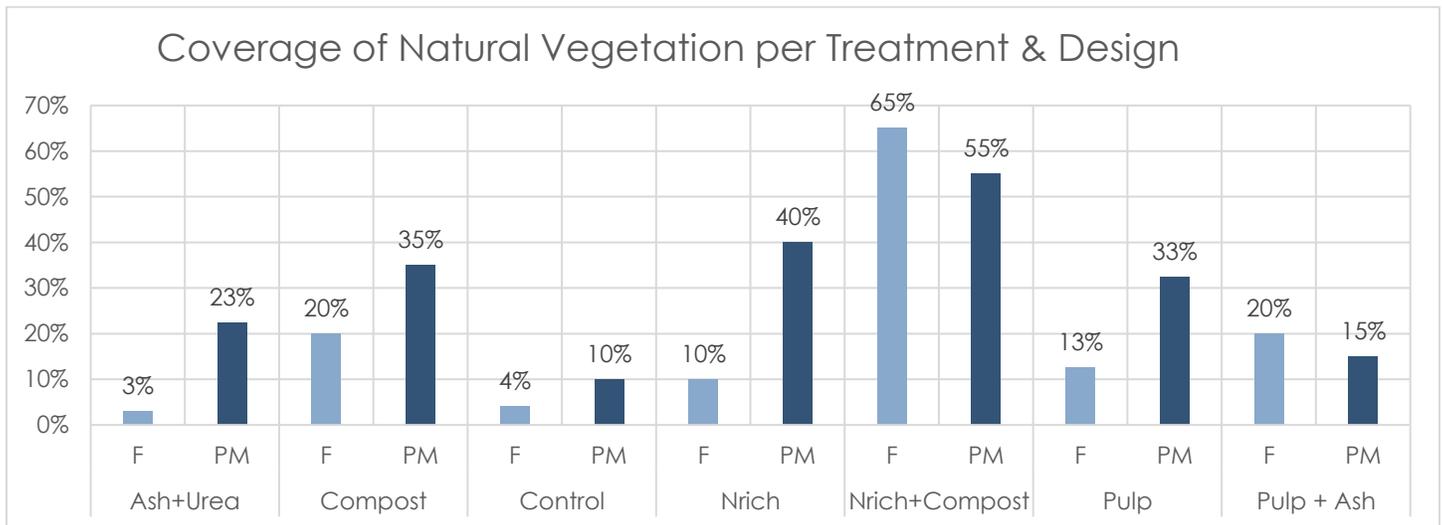
Figure 23: Average plot coverage from natural vegetation

The bar graph presents the coverage of natural vegetation (as a percentage) measured across the seven soil treatments and the two different microtopography designs.

Natural vegetation coverage varies substantially according to both the amendment treatment and the plot design. Across nearly all treatments, the Pits & Mounds (PM) design consistently results in higher vegetation coverage than Flat plots. For example, with Ash + Urea, coverage rises from 3% in Flat to 23% in Pits & Mounds. A similar trend is observed with Compost (20% F, 35% PM), Control (4% F, 10% PM), and NRICH (10% F, 40% PM), indicating that microtopography—particularly the Pits & Mounds approach—promotes a more favorable environment for natural vegetation establishment and spread.

Among all treatments, NRICH + Compost produced the highest overall cover, reaching 65% in Flat plots and 55% in Pits & Mounds. In this case, the Flat design slightly outperformed Pits & Mounds, a reversal of the general trend, and highlights that this combined soil enrichment is particularly effective in facilitating rapid ground cover regardless of microtopography. The Pulp treatment also resulted in notably enhanced vegetation cover, especially in Pits & Mounds plots (33%) compared to Flat (13%). However, for Pulp + Ash, vegetation cover remained moderate across both designs (20% F, 15% PM).

The Control and Ash + Urea treatments resulted in the lowest vegetation coverage, especially in Flat plots, where coverage stayed below 5%. These results indicate that neither the absence of amendment nor the application of Ash + Urea alone is effective in promoting the natural development of the ground-layer vegetation.

Overall, the data indicated that soil amendments, particularly NRICH + Compost and Pulp, support greater natural vegetation cover, and that, for most treatments, the Pits & Mounds microtopography further enhances ground cover compared to Flat plots. This suggests that combining advanced soil amendments with microtopographic variation offers the most favorable conditions for rapid natural vegetation establishment in restoration or reforestation settings.

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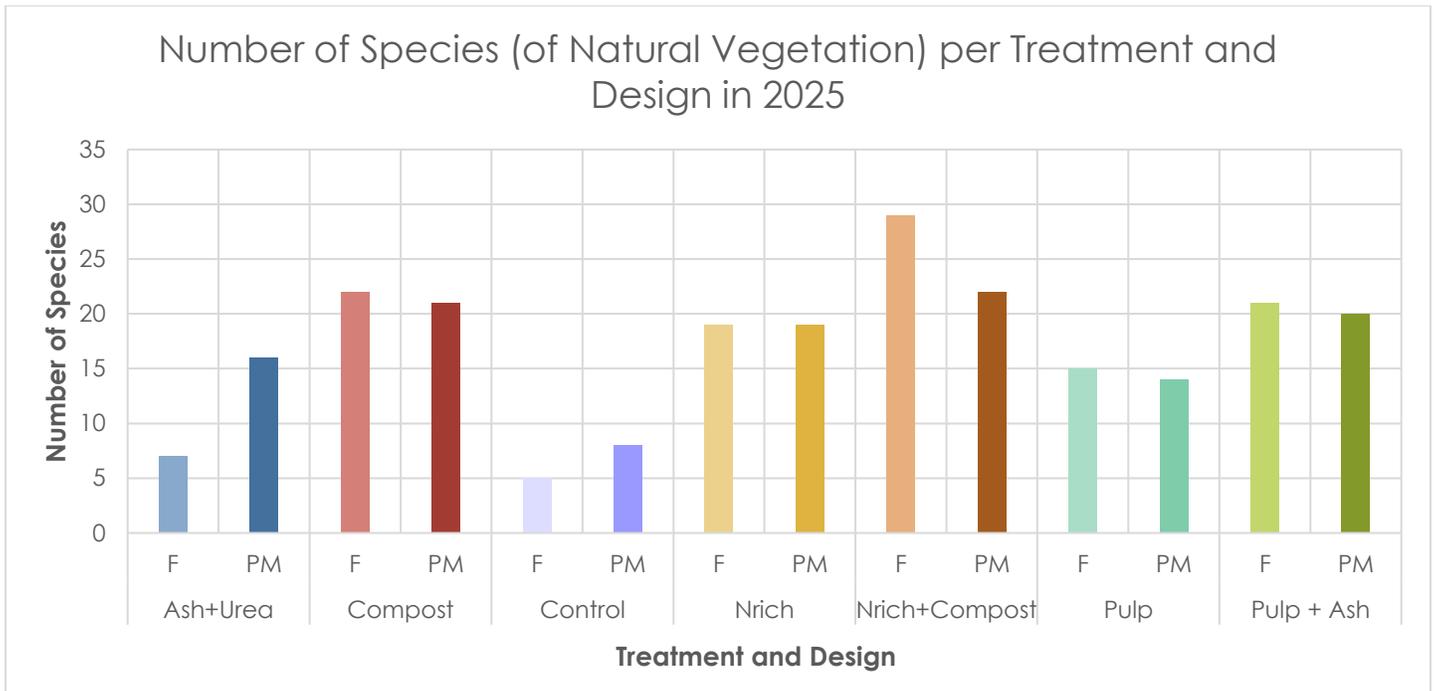
Figure 24: Number of species (Natural Vegetation) per treatment and microtopography in 2025.

