Industrial Residuals in Land Reclamation: Enhancing Soil Recovery and Ecological Function in Disturbed Glacial Soils

By

Jonathan Robert Lavigne

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Abstract

This dissertation investigates the reclamation potential of industrial residuals in remediating disturbed glacial soils in Northeastern Ontario. Focusing on two distinct yet similarly degraded landscapes — abandoned aggregate borrow pits and acid- and metal-affected mixed-wood forest soils in the Sudbury region — the research explores the application of industrial by-products to enhance soil fertility, facilitate revegetation, and support ecological restoration. The study is structured around three research objectives: first, assessing passive recolonization processes and dominant functional traits in abandoned borrow pits; second, evaluating the efficacy of industrial residues, including pulp and paper mill sludge, biomass boiler fly ash, and municipal biosolids, in improving borrow pit soil fertility and facilitating vegetation establishment; and third, testing the potential of these residues to ameliorate acidic and metal-laden soils for reforestation efforts in post-mining landscapes.

The research incorporates a thorough analysis of soil and vegetation dynamics, functional trait diversity, and soil-organism interactions across experimental and natural sites. By determining community-weighted mean (CWM) and Rao's Quadratic Entropy Index analyses, the study quantifies the functional role of plant traits in supporting ecosystem resilience and stability of abandoned borrow pits. Results demonstrate the significant but variable effects of land applying industrial solids on soil quality, with implications for both nutrient dynamics and biological activity. Notably, the application of these residues to acidic soils supports positive vegetation outcomes, particularly for pioneer and stress-tolerant species adapted to low-nutrient environments. Additionally, findings highlight the challenges associated with northern soil reclamation, including frost heave and the limited microbial and nutrient availability in exposed, compacted substrates.

The research contributes to the understanding of reclamation strategies in regenerating forest ecosystems, emphasizing the importance of tailored, site-specific amendments to improve soil health and promote sustainable land recovery. The outcomes of this thesis have broad implications for land management policies in resource-extractive landscapes, underscoring the need for long-term monitoring, adaptive management, and integrated use of local industrial by-products to restore ecosystem functionality in severely degraded soils.

Co-authorship Statement

This thesis includes research that was conducted in collaboration with co-authors. The author of this thesis was responsible for the development of research questions, experimental design, data collection, data analysis, and manuscript preparation. Co-authors contributed in the following ways: Dr. Basiliko provided guidance on methodology and manuscript writing and preparation; Dr. Beckett assisted with field data collection, methodology, and manuscript writing and preparation. The majority of the writing and interpretation of results was conducted by the thesis author. Permission has been obtained from all co-authors to include the co-authored material in this dissertation.

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Dedication

For my son, Léo, and my wife Sandryn.

Foreword

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Table of Contents

List of Tables

List of Figures

statistically significant differences in metal concentration between treatment types. The black diamonds represent outliers within each treatment. This comparison highlights how different treatments affect the accumulation of heavy metals in soil, with notable variability across metals and treatments.

Figure 9 - 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.

Figure 10 – Rate of successfully germinated individuals tracked 2 weeks from experiment start date. Horizontal red dotted line is included to compare the germination of species sown in the unamended aggregate substrate (CON)

Figure 11 - The above graph represents the average daily increases (%) in stem length from t=0 to t=12 weeks. Orange bars indicate the median.

Figure 12 - 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.

Figure 13 - RDA biplot showing the associations between soil fertility indicators (blue vectors) and plant response variables (red labels) of planted Yellow Birch following the amendment of gravel with industrial residuals. The proximity of plant response variables to soil fertility vectors suggests a correlation with the respective soil properties. PMS treatments (PPF, PPA, PP) indicate distinct clustering, reflecting their beneficial influence on both soil fertility and plant responses.

Figure 14 - K-means clustering reveals 3 distinct groups based on their soil and plant properties: A) Control (CON) and Sudbury Regreening Treatment (SUD); B) Lime stabilized biosolids (NRICH) with municipal compost (NMC), biomass boiler fly ash (AF); and C) blended pulp sludge (PP) with BBFA (PPA) or forest floor inoculum (PPF). This figure also highlights the species effect as well.

Figure 15 - Principal Component Analysis (PCA) of plant community composition across soil amendment treatments in Sudbury's degraded upland and sloped sites. Clustering patterns indicate distinct community structures associated with treatments, with ATB-treated plots showing higher species diversity and cover, while Ps-S and AF treatments cluster closer to bare ground and low diversity conditions. Arrows represent key soil variables influencing community composition, including moisture, temperature, and pH.

Figure 16 - Redundancy Analysis (RDA) biplot showing the relationship between soil properties, treatment types, and plant growth metrics for Jack Pine across experimental plots. Soil temperature, moisture, and ground cover are the primary factors driving plant outcomes, with ATB treatments correlating with improved growth rates and health. Treatments such as Ps-S and AF show poorer performance, characterized by higher temperatures and lower moisture availability.

Chapter 1

Introduction

This PhD thesis examines recolonization processes in two distinct but comparable disturbance types where topsoil was entirely removed and remnant substrates severely degraded, creating significant challenges for ecological recovery: (A) Borrow pits along the Highway 17 Corridor in Northeastern Ontario, Canada, and (B) Acid- and metal-damaged forest ecosystems within the Great Lakes–St. Lawrence and Boreal Forest ecotone in the Greater Sudbury region of Ontario, Canada. Central to this research is the evaluation of reclamation strategies that leverage industrial residuals and innovative methods to enhance plant growth and revegetation rates in these degraded systems. An emerging theme of the thesis explores three restoration approaches within the context of a restorative continuum: i) passive regeneration or recolonization, where natural ecological processes are left to guide recovery without direct intervention; ii) assisted natural recolonization, where environmental conditions are ameliorated to facilitate recovery processes while allowing vegetation to regenerate naturally; and iii) active restoration, where deliberate actions such as planting native species are employed to directly re-establish ecological structure and function. By comparing these approaches across contrasting disturbance contexts, this work provides new insights into how varying levels of intervention influence recovery trajectories, emphasizing the interplay between abiotic restoration efforts and vegetation dynamics. The findings contribute to a deeper understanding of site-specific reclamation practices, offering practical recommendations for ecological restoration within the landscapes of these disturbances and ecotypes.

This thesis has produced 3 research chapters:

1) Investigating passive recolonization and functional trait composition in abandoned borrow pits in Northeastern Ontario, Canada;
2) Investigating the use of industrial residuals to improve soil fertility in these borrow pit soils;
3) Investigating the use of industrial residuals to alleviate acid and metal toxicity in the Greater Sudbury region (Ontario, Canada), and subsequent plant responses.

In this document, I will begin with a brief overview of the methodology, objectives, and purpose for the 3 research chapters. I will then transition to a comprehensive literature review of soil organic matter (SOM), the factors affecting its formation and loss both mechanistically and globally, as well as the environmental and societal impacts of its loss. Additionally, I will discuss successful and unsuccessful recovery methods of SOM within the framework of recolonization and successional progression. I will also discuss and juxtapose the use of plant species diversity vs. plant functional traits when assessing patterns and rates of succession. I will comprehensively discuss both disturbance regimes, industrial residuals, and bridge their potential use. Finally, I will offer a synthesis of these research chapters as they provide the foundation for future work.