The bar graph illustrates the number of natural vegetation species recorded in 2025, across seven soil amendment treatments and two microtopography designs—Flat (F) and Pits & Mounds (PM).

Species richness varies noticeably based on both the amendment treatment and the landscape design. Natural vegetation included mosses, ferns, wildflowers, shrubs and tree seedlings (Annex B) In general, plots treated with compost-based amendments consistently support the highest number of species, while untreated (Control) or minimally amended (Ash+Urea) plots have the lowest species counts.

A clear pattern emerges: most treatments result in higher species richness under the Pits & Mounds (PM) design compared to Flat (F) plots. For example, Ash+Urea treatment supports just 6 species in Flat plots but rises to 16 species in Pits & Mounds plots, suggesting that microtopographic variation enhances conditions for a greater diversity of native vegetation.

Compost-treated plots display robust species richness, exceeding 20 species in both designs (22 in F, 21 in PM). Similarly, the combined Nrich+Compost treatment yields the single highest count in the dataset: 29 species in Flat plots. For this treatment, however, the Flat design slightly outperforms Pits & Mounds (22 species), breaking the overall trend and emphasizing that strong soil enrichment can sometimes mitigate the advantages of microtopography.

The Nrich amendment alone results in moderate diversity (19 species in both designs), while the Pulp and Pulp+Ash treatments also support respectable numbers (15–21 species). The Control and Ash+Urea treatments, by contrast, remain at the bottom in terms of species counts—fewer than 10 species in Flat plots, with modest gains in the PM design.

Overall, these results underscore two key insights:

- o Soil amendments, especially those involving compost or combinations with nutrient-rich substrates, substantially increase the diversity of natural vegetation re-establishing in restoration settings.

- o Microtopographic variation through the Pits & Mounds design generally enhances species richness, likely by creating a broader range of microsites and niches for colonization.

Together, these findings suggest that pairing advanced soil amendments with carefully designed microtopographic features produces the most favorable conditions for maximizing natural vegetation diversity in ecosystem restoration or reforestation efforts.

4.3 Environmental Considerations

Environmental conditions during the field trial introduced several challenges that could have influenced plant establishment and soil amendment performance. Extreme heat events posed a significant risk, particularly in the early stages of planting when seedlings were still adapting to their environment. Prolonged high temperatures increased evapotranspiration, which, combined with the coarse-textured soil's limited water-holding capacity, heightened drought stress and may have impacted seedling survival and growth rates.

Periods of drought further compounded these challenges, as the trial site was left to natural conditions with no supplemental watering. Extended dry spells could have reduced nutrient availability, slowed microbial activity, and limited the effectiveness of organic amendments that rely on moisture for decomposition and nutrient release. Conversely, intense rainfall events presented additional risks. Heavy rains over short periods may have led to surface runoff, potentially washing away amendments from the flat plots and altering the distribution of nutrients within the soil. In areas with pit-and-mound microtopography, excessive rainfall may have caused temporary water pooling in lower areas, creating anaerobic conditions unfavorable to certain plant species.

Another factor influencing the trial was seasonal variability, including fluctuations in temperature and precipitation patterns. Rapid temperature shifts between day and night may have stressed young seedlings, particularly those in exposed areas with little shading or organic matter to buffer soil temperature extremes. Additionally, wind exposure in the open aggregate pit could have led to desiccation, particularly for species with smaller root systems that had not yet established deep anchorage in the soil.

These environmental variables highlight the importance of long-term monitoring to distinguish between the effects of soil amendments and the influence of natural climatic fluctuations on plant performance. Understanding how amendments respond to real-world weather conditions will be critical in determining their viability for large-scale reclamation projects.

5. Discussion

5.1 Soil Property Enhancements

The data indicates strong differences in soil chemical properties across both amendment treatments and microtopographic forms, with clear implications for soil rehabilitation and plant establishment. The control treatments in all microtopography had consistently low nutrient concentrations, particularly for essential elements such as calcium and magnesium, and the highest concentrations of potentially toxic aluminum (up to 612.5 mg/kg in pit). This confirms that unamended aggregate pit soils are poorly suited for immediate revegetation and restoration and are likely to require significant intervention. Amendments produced notable improvements, particularly when paired with pit or mound microtopographys. NRICH + Compost stood out, providing the best reduction of aluminum (down to 4.6 mg/kg in pit and 6.7 mg/kg in mound) and exceptionally high calcium (8433.1 mg/kg in mound, 7693.9 mg/kg in pit, 5928.8 mg/kg in flat). Boron was also highest with this blend (up to 3.99 mg/kg in pit), further supporting plant health. However, this treatment was characterized by very low phosphorus

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(as low as 1.93 mg/kg), suggesting a risk of phosphorus deficiency for plants and the need for targeted supplementation if this amendment is used alone. Compost alone also had a strong positive effect, especially in pit and mound positions. Phosphorus levels were elevated (104.31 mg/kg in pit, 76.47 mg/kg in flat), and potassium and calcium were also higher. Aluminum was reduced compared to control, though still at a moderate level (640.3 mg/kg in pit, 796 mg/kg in flat), which could require monitoring but is a considerable improvement. The broad increase across most macro- and micronutrients suggests compost is an effective general amendment in these soils. Ash-based treatments offered rapid improvement in specific nutrients. Ash + Urea, for example, greatly increased calcium in pit microtopography (4002.8 mg/kg), magnesium (295.6 mg/kg), and provided a moderate reduction in aluminum (down to 388.2 mg/kg in pit). However, sodium increased with these treatments (up to 12.8 mg/kg), particularly in pits, which may challenge some plant species sensitive to salinity. Pulp + Ash increased phosphorus and calcium—most pronounced in pits (P: 126.23 mg/kg, Ca: 4141.8 mg/kg)—with moderate levels of aluminum and similar sodium concerns (Na: 51.2 mg/kg in pit, 38.9 mg/kg in mound). NRICH, when used alone, had very mixed results depending on microtopography. In pits, it drove aluminum to extremely low levels (3.1 mg/kg) and provided excellent calcium (9715.9 mg/kg), but in the mound, aluminum spiked (1397.4 mg/kg), highlighting that the effectiveness of amendments is strongly modulated by soil placement and landscape form. Pulp as a single amendment primarily increased phosphorus (up to 145.45 mg/kg in pits), with modest improvements in calcium and magnesium. However, aluminum and sodium remained relatively elevated, suggesting this treatment is best used as part of a blend, rather than a sole amendment. Comparison across all treatments shows that microtopography had a consistent effect: pit and mound locations generally resulted in higher nutrient concentrations and better aluminum suppression than flat surfaces, likely due to improved moisture retention and greater organic matter accumulation.

Collectively, these findings underscore that a combined approach—using the right amendment tailored to each microtopographic context—is crucial. NRICH + Compost delivered the best results for aluminum reduction and calcium enrichment but requires phosphorus supplementation. Compost and Ash + Urea treatments significantly improve fertility, especially when pits or mounds are used, but sodium and residual aluminum should be monitored. The data demonstrate that the choice of amendment, in synergy with microtopographic manipulation, can transform highly degraded soils into substrates suitable for robust plant growth. Ongoing soil and plant monitoring will be critical to assess long-term amendment stability and ecosystem recovery.