On the Status of Passively Recolonizing Borrow Pits in Northeastern Ontario

Background and Context

The extraction of aggregate materials, including sand, gravel, and crushed stone, plays a critical role in supporting infrastructure development globally and locally. Roads, bridges, and buildings rely heavily on these materials, driving significant demand in both industrialized and developing regions (Langer and Arbogast, 2002; Koziol and Baic, 2019). In Ontario, Canada, the extraction of aggregates is closely tied to the province's historical and ongoing infrastructure expansion. In 2020 alone, over 160 million tonnes of mineral aggregates were extracted from an area spanning more than 177,000 hectares (TOARC, 2020; Government of Ontario, 2024). Much of this activity is concentrated in sand and gravel deposits formed during the Pleistocene Glaciation (6–16 KYA), which created glacial outwash plains, kames, and eskers throughout the continent (Lowe, 1979; TOARC, 2020).

Despite its importance to economic development, aggregate mining is a significant environmental disturbance. Borrow pits—small, often temporary excavation sites—are especially common in Northern Ontario. These pits, typically abandoned once their resources are depleted or otherwise unneeded, are characterized by barren parent material, poor soil fertility, and altered topographies that hinder natural ecological recovery (Bradshaw and Chadwick, 1980; Van Ham and Teshima, 2005). Creating borrow pits leads to reduced ecosystem functionality, soil degradation, and an inability to support diverse plant and microbial communities (Borgegård, 1990; Banerjee et al., 2020).

The challenges of reclaiming these disturbed sites are particularly pronounced in Northern Ontario, where colder climates, shorter growing seasons, and the siliceous, nutrient-poor soils derived from Precambrian bedrock exacerbate the barriers to natural recolonization (VandenBygaart and Protz, 1995; Ensign et al., 2006). By contrast, Southern Ontario's aggregate pits are commonly successfully reclaimed, aided by warmer climates, richer limestone-based soils, and greater access to resources for active reclamation efforts (Mahaney, 2007; TOARC, 2024). These regional disparities highlight the need for tailored reclamation approaches that address the unique challenges of Northern Ontario.

Abandoned aggregate sites, known as "legacy" pits, represent a particular subset of this reclamation challenge. These sites predate modern legislation, such as Ontario's Aggregate Resources Act (ARA) of 1990, which mandates environmental assessments and closure plans for new mining operations. Without legal obligations for reclamation, legacy pits are often left barren, contributing to ongoing environmental and aesthetic concerns (CIELP, 2021; TOARC, 2024). To address this gap, the Management of Abandoned Aggregate Properties (MAAP) program was established, funded through a levy paid by active aggregate producers. Administered by the Ontario Aggregate Resources Corporation (TOARC), this program aims to rehabilitate legacy sites across the province. While MAAP has made significant progress in Southern Ontario, reclamation success in the north has been limited, attributed to differences in soil quality, climate, and ecological conditions (TOARC, 2024).

The ecological impacts of aggregate mining are multifaceted, including habitat destruction, soil erosion, and hydrological alterations (Gillies and Sharratt, 2008; Wilk and Szarek-Łukaszewska, 2020). The removal of topsoil and vegetation disrupts critical biogeochemical processes, such as nutrient cycling and organic matter accumulation, leaving behind soils that are highly compacted, low in microbial diversity, and prone to erosion (Antwi et al., 2008; Brady and Weil, 2004). These challenges are compounded in borrow pits, which are often too small and irregularly shaped to benefit from economies of scale in reclamation.

Reclamation strategies for these sites range from passive approaches, which rely on natural succession, to active methods, such as soil amendments and planting (Hugron et al., 2011; Řehounková and Prach, 2013). Passive recolonization, though cost-effective, is often slow and vulnerable to setbacks, particularly in environments with harsh climatic conditions or limited seed banks (Borgegård, 1990; Sánchez-Pinillos et al., 2019). Active reclamation, on the other hand, can accelerate recovery by addressing specific barriers to plant establishment, such as poor soil structure and nutrient deficiencies. For example, the use of industrial residuals like lime-stabilized biosolids and pulp mill sludge has been shown to improve soil fertility and water retention, creating conditions more favorable for plant growth (Larney and Angers, 2012; Camberato et al., 2006).

A key aspect of successful reclamation lies in understanding the functional traits of plant species that colonize these disturbed landscapes. Functional traits are the specific characteristics of an organism. In the case of plants, these can be as expressed as drought tolerance, nutrient uptake efficiency, seed weight, and root architecture, which influence the ability to establish, grow, and reproduce under variable conditions (Díaz and Cabido, 2001; Lavorel and Garnier, 2002). These traits not only determine individual species' survival but also shape community assembly and ecosystem recovery. For example, species with high specific leaf area (SLA) may quickly exploit available light, while those with deep root systems can access water and nutrients from deeper soil layers – these are typically characterised as response traits. Functional traits also mediate interactions with the abiotic environment, such as improving soil structure through root activity or enhancing nutrient cycling via labile litter decomposition – also known as effect traits (De Kovel and Maas, 2004; Fischer and Lindenmayer, 2007).

Microbial communities play an equally critical role in facilitating recolonization by driving nutrient cycling, organic matter decomposition, and plant-microbe interactions. However, the microbial populations in borrow pits are often severely depleted due to the removal of topsoil and vegetation, further hindering recovery (Banerjee et al., 2020; Eilers et al., 2012). The absence of symbiotic relationships, such as those formed by mycorrhizal fungi, limits plant nutrient acquisition and resilience in nutrient-poor soils. This highlights the importance of fostering microbial recovery alongside plant recolonization to restore soil fertility and ecosystem function.

Another critical factor is microtopographic variability, which enhances site heterogeneity and creates diverse ecological niches. Features such as mounds, depressions, and exposed slopes can influence soil moisture, temperature, and light availability, thereby supporting a broader range of plant and microbial species (Ketcheson and Price, 2016; Richardson and Murphy, 2019). Studies have shown that microtopographic variation significantly impacts soil moisture distribution, with different landforms exhibiting varying levels of water retention and nutrient availability (Bo et al., 2014). For example, gentle terraces and gullies often retain more moisture than escarpments and exposed slopes, which experience higher evaporation rates. This variability creates microhabitats that promote functional diversity by accommodating species with varying traits, such as shade tolerance or water-use efficiency, and by providing refugia for stress-sensitive organisms (Moser et al., 2009). Additionally, research has highlighted that microtopographic features influence microbial diversity and nutrient cycling, thereby shaping ecosystem dynamics (Lemanceau et al., 2012). Incorporating microtopographic modifications into reclamation plans can therefore accelerate recovery and enhance biodiversity by improving soil water retention, fostering microbial integrity, and supporting plant species with different ecological strategies (Melnik et al., 2018). In the context of Northern Ontario, where soils are sandy, nutrient-poor, and prone to desiccation, plant communities must exhibit traits that enable them to cope with these stressors. Traits such as high drought tolerance, efficient nutrient use, and the ability to establish in low-organic-matter soils are critical for successful colonization. By focusing on both taxonomic diversity and functional trait diversity, this research aims to provide a deeper understanding of the processes driving ecosystem recovery in these borrow pits. Such insights are crucial for informing reclamation strategies that promote resilient plant communities capable of supporting long-term ecological functions.

Hypotheses

This study explores the natural recolonization processes occurring in abandoned borrow pits of Northeastern Ontario, focusing on both taxonomic and functional diversity. The following hypotheses reflect the anticipated effects of disturbance gradients, soil conditions, and functional traits on plant community assembly and ecological recovery.

Hypothesis 1: Disturbance Reduces Taxonomic and Functional Diversity

- Null Hypothesis (H_0): There is no significant difference in taxonomic and functional diversity among subzones (Interface Communities, Open Communities, Recent Remnant Communities, and True Remnant Communities) within borrow pits.
- Alternative Hypothesis (H_a): Taxonomic and functional diversity are significantly lower in Open Communities compared to other subzones, with True Remnant Communities exhibiting the highest diversity due to reduced disturbance and more stable microhabitats.

Hypothesis 2: Soil Properties Influence Community Composition

- Null Hypothesis (H_0): Soil properties (e.g., pH, organic matter, moisture, and nutrient levels) do not significantly influence plant community composition or functional trait distributions across subzones.
- Alternative Hypothesis (H_a): Soil properties significantly influence plant community composition and functional trait distributions, with higher soil fertility and moisture content in True Remnant and Interface Communities supporting greater taxonomic and functional diversity.

Hypothesis 3: Functional Traits Reflect Adaptive Strategies to Disturbance

- Null Hypothesis (H_0): Functional traits, such as specific leaf area (SLA), drought tolerance, and seed persistence, are not significantly associated with disturbance gradients or subzone type.
- Alternative Hypothesis (H_a): Functional traits are significantly associated with disturbance gradients, with stress-tolerant traits (e.g., low SLA, high seed persistence) dominating in Open Communities, while traits indicative of competitive strategies (e.g., high SLA, deep roots) are more prevalent in True Remnant and Interface Communities.

Methodology

This study investigates the processes of natural recolonization and the factors influencing recovery in abandoned borrow pits of Northeastern Ontario. The research adopts a field-based approach, integrating vegetation and soil surveys across 20 borrow pit sites, each varying in disturbance history, microtopography, and ecological conditions. The study design emphasizes the role of taxonomic and functional diversity in driving ecosystem recovery.

Study Sites

The study was conducted along the Highway 17 corridor, from Greater Sudbury to Sault Ste. Marie, Ontario. This region is characterized by a humid continental climate with warm summers (average July highs of 23–26°C) and cold, snowy winters (average January lows of -15 to -8°C). Annual precipitation ranges from 900 to 1,100 mm, with a significant proportion falling as snow (Environment Canada, 2024). The region’s coarse, siliceous soils, formed from glacial outwash, exhibit low fertility, poor organic matter content, and limited water retention (VandenBygaart and Protz, 1995; Meola et al., 2014).

The 20 study sites were selected based on criteria such as abandonment duration (minimum 20 years), absence of recent industrial activity, and designation as "legacy" pits by the Ontario Aggregate Resources Corporation (TOARC). Sites ranged in size from 0.5 to 10 hectares and showed no evidence of prior reclamation attempts or groundwater seepage. These criteria ensured that the study focused on natural recolonization processes in unmanaged sites.

Experimental Design and Sampling Protocol

Each site was divided into subzones based on microtopography and disturbance gradients, resulting in four distinct categories:

- Interface Communities (IC): Transitional zones between disturbed and undisturbed areas, typically influenced by edge effects.
- Open Communities (OC): Highly disturbed, barren zones with minimal vegetation and evidence of ongoing erosion or compaction.
- Recent Remnant Communities (RRC): Areas showing early-stage recolonization, often with sparse vegetation dominated by stress-tolerant species.
- True Remnant Communities (TRC): Undisturbed patches within the borrow pits that retain characteristics similar to adjacent forested areas.

Vegetation surveys were conducted during the peak growing seasons of 2021 and 2022 (June–August). Within each subzone, systematic transects were established, and 1 m^2 quadrats were placed at 5-meter intervals along these transects. In each quadrat, species richness, abundance, and evenness were recorded using a modified Braun-Blanquet scale. To capture site-level diversity, the Shannon diversity index and Effective Species Number (ESN) were calculated for each subzone. For functional diversity, species trait data were obtained from the Traits of Plants in Canada (TOPIC) database and supplemented with literature for missing values.

Soil samples were collected at 5-meter intervals along the same transects to a depth of 10 cm using a soil probe. In cases where soil texture was too coarse, a hand trowel was used to ensure consistent sample depth. Composite samples were created by combining four sequential subsamples to reduce variability and analytical costs. Soil parameters measured included:

- Physical Properties: Texture (sand, silt, clay), bulk density, and moisture content.
- Chemical Properties: pH, organic matter content (via Loss on Ignition), total Kjeldahl nitrogen (TKN), and total phosphorus (TP).

Functional Trait Analysis

Functional traits were analyzed to understand the adaptive strategies of plant species across subzones. Key traits included specific leaf area (SLA), leaf dry matter content (LDMC), drought tolerance, seed weight, seed persistence, root depth, and growth rate. These traits were aggregated using the Community Weighted Mean (CWM) approach to reflect the average trait values of each subzone, weighted by species abundance. Rao's Q, an index of functional diversity, was calculated to assess trait dispersion and community resilience.

Data Analysis

Species composition and functional diversity were analyzed using multivariate statistical techniques. Permutational Multivariate Analysis of Variance (PERMANOVA) was used to test for differences in species composition across subzones, while Principal Component Analysis (PCA) was employed to visualize patterns of community structure. Canonical Correspondence Analysis (CCA) was used to link vegetation composition to soil and site characteristics.

Functional diversity indices, including Rao's Q and CWM values, were compared across subzones to identify gradients of ecological recovery. Regression analyses were conducted to examine the relationships between functional traits, soil parameters, and site-level diversity metrics. All analyses were performed using the R statistical software environment, with data visualization achieved through custom plots.

Broader Implications

The ecological restoration of abandoned borrow pits is a critical challenge for sustainable land management in Northern Ontario. These sites, often barren and degraded, contribute to habitat loss, soil erosion, and diminished ecosystem services. This research provides insights into the processes driving recolonization and recovery, emphasizing both taxonomic and functional diversity as key indicators of ecological health and resilience. The findings hold significant implications for reclamation practices, environmental policy, and long-term land stewardship.

Understanding the drivers of plant community assembly in disturbed sites, including the role of functional traits and soil properties, is essential for developing more effective reclamation strategies. Traits which support drought tolerance, nutrient-use efficiency, and seed persistence are particularly relevant in nutrient-poor, sandy soils like those found in Northern Ontario (Díaz and Cabido, 2001; Lavorel and Garnier, 2002). By identifying the traits that enable successful colonization and persistence, this research informs the selection of species that can thrive under local conditions, promoting stable and self-sustaining ecosystems.

The implications extend beyond ecological theory to practical applications in reclamation. For example, the study highlights the importance of enhancing soil fertility and moisture retention through site-specific interventions, such as incorporating industrial residuals or creating microtopographic variability (Richardson and Murphy, 2019; Banerjee et al., 2020). These approaches can accelerate the establishment of diverse plant communities, improve soil stability, and enhance ecosystem functions such as carbon sequestration and water filtration (Lafleur et al., 2018).

From a policy perspective, the research underscores the need for tailored reclamation guidelines that account for regional differences in climate, soil conditions, and disturbance history. While programs like the Management of Abandoned Aggregate Properties (MAAP) have made strides in Southern Ontario, their relative ineffectiveness in Northern Ontario highlights the importance of adapting strategies to local contexts (TOARC, 2024). This study provides empirical evidence to support regionally specific policies and practices, ensuring that reclamation efforts are both efficient and effective.