5.2 Seedling Performance

The data also demonstrate that soil amendment choice significantly influenced tree seedling performance across all measured variables—height growth, stem diameter, and survival—during the initial establishment phase. Treatments delivering the greatest nutrient enrichment and organic content, specifically Pulp, Pulp + Ash, and NRICH + Compost, produced the highest average gains in both seedling height and diameter after one growing season. In these treatments, seedlings collectively showed more vigorous and uniform growth, with height increments often doubling those observed in minimally or untreated soils, and stem diameter increases noticeably outpacing other amendments. These enhancements are consistent with the understanding that nutrient-poor, recently disturbed substrates benefit rapidly and dramatically from organic matter inputs and comprehensive fertility improvement.

Survival rates echoed these trends, with Pulp, Pulp + Ash, and NRICH + Compost supporting robust establishment and minimal mortality for the planted cohort overall. NRICH and Compost alone also promoted strong growth and survival, though results were somewhat less pronounced than the more intensively enriched blends. By contrast, the Control (no amendment) and basic mineral amendments

such as Ash + Urea produced the lowest growth rates and were associated with the smallest stem diameters and, in some cases, marginally higher mortality. These results affirm that soil fertility, as enhanced by substantial organic matter and nutrient amendments, is a primary driver of early tree growth and establishment in aggregate pit rehabilitation.

Natural vegetation cover and species richness responded most strongly to the combination of treatment and microtopographic design. Across all treatments, the Pits & Mounds (PM) microtopography consistently facilitated higher ground cover and greater species diversity than flat designs. This effect was especially pronounced in plots amended with NRICH + Compost and Pulp, where natural regeneration not only established more quickly but also encompassed a broader range of native species. The improved microclimate and resource heterogeneity of the Pits & Mounds design likely expanded the diversity of germination and survival microsites for natural colonizers, a pattern well supported in restoration literature.

Among soil amendments, NRICH + Compost produced the most substantial gains in natural vegetation, achieving the highest average coverage and species counts in both Flat and PM settings. However, in the PM design, even mid-tier amendments like Compost and Pulp yielded remarkable improvements over the Control and Ash + Urea, pointing to the additive effect of physical and chemical enhancement in restoration. Plots with neither amendment nor microtopographic variability consistently experienced the slowest or most limited natural recolonization, with sparse plant cover and low diversity even after the first growing season.

In summary, the most effective strategy for facilitating both robust seedling growth and rapid, diverse natural regeneration was the integration of high-quality organic amendments—particularly NRICH + Compost or Pulp-based treatments—with a Pits & Mounds landscape design. This dual approach optimized both the abiotic (soil fertility, moisture retention, structure) and biotic (ecological diversity, competition) conditions necessary for successful ecosystem assembly on disturbed aggregate substrates. Long-term monitoring will be necessary to determine whether these early trends persist and to evaluate how different species adapt as the site continues to develop.

6. Conclusion

This study provides robust evidence that both soil amendment strategies and microtopographic design significantly influence the early stages of ecological restoration in aggregate pit environments. The application of organic and nutrient-enriched amendments—particularly pulp-based treatments, ash amendments, and the **NRICH + Compost** combination—resulted in marked improvements in key soil physicochemical properties. These included elevated concentrations of essential macronutrients such as calcium and magnesium, increased availability of beneficial micronutrients like boron, and substantial reductions in exchangeable aluminum, a known phytotoxic element. While these treatments generally enhanced overall soil quality, some, such as NRICH + Compost, exhibited specific nutrient imbalances (e.g., low phosphorus availability), highlighting the need for amendment formulations tailored to the target vegetation's nutritional requirements.

These improvements in soil fertility and structure had direct and measurable effects on tree seedling performance. Across all treatments, seedlings in amended plots showed significantly greater height and diameter growth compared to those in control treatments, with the most pronounced growth occurring under Pulp, Pulp + Ash, and **NRICH + Compost** amendments.

Survival rates also reflected the efficacy of these treatments, remaining high across most species, though sensitivity to certain amendment–microtopography interactions—particularly among conifer species in Pits & Mounds configurations—emphasized the need for species-specific considerations in

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restoration planning. Nonetheless, the overall pattern confirms that comprehensive soil enhancement strategies are essential for overcoming the chemical and structural limitations of disturbed substrates typical of aggregate extraction sites. In addition to improving the growth and survival of planted seedlings, soil amendments and microtopography exerted significant effects on natural vegetation recruitment. The **Pits & Mounds** design consistently facilitated greater coverage and higher species richness of naturally colonizing vegetation compared to flat treatments.

When combined with organic amendments—especially **NRICH + Compost** and pulp-based treatments—this topographic heterogeneity further enhanced early successional community development, likely due to improved microsite conditions such as moisture retention, temperature buffering, and reduced competition. Notably, the **NRICH + Compost** treatment achieved the highest levels of vegetation cover and species richness even in flat plots, suggesting that high-quality amendments can, in some cases, compensate for the absence of physical microtopographic variation. Collectively, these findings support the adoption of an integrated restoration strategy that combines high-input organic amendments with topographic heterogeneity to optimize soil function, accelerate plant establishment, and promote greater biodiversity. The dual benefits of improved soil chemistry and enhanced microsite variability suggest a synergistic pathway for ecological recovery in severely degraded systems such as aggregate pits. Restoration practitioners should prioritize treatments that simultaneously remediate soil properties and diversify site conditions to establish structurally complex, resilient, and biodiverse ecosystems.

This approach will not only improve short-term restoration outcomes but also enhance the long-term sustainability and ecological functionality of rehabilitated sites. Based on the combined results of soil improvement, seedling performance, and natural regeneration, the NRICH + Compost treatment applied within a Pits & Mounds microtopography consistently produced the most favorable outcomes and is therefore recommended as the optimal strategy for effective aggregate pit rehabilitation. However, these conclusions are based on T0 and T1 data, and continued monitoring will be essential to evaluate long-term performance and ecosystem development.

Figure 25: from left to right: Katherine Benkovich (Sudbury INO), Danielle Solondz (TOARC), Olivia Baudet (Collège Boréal), Nathan Basiliko (Lakehead University), Peter Beckett (Laurentian University).

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7. Challenges and Recommendations for Next Steps

The field trial faced multiple challenges that impacted both the research process and overall seedling performance. Securing a suitable trial site was particularly difficult, as multiple aggregate pits were considered, but ownership disputes and reluctance to sign the necessary paperwork delayed site selection. Another major hurdle was the delay in obtaining permits for the pulp treatment, which postponed amendment application and disrupted the project timeline. Even after securing approval, sourcing the pulp presented further complications, as the closure of a local mill forced the team to acquire material from a facility three hours away, creating logistical and transportation difficulties. Seed availability also posed a constraint; while multiple species were initially selected for the trial, several had to be excluded due to insufficient seed stock, reducing the overall diversity of planted species. Additionally, extreme climate conditions in 2024 added another layer of difficulty. The field season was marked by prolonged periods of heat and drought, making it particularly challenging for both tree seedlings and the research team. The lack of consistent rainfall placed additional stress on the young plants, likely influencing survival rates and early growth, while working conditions in high temperatures made fieldwork physically demanding. These challenges highlight the complexities of conducting large-scale ecological restoration trials and underscore the importance of flexibility and contingency planning in field research.

To build on the findings of this trial, continued monitoring of vegetative growth, survival rates, and soil properties over time is essential to assess the long-term effectiveness of the soil amendments. Regular soil testing should be maintained to track changes in nutrient availability, moisture retention, and microbial activity, ensuring a comprehensive understanding of soil development and its impact on plant establishment. An additional recommendation for future research is the introduction of forest floor transplants in half of the plots to compare growth rates and biodiversity responses over the coming years. By incorporating an intact layer of forest litter, organic material, and microbial communities, this method could accelerate natural succession, enhance soil health, and promote a more diverse plant community. This approach would help mitigate the risk of creating a "green desert," where only the planted species thrive, by fostering spontaneous regeneration and increasing overall ecosystem resilience. Ultimately, the goal is to establish a self-sustaining ecosystem where natural recruitment and biodiversity can drive the site's long-term recovery without continued intervention.

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Appendix

Appendix A

Vegetation Survey-June 2023	
Latin name	**English name**
Abies balsamea	Balsam Fir
Populus balsamifera	Balsam Poplar
Pterdidium aquilinum	Bracken Fern
Cornus canadensis	Bunchberry dogwood
Diervilla lonicera	Bush Honeysuckle
Krigia virginica	Dwarf Dandelion
Lycopodium digitatum	Fan clubmoss
Pinus banksiana	Jack Pine
Eurybia macrophylla	Large leaf Aster
Populus granditata	Largetooth Aspen
Maianthemum	Mayflower
Anaphalis margaritacea	Pearly everlasting
Prunus pensylvanica	Pin Cherry
Acer rubrum	Red Maple
Quercus Rubra	Red Oak
Cornus sericea	Red Osier Dogwood
Pinus resinosa	Red Pine
Viburnum nudum	Smooth whiterod
Comptonia peregrina	Sweetfern
Populus tremuloides	Trembling Aspen
Chimaphila umbellata	Umbellate Wintergreen
Vaccinium myrtilloides	Velvet-leaved Blueberry
Betula papyrifera	White Birch
Pinus strobus	White Pine
Picea Glauca	White Spruce
Rubus idaeus	Wild red raspberry
Aralia nudicaulis	Wild sarsaparilla
Salix spp.	Willow

Appendix B

Natural Vegetation Identification-TOARC project (July 2025)			
Plot ID	**Species Scientific name**	**Species Common name**	**Coverage (%)**
Nrich-PMA	Carex bebbii	Bebb's Sedge	40%

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	Marchantia polymorpha	Common Liverwort	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Vaccinium angustifolium	Lowbush Blueberry	
	Polygonum aviculare	Prostrate Knotweed	
	Agrostis scabra	Rough Bentgrass	
	Comptonia peregrina	Sweet Fern	
	Panicum capillare	Tickle grass	
	Populus tremuloides	Trembling Aspen	
	Betula papyrifera	White Birch	
	Creptis tectorum	Yellow Hawk's beard	
Pulp-PMA	Medicago lupulina	Black Medick	60%
	Taraxacum officinale	Common Dandelion	
	Chamaenerion angustifolium	Fireweed	
	Crepis tectorum	Narrowleaf hawksbeard	
	Polygonum aviculare	Prostrate Knotweed	
	Betula papyrifera	White Birch	
	Creptis tectorum	Yellow Hawk's beard	
Control-PMB	Carex bebbii	Bebb's Sedge	15%
	Fallopia baldschuanica	Climbing knotweed	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Agrostis scabra	Rough Bentgrass	
	Panicum capillare	Tickle grass	
	Betula papyrifera	White Birch	
	Aralia nudicaulis	Wild sarsaparilla	
Ash+Urea- PMB	Carex bebbii	Bebb's Sedge	35%
	Salix Bebbiana	Bebb's Willow	
	Chamaenerion angustifolium	Fireweed	
	Verbascym thapsus	Grande molène	
	Erigeron canadensis	Horseweed	
	Crepis tectorum	Narrowleaf hawksbeard	
	Populus tremuloides	Trembling Aspen	
	Betula papyrifera	White Birch	
	Creptis tectorum	Yellow Hawk's beard	
Nrich+Compost-PMB	Carex bebbii	Bebb's Sedge	60%
	Solidago canadensis	Canada Goldenrod	
	Fallopia baldschuanica	Climbing knotweed	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Epilobium ciliatum	Northern Willowherb	
	Pilosella aurantiaca	Orange Hawkweed	
	Silphium integrifolium	Rosinweed	
	Betula papyrifera	White Birch	
	Creptis tectorum	Yellow Hawk's beard	
Ash+Urea-PMA	Salix Bebbiana	Bebb's Willow	10%
	Medicago lupulina	Black Medick	

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	Plantago major	Broadleaf plantain	
	Chamaenerion angustifolium	Fireweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Calamagrostis pickeringii	Pickering's reed grass	
	Betula papyrifera	White Birch	
Pulp + Ash PMA	Erichtites hieraciifolius	American Burnweed	15-20%
	Salix Bebbiana	Bebb's Willow	
	Medicago lupulina	Black Medick	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Pohlia nutan	Nodding thread-moss	
	Crepis tectorum	Narrowleaf hawksbeard	
	Lactuca Serriola	Prickly Lettuce	
	Coltricia cinnamomea	Shiny cinnamon polypore (mushrooms)	
	Lespedza virginica	Slenderbush Clover	
	Panicum capillare	Tickle grass	
Compost PMA	Carex bebbii	Bebb's Sedge	30%
	Cirsium arvense	Canada Thistle	
	Taraxacum officinale	Common Dandelion	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Lactuca Serriola	Prickly Lettuce	
	Agrostis scabra	Rough Bentgrass	
Nrich+Compost-PMA	Carex bebbii	Bebb's Sedge	50%
	Taraxacum officinale	Common Dandelion	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Epilobium ciliatum	Northern Willowherb	
	Anaphalis margaritacea	Pearly Everlasting	
	Prunus pensylvanica	Pin Cherry	
	Phlox pilosa	Prairie Phlox	
	Lactuca Serriola	Prickly Lettuce	
	Polygonum aviculare	Prostrate Knotweed	
	Sonchus arvensis	Sow Thistle	
	Apocynum androsaemifolium	Spreading Dogbane	
Compost PMB	Carex bebbii	Bebb's Sedge	40%
	Carex bebbii	Bebb's Sedge	
	Salix Bebbiana	Bebb's Willow	
	Solidago canadensis	Canada Goldenrod	
	Veronicastrum virginicum	Culvert's Root	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Anaphalis margaritacea	Pearly Everlasting	
	Phlox pilosa	Prairie Phlox	
	Lactuca Serriola	Prickly Lettuce	