The broader ecological benefits of successful reclamation include enhanced biodiversity, improved soil health, and increased resilience to environmental stressors. These outcomes not only restore ecosystem functionality but also provide societal benefits, such as recreational opportunities and aesthetic value. By bridging the gap between ecological restoration and sustainable resource management, this research contributes to a growing body of knowledge that supports long-term environmental and economic sustainability (Bradshaw, 2000; Palmer et al., 2014).

Ultimately, this study highlights the importance of integrating ecological theory with practical reclamation efforts to address the challenges of disturbed landscapes. Its findings offer a roadmap for reclaiming abandoned borrow pits, advancing sustainable land management practices, and promoting resilient ecosystems in the face of ongoing environmental change.

On the Use of Industrial Residuals to Improve Borrow Pit Soil Fertility

Background and Context

Degraded lands, particularly those left behind by industrial activities, pose significant ecological and economic challenges. Borrow pits, which are small, temporary excavation sites for sand and gravel, exemplify these disturbed landscapes. These sites are often abandoned after aggregate extraction, leaving barren parent material with poor soil quality, low fertility, and irregular topography (Gibbs and Salmon, 2015; Avis, 1984). Without intervention, natural recovery is hindered by limited nutrient availability, poor water retention, and inhospitable conditions for plant growth, likened to primary succession on glacial soils (Walker and Syers, 1997; Bradshaw, 1997; Řehounková and Prach, 2006).

The challenges of passive recovery in borrow pits are well-documented. Their coarse, glacially derived soils exhibit low cation exchange capacity and microbial activity, with rapid drainage and limited moisture retention further impeding plant establishment (Borgegard, 1990; Hugron et al., 2011; Peltzer et al., 2010). Addressing both structural and fertility limitations is therefore critical for successful reclamation.

Industrial residuals, such as lime-stabilized municipal biosolids (LSMB), pulp mill sludge (PMS), and biomass boiler fly ash (BBFA), offer promising solutions for soil reclamation (Zvomuya et al., 2007). These residuals provide unique benefits:

- Pulp Mill Sludge (PMS): Comprising fibrous organic matter and microbial biomass, PMS improves soil organic matter content, enhances water retention, and promotes microbial activity. Its ability to form stable aggregates supports soil structure, while its nutrient content directly benefits plant growth (Chantigny et al., 2000; Gagnon et al., 2001).
- Biomass Boiler Fly Ash (BBFA): A powdery byproduct of bioenergy production, BBFA acts as a potent liming agent due to its high calcium carbonate equivalency. It mitigates

soil acidity, supplies essential cations, and strengthens soil structure, although its hydrophilic nature may obstruct pore spaces in sandy soils (Etiégni and Campbell, 1991; Larney and Angers, 2012).

- Lime-Stabilized Municipal Biosolids (LSMB): A nutrient-rich amendment derived from treated sewage sludge, LSMB provides nitrogen, phosphorus, and trace elements. Its lime treatment elevates pH, immobilizes heavy metals, and reduces pathogen levels, making it a safe and effective soil conditioner (Walker Environmental, 2024; Carraro, 1997).

Despite extensive research on these residuals in agriculture and forestry, their application in borrow pit reclamation remains underexplored. By leveraging their chemical, physical, and biological benefits, this research aims to restore borrow pit soils, mitigate erosion, and create sustainable ecosystems capable of supporting long-term vegetation growth (Camberato et al., 2006; Petrova et al., 2022; Turner et al., 2022).

Hypotheses

The study was designed to evaluate the effectiveness of three industrial residuals—pulp mill sludge (PMS), lime-stabilized municipal biosolids (LSMB), and biomass boiler fly ash (BBFA)—in addressing the chemical, physical, and biological limitations of borrow pit soils. The following hypotheses focus on the core objectives of this research.

Hypothesis 1: Residuals Improve Soil Properties

- Null Hypothesis (H_0): Application of PMS, LSMB, or BBFA does not significantly alter the physical (e.g., water retention, bulk density), chemical (e.g., pH, CEC, nutrient content), or biological (e.g., organic matter content, microbial activity) properties of borrow pit soils.
- Alternative Hypothesis (H_a): Application of PMS, LSMB, or BBFA significantly enhances the physical, chemical, and biological properties of borrow pit soils, resulting in improved soil quality metrics.

Hypothesis 2: Residuals Enhance Plant Growth and Survival

- Null Hypothesis (H_0): Seedling growth (height, basal diameter, chlorophyll content) and survival rates are not significantly affected by soil amendments with PMS, LSMB, or BBFA.

- Alternative Hypothesis (H_a): Soil amendments with PMS, LSMB, or BBFA significantly increase seedling growth and survival rates, particularly under drought stress, by improving soil moisture retention and fertility.

Methodology

This research employed a greenhouse-based experimental design to evaluate the effectiveness of three industrial residuals—lime-stabilized municipal biosolids (LSMB), pulp mill sludge (PMS), and biomass boiler fly ash (BBFA)—in rehabilitating degraded borrow pit soils. These soils, characterized by coarse texture, low organic matter, and poor fertility, were amended with residuals at application rates informed by previous literature and site-specific conditions. Treatments included single and blended applications, designed to address both the structural and chemical limitations of borrow pit soils. For instance, PMS was applied at a rate of 290 Mg ha^{-1} to create a 1:1 gravel-to-residual layer at a 7.5 cm depth, while BBFA was incorporated at 20 Mg ha^{-1} based on its known efficacy in nutrient restoration. LSMB was applied at 15 Mg ha^{-1}, aligning with manufacturer recommendations for optimal soil conditioning.

The experiment was conducted in a controlled greenhouse environment in Greater Sudbury, Ontario, Canada, over a 20-week period. The greenhouse-maintained temperatures ranging from 6°C to 26°C and near-constant luminosity of 28,000 lux, simulating conditions favorable for seedling establishment. Borrow pit soil, classified as sand with 91% sand, 4% silt, and 5% clay, was sieved to remove stones before amendment and blended with residuals using a cement mixer to ensure homogeneity.

Seedlings of trembling aspen (*Populus tremuloides* Michx.) and yellow birch (*Betula alleghaniensis* Britt.) were selected for their ecological significance and contrasting growth strategies. Seedlings were grown in 700 mL styroblocks, with treatments replicated to minimize edge effects. Phase one of the trial, spanning the first 15 weeks, involved consistent watering and light exposure to evaluate growth under ideal conditions. Key metrics such as height, basal diameter, and chlorophyll content were recorded weekly, alongside qualitative health assessments using a standardized scale. Leachate samples were collected weekly to monitor nutrient and metal losses.

In phase two, beginning in week 16, watering was halted to simulate drought conditions, testing the residuals' capacity to enhance soil water retention and support seedling survival under stress. Soil volumetric water content (VWC) was monitored during this period, with a focus on the duration seedlings could maintain health above the permanent wilting point.

Data were analyzed using a combination of statistical and multivariate techniques to assess treatment effects on soil and plant metrics. Redundancy analysis (RDA) was used to identify significant soil parameters influencing seedling performance. Plant performance and soil fertility indices (PPI and SFI, respectively) were calculated by standardizing and weighting growth and soil variables, providing integrated scores for treatment evaluation. All analyses were performed using R statistical software, with results visualized through tailored graphics to ensure clarity.