	Salix discolor	Pussy Willow	
	Agrostis scabra	Rough Bentgrass	
	Sonchus arvensis	Sow Thistle	
	Apocynum androsaemifolium	Spreading Dogbane	
Pulp PMB	Lotus corniculatus	Bird's Foot Trefoil	5%
	Medicago lupulina	Black Medick	
	Fuligo septica	Dog vomit slime mold	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Lactuca Serriola	Prickly Lettuce	
	Coltricia cinnamomea	Shiny cinnamon polypore (mushrooms)	
	Trifolium repens	White Clover	
Pulp+Ash PMB	Carex bebbii	Bebb's Sedge	15%
	Medicago lupulina	Black Medick	
	Sambucus canadensis	Common Elderberry	
	Marchantia polymorpha	Common Liverwort	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Lactuca Serriola	Prickly Lettuce	
	Trifolium repens	White Clover	
Nrich PMB	Carex bebbii	Bebb's Sedge	15-20%
	Lotus corniculatus	Bird's Foot Trefoil	
	Medicago lupulina	Black Medick	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Pohlia nutan	Nodding thread-moss	
	Lactuca Serriola	Prickly Lettuce	
	Agrostis scabra	Rough Bentgrass	
	Panicum capillare	Tickle grass	
Control PMA	Vaccinium angustifolium	Lowbush Blueberry	5%
Control FB	Carex bebbii	Bebb's Sedge	5%
	Fallopia baldschuanica	Climbing knotweed	
	Agrostis capillaris	Common bent	
	Kalmia angustifolia	Sheep Laurel	
Ash+Urea FB	Carex bebbii	Bebb's Sedge	1-5%
	Chamaenerion angustifolium	Fireweed	
	Lactuca Serriola	Prickly Lettuce	
Pulp FA	Carex bebbii	Bebb's Sedge	10%
	Lotus corniculatus	Bird's Foot Trefoil	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Lactuca Serriola	Prickly Lettuce	
	Trifolium repens	White Clover	
Nrich + Compost FB	Salix Bebbiana	Bebb's Willow	70%
	Solidago canadensis	Canada Goldenrod	

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	Agrostis capillaris	Common bent	
	Taraxacum officinale	Common Dandelion	
	Erigeron annuus	Daisy Fleabane	
	Oenothera biennis	Evening primrose	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Vaccinium angustifolium	Lowbush Blueberry	
	Dryopteris marginalis	Marginal Wood Fern	
	Pilosella caespitosa	Meadow Hawkweed	
	Asclepias fascicularis	Narrowleaf Milkweed	
	Epilobium ciliatum	Northern Willowherb	
	Agrostis scabra	Rough Bentgrass	
	Dasiphora fructicosa	Shruby Cinquefoil	
	Apocynum androsaemifolium	Spreading Dogbane	
	Holcus lanatus	Velvet Grass	
	Creptis tectorum	Yellow Hawk's beard	
Ash+Urea FA	Oenothera biennis	Evening primrose	1-5%
	Anaphalis margaritacea	Pearly Everlasting	
	Agrostis scabra	Rough Bentgrass	
	Apocynum androsaemifolium	Spreading Dogbane	
Control FA	N/A	N/A	1-5%
Compost FB	Salix Bebbiana	Bebb's Willow	30%
	Lotus corniculatus	Bird's Foot Trefoil	
	Solidago canadensis	Canada Goldenrod	
	Mollugo verticillata	Carpetweed	
	Taraxacum officinale	Common Dandelion	
	Oenothera biennis	Evening primrose	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Dryopteris marginalis	Marginal Wood Fern	
	Pilosella caespitosa	Meadow Hawkweed	
	Epilobium ciliatum	Northern Willowherb	
	Lactuca Serriola	Prickly Lettuce	
	Agrostis scabra	Rough Bentgrass	
	Apocynum androsaemifolium	Spreading Dogbane	
	Spirea Alba	White Meadowsweet	
Pulp+Ash FB	Carex bebbii	Bebb's Sedge	20%
	Lotus corniculatus	Bird's Foot Trefoil	
	Silphium perfoliatum	Cup Plant	
	Dichanthelium clandestinum	Deertongue Grass	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Lactuca Serriola	Prickly Lettuce	
	Agrostis scabra	Rough Bentgrass	
	Lespedza virginica	Slenderbush Clover	

Boréal

	Comptonia peregrina	Sweet Fern	
	Trifolium repens	White Clover	
	Aralia nudicaulis	Wild sarsaparilla	
Nrich+Compost FA	Carex bebbii	Bebb's Sedge	60%
	Mollugo verticillata	Carpetweed	
	Fallopia baldschuanica	Climbing knotweed	
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Epilobium ciliatum	Northern Willowherb	
	Pilosella aurantiaca	Orange Hawkweed	
	Lactuca Serriola	Prickly Lettuce	
	Agrostis scabra	Rough Bentgrass	
	Dasiphora fructicosa	Shruby Cinquefoil	
	Creptis tectorum	Yellow Hawk's beard	
Nrich FB	Carex bebbii	Bebb's Sedge	1-5%
	Plantago major	Broadleaf plantain	
	Erigeron canadensis	Horseweed	
	Cerastium fontanum	Mouse-ear chickweed	
	Pilosella aurantiaca	Orange Hawkweed	
	Anaphalis margaritacea	Pearly Everlasting	
	Agrostis scabra	Rough Bentgrass	
	Comptonia peregrina	Sweet Fern	
	Creptis tectorum	Yellow Hawk's beard	
Nrich FA	Plantago major	Broadleaf plantain	10%
	Chamaenerion angustifolium	Fireweed	
	Erigeron canadensis	Horseweed	
	Pilosella caespitosa	Meadow Hawkweed	
	Tragopogon pratensis	Meadow Salsify	
	Pilosella aurantiaca	Orange Hawkweed	
	Polygonum aviculare	Prostrate Knotweed	
	Agrostis scabra	Rough Bentgrass	
	Trifolium repens	White Clover	
	Creptis tectorum	Yellow Hawk's beard	
Pulp FB	Carex bebbii	Bebb's Sedge	15%
	Medicago lupulina	Black Medick	
	Fallopia baldschuanica	Climbing knotweed	
	Chamaenerion angustifolium	Fireweed	
	Polygonum aviculare	Prostrate Knotweed	
	Agrostis scabra	Rough Bentgrass	
	Rumex thyrsiflorus	Thyrse Sorrel	
	Trifolium repens	White Clover	
	Creptis tectorum	Yellow Hawk's beard	
Pulp+Ash FA	Carex bebbii	Bebb's Sedge	10-15%
	Erigeron canadensis	Horseweed	
	Tragopogon pratensis	Meadow Salsify	
	Prunus pensylvanica	Pin Cherry	
	Polygonum aviculare	Prostrate Knotweed	

Boréal

	Agrostis scabra	Rough Bentgrass	
	Trifolium repens	White Clover	
	Creptis tectorum	Yellow Hawk's beard	
Compost FA	Chamaenerion angustifolium	Fireweed	10%
	Vicia villosa	Hairy vetch	
	Erigeron canadensis	Horseweed	
	Pilosella aurantiaca	Orange Hawkweed	
	Anaphalis margaritacea	Pearly Everlasting	
	Agrostis scabra	Rough Bentgrass	
	Creptis tectorum	Yellow Hawk's beard	

Appendix C

Boréal

WORK ORDER RESULTS

Sample Description	NRICH+COMPOST PM		ASH+UREA PM		NRICH PM		Pulp PM		
Sample Date	7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		
Lab ID	2178630		2178631		2178632		2178633		
Anions (Soil)	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Bromide	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	µg/g
Chloride	1.0	0.4	1.2	0.4	0.5	0.4	0.4	0.4	µg/g
Fluoride	0.8	0.2	<0.2	0.2	0.3	0.2	<0.2	0.2	µg/g
Nitrate (as N)	1.2	0.2	<0.2	0.2	1.2	0.2	3.9	0.2	µg/g
Nitrite (as N)	<0.1	0.1	<0.1	0.1	<0.1	0.1	<0.1	0.1	µg/g
Sulphate	14	2	5	2	39	2	10	2	µg/g

Sample Description	Compost PM		PULP+Ash PM		Control PM		NRICH+COMPOST F		
Sample Date	7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178634		2178635		2178636		2178637		
Anions (Soil)	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Bromide	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	µg/g
Chloride	0.5	0.4	1.0	0.4	<0.4	0.4	0.9	0.4	µg/g
Fluoride	<0.2	0.2	<0.2	0.2	<0.2	0.2	0.5	0.2	µg/g
Nitrate (as N)	<0.2	0.2	20.1	0.2	0.2	0.2	1.2	0.2	µg/g
Nitrite (as N)	<0.1	0.1	<0.1	0.1	<0.1	0.1	<0.1	0.1	µg/g
Sulphate	2	2	29	2	6	2	9	2	µg/g

Sample Description	ASH+UREA F		NRICH F		Pulp F		Compost F		
Sample Date	7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178638		2178639		2178640		2178641		
Anions (Soil)	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Bromide	<0.2	0.2	<0.2	0.2	<0.2	0.2	<0.2	0.2	µg/g
Chloride	0.9	0.4	1.2	0.4	0.5	0.4	0.5	0.4	µg/g
Fluoride	<0.2	0.2	0.8	0.2	<0.2	0.2	<0.2	0.2	µg/g
Nitrate (as N)	<0.2	0.2	1.9	0.2	<0.2	0.2	<0.2	0.2	µg/g
Nitrite (as N)	<0.1	0.1	<0.1	0.1	<0.1	0.1	<0.1	0.1	µg/g
Sulphate	<2	2	9	2	7	2	<2	2	µg/g

Sample Description	PULP+Ash F		Control F		
Sample Date	7/23/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178642		2178643		
Anions (Soil)	Result	MDL	Result	MDL	Units
Bromide	<0.2	0.2	<0.2	0.2	µg/g
Chloride	<0.4	0.4	<0.4	0.4	µg/g
Fluoride	<0.2	0.2	<0.2	0.2	µg/g
Nitrate (as N)	<0.2	0.2	<0.2	0.2	µg/g
Nitrite (as N)	<0.1	0.1	<0.1	0.1	µg/g
Sulphate	6	2	<2	2	µg/g

Boréal

Sample Description	NRICH+COMPOST PM		ASH+UREA PM		NRICH PM		Pulp PM		
Sample Date	7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		
Lab ID	2178630		2178631		2178632		2178633		
General Chemistry	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
% Moisture	9.4	0.1	18.6	0.1	3.0	0.1	8.5	0.1	%
pH	6.06	N/A	6.62	N/A	6.73	N/A	5.31	N/A	pH
Total Carbon	5.700	0.009	13.700	0.009	0.061	0.009	0.684	0.009	%
Total Kjeldahl Nitrogen	645 [820]	60*	180	100*	<50	50*	250	80*	mg/kg

Sample Description	Compost PM		PULP+Ash PM		Control PM		NRICH+COMPOST F		
Sample Date	7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178634		2178635		2178636		2178637		
General Chemistry	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
% Moisture	6.3	0.1	6.2	0.1	3.3	0.1	4.0	0.1	%
pH	5.64	N/A	6.15	N/A	5.4	N/A	6.45	N/A	pH
Total Carbon	1.990	0.009	3.780	0.009	0.542	0.009	2.380	0.009	%
Total Kjeldahl Nitrogen	190	90*	210	70*	63	60*	340	90*	mg/kg

Sample Description	ASH+UREA F		NRICH F		Pulp F		Compost F		
Sample Date	7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178638		2178639		2178640		2178641		
General Chemistry	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
% Moisture	2.8	0.1	2.7	0.1	3.6	0.1	5.9	0.1	%
pH	6.15	N/A	7.11	N/A	5.77	N/A	6.06	N/A	pH
Total Carbon	0.073	0.009	0.845	0.009	0.254	0.009	1.970	0.009	%
Total Kjeldahl Nitrogen	<90	90*	150	70*	210	60*	440	80*	mg/kg

Sample Description	PULP+Ash F		Control F		
Sample Date	7/23/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178642		2178643		
General Chemistry	Result	MDL	Result	MDL	Units
% Moisture	4.0	0.1	2.9	0.1	%
pH	5.77	N/A	5.6 [5.41]	N/A	pH
Total Carbon	0.191	0.009	<0.009 [<0.009]	0.009	%
Total Kjeldahl Nitrogen	110	60*	<50	50*	mg/kg

Boréal

Sample Description	NRICH+COMPOST PM		ASH+UREA PM		NRICH PM		Pulp PM		
Sample Date	7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		
Lab ID	2178630		2178631		2178632		2178633		
Metals	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Aluminum	12700	50*	12700	50*	13100	50*	11100	50*	µg/g
Antimony	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Arsenic	8.5	0.5*	8.7	0.5*	11.5	0.5*	11.5	0.5*	µg/g
Barium	102	5*	569	5*	56.1	0.5*	50.3	0.5*	µg/g
Beryllium	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Bismuth	2.6	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Boron	5.2	0.5*	33.7	0.5*	1.8	0.5*	1.5	0.5*	µg/g
Cadmium	1.01	0.05*	2.87	0.05*	0.16	0.05*	0.20	0.05*	µg/g
Calcium	53100	300*	81500	300*	3580	30*	2170	30*	µg/g
Cerium	31.0	0.5*	26.3	0.5*	31.9	0.5*	29.8	0.5*	µg/g
Cesium	1.9	0.5*	0.8	0.5*	0.7	0.5*	0.6	0.5*	µg/g
Chromium	31.7	0.5*	35.5	0.5*	34.8	0.5*	32.1	0.5*	µg/g
Cobalt	13.40	0.05*	14.70	0.05*	13.90	0.05*	13.80	0.05*	µg/g
Copper	83	5*	75	5*	47.8	0.5*	46.1	0.5*	µg/g
Europium	<0.5	0.5*	0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Gallium	6.6	0.5*	20.2	0.5*	5.4	0.5*	4.9	0.5*	µg/g
Iron	20900	1000*	20000	1000*	19100	1000*	17900	1000*	µg/g
Lanthanum	14.0	0.5*	12.5	0.5*	11.1	0.5*	12.2	0.5*	µg/g
Lead	33.6	0.5*	9.8	0.5*	11.2	0.5*	7.9	0.5*	µg/g
Lithium	10	3*	7	3*	10	3*	9	3*	µg/g
Magnesium	6180	2*	11700	2*	6350	2*	6370	2*	µg/g
Manganese	321	5*	1860	50*	268	5*	275	5*	µg/g
Mercury	<0.05	0.05*	<0.05	0.05*	<0.05	0.05*	<0.05	0.05*	µg/g
Molybdenum	0.7	0.5*	0.7	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Nickel	54.9	0.5*	35.9	0.5*	37.9	0.5*	33.2	0.5*	µg/g
Niobium	0.8	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Phosphorus	<3000	3000*	<3000	3000*	406	30*	456	30*	µg/g
Potassium	2010	50*	1680	50*	709	50*	701	50*	µg/g
Rubidium	14.2	0.5*	14.6	0.5*	7.6	0.5*	6.9	0.5*	µg/g