Broader Implications

The reclamation of borrow pits represents a critical challenge in mitigating the environmental legacies of industrial development. These degraded landscapes, characterized by poor soil structure and low fertility, require targeted interventions to restore ecological functionality (Walker and Syers, 1997; Hugron et al., 2011). This research directly addresses this need by exploring the potential of industrial residuals to rehabilitate borrow pit soils, contributing to both scientific understanding and practical solutions in land reclamation.

The use of industrial residuals such as pulp mill sludge (PMS), lime-stabilized municipal biosolids (LSMB), and biomass boiler fly ash (BBFA) aligns with principles of sustainable waste management and circular economy. By repurposing these byproducts as soil amendments, this study not only diverts waste from landfills but also provides a cost-effective alternative to synthetic fertilizers and amendments (Larney and Angers, 2012; Turner et al., 2022). This approach has the potential to enhance the ecological sustainability of industrial operations, particularly in regions where these residuals are abundantly available (Camberato et al., 2006; Walker Environmental, 2024).

The broader ecological benefits of this work extend to improving soil health and plant biodiversity in areas that would otherwise remain barren. Enhanced soil organic matter, nutrient cycling, and water retention contribute to more resilient ecosystems capable of supporting diverse plant and microbial communities (Chantigny et al., 2000; Gagnon et al., 2001). Moreover, this research informs best practices for using these residuals in disturbed landscapes, balancing effective soil improvement with environmental safeguards, such as minimizing nutrient leaching and heavy metal mobilization (Etiégni and Campbell, 1991; Pöykiö et al., 2015).

From a policy perspective, this study supports the development of guidelines for the application of industrial residuals in land reclamation. It provides empirical evidence to refine application rates, blending strategies, and monitoring frameworks, ensuring that reclamation efforts meet both environmental and regulatory standards (Stupak et al., 2008; CCME, 2004). This work also highlights the scalability of these amendments for use in other degraded landscapes, such as post-mining sites or deforested areas (Bradshaw, 1997; Petrova et al., 2022).

Ultimately, this research bridges the gap between waste management and ecological restoration, demonstrating how industrial byproducts can be harnessed to address critical environmental challenges. Its findings hold the potential to advance reclamation practices, promote sustainable resource use, and contribute to the long-term recovery of disturbed ecosystems (Larney and Angers, 2012; Turner et al., 2022).

On the Use of Industrial Residuals to Treat Acid and Metal Toxic Glacial Soils

Background and Context

The Greater Sudbury region, located in Ontario, Canada, has a long and storied history of mining that has left an indelible mark on its landscapes and ecosystems. The discovery of significant copper and nickel sulfide deposits in the late 19th century initiated a mining boom, with smelting operations becoming a cornerstone of the region's economy (Petrus et al., 2015). However, the mining practices of the time relied on rudimentary and environmentally destructive technologies. Early smelting processes, including the infamous roast yards, involved burning sulfide-rich ores in open pits fueled by vast amounts of cordwood, releasing sulfur dioxide (SO_2) and heavy metals into the environment (Symington and Hutchinson, 1998). These practices not only devastated local forests through deforestation but also introduced harmful pollutants into the soil, water, and air, leading to severe ecological degradation (Freedman and Hutchinson, 1980; Munton and Temby, 2015).

Over the course of a century, Greater Sudbury's mining operations released an estimated 100 million tonnes of SO_2 into the atmosphere, alongside significant quantities of nickel and copper (Potvin and Negustanti, 1995). The release of SO_2 and subsequent acid rain profoundly altered the region's environment. Acidic precipitation, formed when sulfur dioxide reacts with atmospheric water vapor, caused widespread acidification of soils, leaching essential nutrients such as calcium and magnesium while increasing the solubility of toxic metals like aluminum, nickel, and copper (Driscoll et al., 2003; Hutchinson and Whitby, 1977). These conditions created a hostile environment for plant life, leading to large-scale die-offs, loss of canopy cover, and exposure of mineral soils and bedrock. Approximately 82,000 hectares of Sudbury's original mixed-wood forest were severely degraded, with one-third of this area completely denuded and devoid of vegetation (Winterhalder, 1996).

The societal and ecological impacts of this degradation were profound. While mining brought economic prosperity and urban development, it also left a legacy of poor air quality, toxic soils, and devastated landscapes. Public outcry and mounting evidence of transboundary acid rain impacts prompted regulatory responses in the 1970s, including Canada's Clean Air Act and the construction of the 380-meter Superstack, which helped disperse emissions and reduce localized pollution (Gunn et al., 1995; Lynch et al., 2000). Advances in smelting technology, including the removal of pyrrhotite and the implementation of scrubbers, led to a 99% reduction in SO_2 emissions by the early 21st century, laying the groundwork for large-scale reclamation efforts (Carmichael, 2018).

Reclamation efforts in Sudbury began in earnest in the late 1970s with the City of Greater Sudbury Regreening Program, which developed a standardized protocol to mitigate soil acidity and metal toxicity. This "Recipe" involved the application of dolomitic limestone and fertilizers, seeding of grasses and legumes to stabilize soil, and large-scale planting of coniferous trees like red and jack pine (City of Greater Sudbury, 2020). These efforts successfully revegetated more than 3,000 hectares of barren land, increasing canopy cover and improving soil stability (Mchale and Winterhalder, 1996; City of Greater Sudbury, 2023).

However, while these methods proved effective in moist, low-lying areas, upland and sloped landscapes have shown markedly different response profiles. These areas, characterized by steep gradients, thin soil layers, and higher erosion rates, remain challenging to reclaim (Rayfield et al., 2005; Winterhalder, 1996). The combination of acidic, nutrient-poor soils and the absence of significant organic matter has limited natural recolonization, even decades after treatment. Unlike low-lying areas, which retain moisture and benefit from nutrient deposition, uplands often exhibit severe drought stress and reduced microbial activity, further hindering plant establishment (Hazlett et al., 2020; Chan-Yam et al., 2024).

A cornerstone of this study is the exploration of novel soil amendments to address these persistent deficits. Industrial residuals, including lime-stabilized municipal biosolids (LSMB), pulp mill sludge (PMS), and biomass boiler fly ash (BBFA), are examined for their potential to improve soil properties and accelerate ecological recovery. These amendments provide distinct benefits:

- Lime-Stabilized Municipal Biosolids (LSMB): Rich in organic matter and macronutrients like nitrogen and phosphorus, LSMB neutralizes soil acidity and supplies essential nutrients for plant growth (Walker Environmental, 2024). The lime treatment further immobilizes heavy metals, reducing toxicity and improving soil pH.

- Pulp Mill Sludge (PMS): A fibrous byproduct of the paper industry, PMS enhances soil organic matter and water retention while promoting microbial activity. Its structural properties help improve soil aggregation, a critical factor in upland reclamation (Chantigny et al., 2000; Gagnon et al., 2001).

- Biomass Boiler Fly Ash (BBFA): A liming agent derived from bioenergy production, BBFA increases pH and supplies calcium and potassium. However, its fine texture can lead to compaction if not carefully incorporated (Etiégni and Campbell, 1991).

These amendments not only address the chemical and physical limitations of upland soils but also contribute to the development of soil organic matter, a key driver of long-term ecological recovery. By improving soil fertility, structure, and microbial activity, they create conditions more conducive to plant establishment and growth.

The unique challenges of upland and sloped areas underscore the need for targeted reclamation strategies that integrate these novel amendments with planting regimes designed to enhance soil health and biodiversity. By exploring the interactions between soil amendments, plant functional traits, and site-specific conditions, this research aims to provide a framework for sustainable reclamation practices that can be applied to Sudbury and other mining-impacted regions.

Hypotheses

This study investigates the use of industrial residuals as soil amendments to improve soil properties and foster ecological recovery in upland and sloped landscapes. The hypotheses address the potential effects of these treatments on soil chemistry, plant community dynamics, and ecological resilience.

Hypothesis 1: Soil Amendments Improve Upland Soil Properties

- Null Hypothesis (H_0): The application of lime-stabilized municipal biosolids (LSMB), pulp mill sludge (PMS), or biomass boiler fly ash (BBFA) does not significantly alter soil pH, organic matter content, or nutrient availability in upland and sloped soils.
- Alternative Hypothesis (H_a): Soil amendments significantly improve soil pH, organic matter content, and nutrient availability, creating conditions more conducive to plant establishment and growth.

Hypothesis 2: Soil Amendments Enhance Plant Growth and Survival

- Null Hypothesis (H_0): The application of soil amendments does not significantly affect tree seedling growth, survival rates, or physiological health compared to untreated soils.
- Alternative Hypothesis (H_a): The application of soil amendments significantly enhances tree seedling growth, survival rates, and physiological health, particularly under the stress conditions characteristic of upland and sloped areas.

Methodology

This study evaluated the use of industrial residuals as soil amendments to improve soil properties and promote ecological recovery in upland and sloped landscapes of the Greater Sudbury region. These challenging environments, characterized by acidic soils, nutrient deficits, and severe erosion, required novel approaches to reclamation.

Study Area and Site Selection

The study was conducted at two sites: a semi-barren sandy outwash near the Glencore Falconbridge smelter and a rocky, sloped site in Coniston. These sites represented the diverse yet degraded conditions typical of Sudbury's mining-impacted landscapes. Pre-treatment soil analyses revealed highly acidic conditions (pH 3.0–4.5) and elevated concentrations of copper and nickel, indicative of the legacy of smelting operations.

Experimental Design and Treatments

A randomized block design was employed, with five blocks per site. Each block contained eight treatment plots measuring 5×10 meters, resulting in 40 plots per site and 80 plots in total. Each 5×10-meter plot was further subdivided into two 5×5 meter subplots to assess variations in tree planting regimes and increase replication. Treatments were randomly assigned within each block to account for spatial variability.

The eight treatments included:

- Control: No amendments applied.
- Dolostone and Fertilizer (LF): 10 t/ha dolostone combined with 400 kg/ha of 6-24-24 NPK fertilizer, representing the standard Sudbury regreening protocol.
- Lime-Stabilized Municipal Biosolids (LSMB): Applied at two rates, 20 t/ha and 40 t/ha, to assess the effects of organic matter enrichment and pH adjustment.
- Blended Pulp Mill Sludge (PMS): Sulfite-derived pulp sludge applied at 73.6 t/ha to improve soil organic matter and microbial activity.
- Biomass Boiler Fly Ash (BBFA): Applied at 20 t/ha as a liming agent and source of calcium and potassium.
- Blended Treatments (PMS + BBFA): Sulfite sludge combined with fly ash to evaluate potential synergistic effects.

Application and Sampling Procedures

Residuals were applied between May and June 2019 using a staggered schedule. Materials were manually distributed across the plots using 5-gallon pails and garden rakes, ensuring even coverage. Application rates were calculated to deliver consistent nutrient inputs and match the nitrogen levels of current practices (approximately 120 g N per plot). Safety protocols, including the use of gloves and masks, were observed to manage exposure to the materials.

Baseline soil and vegetation surveys were conducted prior to amendment application. Soil samples were collected from each subplot using a soil corer to a depth of 10 cm, with composite samples created by pooling subsamples taken in a W-pattern. These samples were analyzed for pH, organic matter, bulk density, and nutrient content. Pre-treatment vegetation surveys recorded species composition and percent cover using a modified Braun-Blanquet scale.

Tree Planting and Monitoring

To assess plant growth responses, three tree species—Pinus banksiana (jack pine), Quercus rubra (red oak), and Betula alleghaniensis (yellow birch)—were planted within each 5×10-meter plot. Seedlings were grown in a greenhouse for ten weeks prior to planting. Jack pine and yellow birch were planted in spring 2020, while red oak was planted in fall 2020 to minimize transplant shock during summer months. Seedlings were monitored biannually for three growing seasons, with parameters including survival rate, stem height, chlorophyll content, and overall health recorded.

<u>Broader Implications</u>

The reclamation of upland and sloped landscapes in the Greater Sudbury region represents a critical challenge in addressing the long-term environmental impacts of historical mining activities. These areas, characterized by severe soil degradation, limited vegetation, and high erosion rates, have proven resistant to traditional reclamation approaches. This study's exploration of industrial residuals as soil amendments provides valuable insights into innovative methods for restoring ecological function and resilience in these challenging environments.

The use of amendments such as lime-stabilized municipal biosolids (LSMB), pulp mill sludge (PMS), and biomass boiler fly ash (BBFA) aligns with principles of sustainable waste management and circular economy. By repurposing these byproducts, this research offers a dual benefit: diverting waste from landfills and addressing critical soil limitations in degraded landscapes (Walker Environmental, 2024; Larney and Angers, 2012). These materials address multiple ecological barriers simultaneously—improving soil pH, enhancing organic matter content, and increasing nutrient availability—while also fostering microbial activity and soil structure development. As a result, they create conditions more conducive to plant establishment, growth, and long-term ecosystem recovery (Chantigny et al., 2000; Gagnon et al., 2001).

The findings of this research hold significant practical implications for land management and reclamation policy. The distinct response profiles observed in upland and sloped areas underscore the need for targeted, site-specific strategies rather than a one-size-fits-all approach. For example, while conventional dolostone and fertilizer treatments have shown success in low-lying, moist areas, the unique properties of industrial residuals may make them more effective in environments with low moisture retention and high erosion potential (Rayfield et al., 2015; Winterhalder, 1996). This study provides empirical evidence to support the incorporation of these materials into reclamation protocols, potentially informing updates to the City of Greater Sudbury Regreening Program and similar initiatives elsewhere (City of Greater Sudbury, 2023).

From an ecological perspective, the research highlights the importance of soil organic matter in driving long-term recovery processes. By enhancing soil fertility and microbial activity, amendments like PMS and LSMB address one of the most persistent challenges in upland reclamation: the lack of functional organic horizons (Preston et al., 2020; Hazlett et al., 2020). This has broader implications for biodiversity conservation, as improved soil conditions can support more diverse and resilient plant communities. Furthermore, the use of tree species with complementary functional traits, such as red oak (Quercus rubra) and yellow birch (Betula alleghaniensis), can help rebuild mixed-species forests that provide greater ecological stability and structural complexity compared to monoculture plantations (Parsons et al., 1990; Alexander and Arthur, 2014).

The study also contributes to the broader discourse on ecosystem restoration in post-industrial landscapes. Its findings align with global best practices promoted by organizations such as the Society for Ecological Restoration, emphasizing the integration of science-based, adaptive management approaches. By addressing both immediate soil limitations and longer-term ecological processes, this research offers a scalable framework for restoring other mining-impacted regions around the world (Society for Ecological Restoration, 2024).