Boréal

Sample Description	NRICH+COMPOST PM		ASH+UREA PM		NRICH PM		Pulp PM		
Sample Date	7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		
Lab ID	2178630		2178631		2178632		2178633		
Metals	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Scandium	2.9	0.5*	3.8	0.5*	2.6	0.5*	2.8	0.5*	µg/g
Selenium	1.2	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Silicon	1100	300*	<300	300*	<300	300*	<300	300*	µg/g
Silver	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Sodium	250	50*	340	50*	120	50*	120	50*	µg/g
Strontium	81.9	0.5*	169.0	0.5*	16.1	0.5*	14.5	0.5*	µg/g
Sulfur	<400	400*	<400	400*	<400	400*	<400	400*	µg/g
Tellurium	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Thallium	0.6	0.3*	<0.3	0.3*	<0.3	0.3*	<0.3	0.3*	µg/g
Thorium	1.6	0.5*	2.5	0.5*	3.8	0.5*	3.4	0.5*	µg/g
Tin	1.6	0.5*	5.2	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Titanium	411	5*	587	5*	559	5*	509	5*	µg/g
Tungsten	0.7	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Uranium	1.0	0.5*	0.8	0.5*	0.7	0.5*	0.7	0.5*	µg/g
Vanadium	64	5*	33.4	0.5*	42.9	0.5*	36.9	0.5*	µg/g
Yttrium	6.3	0.5*	6.0	0.5*	3.3	0.5*	3.9	0.5*	µg/g
Zinc	84.7	0.5*	582	5*	26.3	0.5*	28.3	0.5*	µg/g
Zirconium	3.8	0.5*	6.1	0.5*	4.3	0.5*	6.4	0.5*	µg/g

Boréal

Sample Description	Compost PM		PULP+Ash PM		Control PM		NRICH+COMPOST F		
Sample Date	7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/22/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178634		2178635		2178636		2178637		
Metals	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Aluminum	10500	50*	11900	50*	14200	50*	11100	50*	µg/g
Antimony	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Arsenic	11.3	0.5*	18.2	0.5*	16.1	0.5*	15.1	0.5*	µg/g
Barium	59.4	0.5*	82	5*	59.6	0.5*	85	5*	µg/g
Beryllium	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Bismuth	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Boron	2.2	0.5*	2.6	0.5*	1.5	0.5*	3.1	0.5*	µg/g
Cadmium	0.24	0.05*	0.35	0.05*	0.17	0.05*	0.31	0.05*	µg/g
Calcium	3410	30*	4870	30*	2060	30*	9100	30*	µg/g
Cerium	29.6	0.5*	41.1	0.5*	35.5	0.5*	39.8	0.5*	µg/g
Cesium	0.5	0.5*	0.9	0.5*	0.8	0.5*	1.0	0.5*	µg/g
Chromium	31.3	0.5*	40.9	0.5*	41.1	0.5*	38.6	0.5*	µg/g
Cobalt	12.70	0.05*	23.90	0.05*	16.60	0.05*	18.90	0.05*	µg/g
Copper	47.2	0.5*	112	5*	60.8	0.5*	80	5*	µg/g
Europium	<0.5	0.5*	0.7	0.5*	<0.5	0.5*	0.6	0.5*	µg/g
Gallium	5.2	0.5*	6.5	0.5*	6.2	0.5*	6.4	0.5*	µg/g
Iron	15700	1000*	24800	1000*	20400	1000*	20600	1000*	µg/g
Lanthanum	12.0	0.5*	19.4	0.5*	14.2	0.5*	18.8	0.5*	µg/g
Lead	7.4	0.5*	10.5	0.5*	13.6	0.5*	12.7	0.5*	µg/g
Lithium	9	3*	10	3*	12	3*	10	3*	µg/g
Magnesium	5780	2*	8670	2*	7040	2*	7420	2*	µg/g
Manganese	291	5*	510	5*	339	5*	392	5*	µg/g
Mercury	<0.05	0.05*	<0.05	0.05*	<0.05	0.05*	<0.05	0.05*	µg/g
Molybdenum	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Nickel	38.7	0.5*	134	5*	42.3	0.5*	43.1	0.5*	µg/g
Niobium	0.7	0.5*	<0.5	0.5*	<0.5	0.5*	0.7	0.5*	µg/g
Phosphorus	572	30*	740	30*	415	30*	815	30*	µg/g
Potassium	1040	50*	1330	50*	818	50*	1710	50*	µg/g
Rubidium	7.3	0.5*	12.2	0.5*	8.5	0.5*	11.6	0.5*	µg/g
Scandium	2.5	0.5*	4.5	0.5*	3.4	0.5*	3.8	0.5*	µg/g
Selenium	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Silicon	<300	300*	<300	300*	<300	300*	<300	300*	µg/g
Silver	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Sodium	99	50*	300	50*	140	50*	200	50*	µg/g
Strontium	18.1	0.5*	26.7	0.5*	18.0	0.5*	34.0	0.5*	µg/g
Sulfur	<400	400*	<400	400*	<400	400*	<400	400*	µg/g
Tellurium	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Thallium	<0.3	0.3*	<0.3	0.3*	<0.3	0.3*	<0.3	0.3*	µg/g
Thorium	3.4	0.5*	4.2	0.5*	4.1	0.5*	3.5	0.5*	µg/g
Tin	<0.5	0.5*	0.7	0.5*	<0.5	0.5*	0.5	0.5*	µg/g
Titanium	470	5*	703	5*	630	5*	569	5*	µg/g
Tungsten	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Uranium	0.7	0.5*	1.1	0.5*	0.8	0.5*	1.0	0.5*	µg/g
Vanadium	35.4	0.5*	58.6	0.5*	46.3	0.5*	49.1	0.5*	µg/g
Yttrium	4.0	0.5*	8.5	0.5*	4.7	0.5*	7.2	0.5*	µg/g
Zinc	37.1	0.5*	56.2	0.5*	30.7	0.5*	50.4	0.5*	µg/g
Zirconium	7.8	0.5*	9.5	0.5*	7.4	0.5*	7.8	0.5*	µg/g