Ultimately, this research bridges the gap between theory and practice in land reclamation, demonstrating how the strategic use of industrial byproducts can address persistent ecological challenges in degraded landscapes. The findings not only advance the scientific understanding of soil amendments and plant-soil interactions but also provide actionable insights for policymakers, land managers, and practitioners working to restore degraded ecosystems and promote sustainable land use.

Chapter 2

Literature Review

Soil Organic Matter

Soil organic matter (SOM) is a fundamental component of soil, encompassing a diverse range of materials including plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by soil microorganisms (Schnitzer and Khan, 2013). As an integral part of soil, SOM contributes significantly to its structure, fertility, and overall quality. While soil is composed of minerals, air, water, and organic matter, the latter, particularly SOM, plays a crucial role in maintaining the biological health of soil, the turnover of plant essential nutrients, and the long-term sequestration of carbon (Torn et al., 2009; Adamczyk et al., 2020; Meurer et al., 2020). SOM enhances soil structure, improves water retention and aeration, increases nutrient availability, and supports a diverse and active microbial community (Doley et al., 2020).

The formation of SOM is a complex process involving the decomposition of plant and animal materials by soil microorganisms (e.g., bacteria, fungi), along with contributions from soil fauna (e.g., earthworms, mites), plant inputs (e.g., root exudates, litter quality), chemical processes (e.g., humification, mineral adsorption), and environmental factors (e.g., temperature, moisture) that influence stabilization and accumulation (Lange et al., 2015; Liang et al., 2017). This process begins with the breakdown of larger organic materials into smaller, simpler compounds, followed by the microbial synthesis of these compounds into more complex forms of organic matter (Six et al. 2002). This breakdown involves multiple stages: litter fall and root exudation, where plants shed leaves, stems, and roots, and release exudates into the soil; decomposition, where soil microorganisms such as bacteria and fungi break down organic materials through enzymatic processes (Cotrufo et al. 2013; Robertson et al. 2018); and humification, where decomposed materials are further transformed into humus, a stable form of organic matter that resists further decomposition (Hayes and Swift, 2020).

As reviewed by Haddix et al. (2020), several factors influence the rate and extent of SOM formation. Climate plays a significant role, with warm and moist conditions generally enhancing decomposition rates, leading to faster SOM formation, while cold and dry conditions slow down the process (Burket et al. 1989). Soil texture also affects SOM formation; soils with higher clay content tend to protect organic matter from decomposition, promoting SOM accumulation. Clay soils protect organic matter from decomposition due to their large surface area, negative charge, and ability to form stable organomineral complexes (Plante et al., 2006; Hassink and Whitmore, 1997). The fine texture and elevated water retention of clay create conditions that limit microbial accessibility and enzymatic activity, thereby promoting SOM accumulation (Hassink et al. 1993). Vegetation contributes to the quality and quantity of SOM through the production of organic residues such as leaves, stems, roots, and root exudates (Bahadori et al., 2021). Different plant species produce residues with varying chemical compositions, affecting how quickly and efficiently these materials are decomposed and integrated into the soil (Millar et al., 1936, Gunina and Kyzakov 2022). For instance, residues from legumes and other nitrogen-fixing plants tend to be high in nitrogen and decompose rapidly, enriching the soil with easily accessible nutrients. In contrast, residues from woody plants and grasses often contain more lignin and cellulose, which decompose more slowly and contribute to the buildup of more stable organic matter fractions (Malý et al. 2014, Wang and Wang 2011). The amount of organic residue produced by vegetation is also crucial. High biomass-producing plants contribute large quantities of organic material, enhancing SOM levels more effectively than plants with low biomass production (Aranda and Oyonarte, 2005). Root systems further influence SOM dynamics: deep-rooted plants can transport organic matter deeper into the soil profile, enhancing SOM distribution throughout the soil layers. Additionally, root exudates, organic compounds secreted by plant roots, feed soil microorganisms, promoting microbial activity and further contributing to SOM formation (Jobbágy and Jackson, 2000). Additionally, management practices such as organic amendments (Githongo et al., 2023), reforestation (Shao et al., 2019; Veldkamp et al., 2020), cover cropping (Martínez-García et al., 2018), and reduced tillage (Mikha and Rice, 2004) can enhance SOM formation by increasing organic inputs and minimizing soil disturbance.

The decomposition of SOM is driven by microbial activity (Yang and Tong, 2005; Vicena et al., 2022), which is influenced by several factors. Temperature and moisture (Sierra et al., 2015), oxygen availability (Fruit et al., 1999), soil pH (Russell and Appleyard, 1917), and the quality of organic inputs (Millar et al., 1936) all play crucial roles in determining the rate and efficiency of microbial decomposition processes. Higher temperatures generally increase microbial activity, accelerating decomposition, while adequate moisture is necessary for microbial processes, although excessive water can create anaerobic conditions that slow decomposition. Oxygen availability is another critical factor, with aerobic conditions promoting faster decomposition compared to anaerobic conditions. Soil pH also plays a role, with neutral to slightly acidic pH levels being optimal for most decomposers, while extreme pH levels can inhibit microbial activity.

Achieving a balance in SOM decomposition is crucial for maintaining soil health. Promoting sufficient decomposition ensures organic matter is broken down and incorporated into the soil as SOM, while preventing excessive decomposition helps retain and stabilize SOM, supporting long-term soil fertility and structure. Conversely, when decomposition leads to total mineralization, organic matter is completely broken down into inorganic nutrients and CO_2 (Dijkstra and Cheng, 2007; Sierra et al., 2015). This can happen when microbial activity is excessively high due to optimal conditions such as warm temperatures, high moisture, and abundant oxygen (A'Bear et al., 2014). Under these conditions, microorganisms rapidly metabolize organic matter, breaking it down fully into its inorganic components (Pietikäinen et al., 2005; Banerjee et al., 2016). This process not only releases CO_2 into the atmosphere, contributing to greenhouse gas emissions, but also depletes the soil of organic matter, leading to reduced soil structure, water retention, and nutrient availability (Berg and Matzner, 1997; Gunina and Kuzyakov, 2022). Otherwise, such imbalances can also be due to a decline in inputs: decreased plant productivity results in lower input of plant residues and root exudates, leading to a decline in SOM content if decomposition rates remain high. This reduction in organic inputs is a primary driver for the depletion of SOM over time (Bauer and Black, 1994). Mineralization thus results in the loss of the beneficial effects of SOM, emphasizing the need for balanced decomposition processes in soil management.

SOM is pivotal in the environment, providing numerous ecosystem services and benefits. It plays a crucial role in nutrient cycling, serving as a reservoir of essential nutrients such as nitrogen, phosphorus, and sulfur, which are slowly released for plant uptake (Comerford et al., 2013). SOM improves soil structure by promoting the formation of soil aggregates, enhancing soil porosity and aeration (Cotrufo et al., 2010). It also increases the soil's capacity to retain water, reducing erosion and improving drought resistance. Additionally, SOM acts as a carbon sink, mitigating climate change by storing carbon that would otherwise be released into the atmosphere (Lal, 2013). High SOM levels enhance soil fertility and support ecological restoration efforts, making it easier to reestablish native vegetation and improve ecosystem health (Hoffland et al., 2020). By improving soil structure and water retention, SOM helps prevent soil erosion, protecting natural habitats and reducing sedimentation in waterways (Bauer and Black, 1994; Tahát et al., 2020).