Boréal

Sample Description	ASH+UREA F		NRICH F		Pulp F		Compost F		
Sample Date	7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178638		2178639		2178640		2178641		
Metals	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Aluminum	12800 [13100]	50*	12300	50*	11400	50*	8940	50*	µg/g
Antimony	0.9 [0.8]	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Arsenic	13.6 [13.6]	0.5*	11.4	0.5*	12.7	0.5*	10.4	0.5*	µg/g
Barium	64.4 [61.4]	0.5*	79	5*	59.6	0.5*	64.4	0.5*	µg/g
Beryllium	<0.5 [<0.5]	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Bismuth	<0.5 [<0.5]	0.5*	1.4	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Boron	1.7 [1.7]	0.5*	4.5	0.5*	1.7	0.5*	2.9	0.5*	µg/g
Cadmium	0.14 [0.14]	0.05*	0.44	0.05*	0.21	0.05*	0.25	0.05*	µg/g
Calcium	2460 [2350]	30*	23000	30*	2440	30*	4730	30*	µg/g
Cerium	35.4 [36.2]	0.5*	37.7	0.5*	34.6	0.5*	27.8	0.5*	µg/g
Cesium	0.6 [0.6]	0.5*	1.6	0.5*	0.6	0.5*	0.6	0.5*	µg/g
Chromium	37.0 [34.9]	0.5*	36.2	0.5*	35.6	0.5*	30.6	0.5*	µg/g
Cobalt	14.40 [13.40]	0.05*	17.20	0.05*	16.20	0.05*	12.20	0.05*	µg/g
Copper	54.0 [51.8]	0.5*	83	5*	59.3	0.5*	46.7	0.5*	µg/g
Europium	<0.5 [<0.5]	0.5*	0.6	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Gallium	5.9 [5.8]	0.5*	6.3	0.5*	5.5	0.5*	5.1	0.5*	µg/g
Iron	20100 [18900]	1000*	22500	1000*	20500	1000*	15800	1000*	µg/g
Lanthanum	13.7 [14.5]	0.5*	17.6	0.5*	14.6	0.5*	14.2	0.5*	µg/g
Lead	78 [72]	5*	19.8	0.5*	8.3	0.5*	28.0	0.5*	µg/g
Lithium	11 [10]	3*	11	3*	10	3*	9	3*	µg/g
Magnesium	6950 [6520]	2*	7140	2*	6880	2*	6070	2*	µg/g
Manganese	322 [301]	5*	369	5*	340	5*	299	5*	µg/g
Mercury	<0.05 [<0.05]	0.05*	<0.05	0.05*	<0.05	0.05*	<0.05	0.05*	µg/g
Molybdenum	<0.5 [<0.5]	0.5*	0.8	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Nickel	35.6 [34.6]	0.5*	44.3	0.5*	59.7	0.5*	33.3	0.5*	µg/g
Niobium	<0.5 [<0.5]	0.5*	<0.5	0.5*	<0.5	0.5*	0.6	0.5*	µg/g
Phosphorus	349 [342]	30*	1110	30*	420	30*	620	30*	µg/g
Potassium	855 [809]	50*	1470	50*	802	50*	1290	50*	µg/g
Rubidium	8.5 [8.0]	0.5*	14.3	0.5*	7.3	0.5*	8.3	0.5*	µg/g

Boréal

Sample Description	ASH+UREA F		NRICH F		Pulp F		Compost F		
Sample Date	7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178638		2178639		2178640		2178641		
Metals	Result	MDL	Result	MDL	Result	MDL	Result	MDL	Units
Scandium	3.3 [3.1]	0.5*	3.6	0.5*	3.3	0.5*	3.0	0.5*	µg/g
Selenium	<0.5 [<0.5]	0.5*	0.7	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Silicon	<300 [<300]	300*	<300	300*	<300	300*	<300	300*	µg/g
Silver	<0.5 [<0.5]	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Sodium	140 [130]	50*	240	50*	160	50*	120	50*	µg/g
Strontium	20.0 [19.3]	0.5*	44.7	0.5*	20.6	0.5*	24.9	0.5*	µg/g
Sulfur	<400 [<400]	400*	<400	400*	<400	400*	<400	400*	µg/g
Tellurium	<0.5 [<0.5]	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Thallium	<0.3 [<0.3]	0.3*	<0.3	0.3*	<0.3	0.3*	<0.3	0.3*	µg/g
Thorium	4.2 [4.3]	0.5*	2.5	0.5*	3.6	0.5*	3.1	0.5*	µg/g
Tin	<0.5 [<0.5]	0.5*	0.9	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Titanium	626 [526]	5*	501	5*	604	5*	457	5*	µg/g
Tungsten	<0.5 [<0.5]	0.5*	<0.5	0.5*	<0.5	0.5*	<0.5	0.5*	µg/g
Uranium	0.8 [0.8]	0.5*	1.1	0.5*	0.8	0.5*	0.8	0.5*	µg/g
Vanadium	43.4 [36.6]	0.5*	52.1	0.5*	46.0	0.5*	34.6	0.5*	µg/g
Yttrium	4.5 [4.4]	0.5*	7.3	0.5*	5.2	0.5*	5.2	0.5*	µg/g
Zinc	33.1 [31.5]	0.5*	50.0	0.5*	27.4	0.5*	58.4	0.5*	µg/g
Zirconium	7.7 [7.6]	0.5*	1.5	0.5*	6.4	0.5*	7.6	0.5*	µg/g

Sample Description	PULP+Ash F		Control F		
Sample Date	7/23/2025 10:00 AM		7/23/2025 10:00 AM		
Lab ID	2178642		2178643		
Metals	Result	MDL	Result	MDL	Units
Aluminum	8860	50*	9810	50*	µg/g
Antimony	<0.5	0.5*	3.2	0.5*	µg/g
Arsenic	11.2	0.5*	11.9	0.5*	µg/g
Barium	50.2	0.5*	47.5	0.5*	µg/g
Beryllium	<0.5	0.5*	<0.5	0.5*	µg/g
Bismuth	<0.5	0.5*	<0.5	0.5*	µg/g
Boron	1.5	0.5*	1.3	0.5*	µg/g
Cadmium	0.14	0.05*	0.13	0.05*	µg/g
Calcium	2400	30*	2190	30*	µg/g
Cerium	27.4	0.5*	29.0	0.5*	µg/g
Cesium	0.5	0.5*	0.5	0.5*	µg/g
Chromium	31.0	0.5*	33.3	0.5*	µg/g
Cobalt	14.60	0.05*	13.90	0.05*	µg/g
Copper	59.1	0.5*	45.8	0.5*	µg/g
Europium	<0.5	0.5*	<0.5	0.5*	µg/g
Gallium	4.7	0.5*	4.7	0.5*	µg/g
Iron	16700	1000*	18000	1000*	µg/g

Boréal

Lanthanum	12.9	0.5*	13.0	0.5*	µg/g
Lead	9.8	0.5*	96	5*	µg/g
Lithium	9	3*	9	3*	µg/g
Magnesium	6180	2*	6450	2*	µg/g
Manganese	284	5*	293	5*	µg/g
Mercury	<0.05	0.05*	<0.05	0.05*	µg/g
Molybdenum	<0.5	0.5*	<0.5	0.5*	µg/g
Nickel	100	5*	29.9	0.5*	µg/g
Niobium	<0.5	0.5*	<0.5	0.5*	µg/g
Phosphorus	376	30*	300	30*	µg/g
Potassium	718	50*	708	50*	µg/g
Rubidium	6.2	0.5*	6.4	0.5*	µg/g
Scandium	3.2	0.5*	3.2	0.5*	µg/g
Selenium	<0.5	0.5*	<0.5	0.5*	µg/g
Silicon	<300	300*	<300	300*	µg/g
Silver	<0.5	0.5*	<0.5	0.5*	µg/g
Sodium	160	50*	130	50*	µg/g
Strontium	18.7	0.5*	17.7	0.5*	µg/g
Sulfur	<400	400*	<400	400*	µg/g
Tellurium	<0.5	0.5*	<0.5	0.5*	µg/g
Thallium	<0.3	0.3*	<0.3	0.3*	µg/g
Thorium	3.3	0.5*	3.6	0.5*	µg/g
Tin	<0.5	0.5*	<0.5	0.5*	µg/g
Titanium	518	5*	590	5*	µg/g
Tungsten	<0.5	0.5*	<0.5	0.5*	µg/g
Uranium	0.8	0.5*	0.8	0.5*	µg/g
Vanadium	41.3	0.5*	42.3	0.5*	µg/g
Yttrium	5.1	0.5*	4.9	0.5*	µg/g
Zinc	25.6	0.5*	24.8	0.5*	µg/g
Zirconium	8.0	0.5*	8.4	0.5*	µg/g

Boréal