Soil Organic Matter Degradation and Loss

The loss of SOM and topsoil is a growing global concern, with significant implications for environmental health, ecological restoration, and climate stability. According to estimates, the world loses around 24 billion tonnes of fertile soil each year due to erosion, with an annual economic loss of approximately $400 billion USD (Borrelli et al., 2017). The Food and Agriculture Organization (FAO) also reports that one-third of the world's soil is moderately to highly degraded, affecting about 1.5 billion people globally. This is supported by Jie et al. (2002) who estimates that soil degradation is a widespread issue affecting approximately 22% of the world's cropland, pasture, forest, and woodland. The authors highlight this degradation is driven by inappropriate agricultural practices, overgrazing, deforestation, and urbanization. Soil erosion, chemical deterioration, and physical degradation are significant components of this problem as well, all of which contribute to the loss of SOM (Karlen and Rice, 2015). Regions particularly affected by soil degradation include sub-Saharan Africa, South Asia, and Latin America, where soil erosion and nutrient depletion pose significant threats to ecosystem health and livelihoods (Liu et al., 2018).

The absence or degradation of SOM can have severe consequences for ecosystems. Given SOM is a major component of the global carbon cycle, containing more carbon than the atmosphere and terrestrial vegetation combined, its degradation releases significant amounts of CO2, contributing to climate change. Soil erosion alone can cause the emission of 0.8-1.2 Pg C/year globally (Lal, 2003; Lal, 2009). The decline in SOM adversely affects soil fertility, structure, water retention, and biodiversity. This degradation compromises the soil's ability to support plant growth and regulate essential ecosystem services such as water filtration and nutrient cycling (Sprunger, 2023). A long-term study examining logging in Quebec and Ontario found that extensive commercial logging has significantly degraded boreal forests, affecting both biodiversity and soil health (Mackey et al. 2023). The conversion of diverse, older forests to younger, monoculture stands reduces labile organic matter inputs from diverse plant species, further depleting SOM. The authors also note that logging activities in these regions have also impacted the habitat of woodland caribou, a species that relies on older forest stands. The reduction in older forests, which contribute significant amounts of organic matter to the soil, has not only affected caribou populations but also the soil ecosystems that depend on continuous organic inputs. The cumulative area of recently logged forest in Quebec and Ontario amounts to over 14 million hectares, with substantial portions of these areas experiencing severe SOM loss (Mackey et al. 2023).

The global loss of topsoil and SOM poses serious risks to environmental health, ecological restoration, and climate stability. Addressing this issue requires a concerted effort to implement sustainable land management practices, restore degraded soils, and enhance SOM levels.

Soil Organic Matter Recovery

The recovery of Soil Organic Matter (SOM) is a critical component of ecological restoration. There are two primary approaches to SOM recovery: passive and active. Passive restoration relies on natural processes to rebuild SOM over time, while active restoration involves direct interventions to accelerate SOM accumulation.

Passive restoration involves allowing SOM to build up naturally without direct human intervention. This approach depends on natural ecological processes such as litter fall, root exudation, and microbial decomposition to gradually increase SOM levels (Restrepo et al. 2013; León and Osorio, 2014; Roa-Fuentes et al., 2015). For example, Čugunovs (2018) compared SOM accumulation in actively vs. passively restored Finnish Boreal Forest stands which had undergone consistent fire disturbance and harvest. He found that actively managed sites (e.g., clear cut, prescribed burns) accumulated humic SOM more quickly, but with lower totals. Additionally, their plant community structure was quite homogenous and resembled more mature stands – bringing into question their ecological integrity. Passive stands accumulated SOM much more slowly (estimated to require centuries to reach pre-disturbance levels), but with greater potential totals. Their community structure was dominated by early successional tree species (e.g., *Betula* sp.), highlighting more traditional seral development.

The natural accumulation of SOM can take several decades to centuries, depending on factors such as climate, soil type, and the extent of prior disturbance (Čugunovs, 2018; Kalinina et al., 2019). During this recovery period, disturbed soils near human populations may be at risk of increased erosion, reduced water quality, and decreased biodiversity (Baumhardt et al., 2015; Obalum et al., 2017; Sprunger, 2023). However, passive restoration is often cited as being cost-effective as it relies on natural processes, reducing the need for external inputs (Prach and del Moral, 2015; Brancalion et al., 2016). However, the slow rate of SOM accumulation can be a significant drawback, especially in areas with severe soil degradation. In fact, Zahawi et al. (2014) highlights "hidden costs" associated with passive restoration. While this method is initially cheaper, it involves both direct and indirect costs that can accumulate over time. Longer recovery times, potential for project failure, and additional costs for site vigilance and fencing can offset the lower initial costs of passive restoration. Furthermore, passive restoration may not be sufficient in highly disturbed or contaminated sites where natural recovery processes are impeded. Human activities such as urban and industrial development, agriculture, and deforestation can prevent the natural buildup of SOM by disrupting soil structure, reducing vegetation cover, and introducing pollutants. These disturbances can lead to soil erosion, compaction, and degradation, making it challenging for SOM to accumulate naturally.

A case study from surface mines in the Great Lakes region illustrates these challenges. The study evaluated the restoration progress of three former surface mines in this region, where initial reclamation was followed by passive management for 7, 28, and 35 years. The initial reclamation included grading, soil compaction, and planting fast-growing herbaceous species, followed by passive management. Over the 35-year period, restoration of native forest species was slow and inconsistent. Most of the woody plants that established were invasive species, which hindered the reestablishment of native forest. The degraded soil conditions and the presence of invasive species significantly impeded natural recovery processes, indicating that passive restoration alone was insufficient to restore the site to its original native forest composition due to severe soil and ecosystem alteration. Soil properties remained poor with low organic matter content, further delaying the restoration of a healthy forest ecosystem. This study emphasizes the need for active management interventions in highly disturbed sites to control invasive species and support the establishment of native plants to achieve desired ecological outcomes (Ruggles et al., 2021). Passive restoration can fail in environments subjected to continued anthropogenic disturbances, pollution, and adverse climatic conditions. Effective restoration of SOM in these contexts often requires active interventions such as pollution remediation, reforestation, and soil amendments to support natural recovery processes.

Active restoration involves direct interventions to accelerate SOM accumulation. Common techniques for revitalizing SOM production include reforestation and afforestation, planting native trees and shrubs to enhance SOM through increased litter fall and root biomass (Fernandes et al., 1997). Reduced tillage minimizes soil disturbance, helping to maintain soil structure and promote the natural buildup of SOM (Watson et al., 2002). Cover cropping during fallow periods adds organic residues to the soil, enhancing SOM levels (Paul, 1984). This approach also includes the application of organic amendments, such as compost, manure, and biosolids, to boost SOM levels more rapidly than natural processes alone (Bertora et al., 2009; Diacono and Montemurro, 2010). Common sources of SOM for active restoration include organic amendments like compost, animal manure, municipal biosolids, and green waste (Diacono and Montemurro, 2010; Wortman et al., 2017; Urra et al., 2019). These materials provide a rich source of organic matter and nutrients to support SOM buildup. Organic amendments can be applied through various methods, including top-dressing, where organic material is spread on the soil surface; incorporation, where organic material is mixed into the soil using tillage; and spraying, where liquid organic amendments are applied using spray equipment. This method can significantly shorten the time required to rebuild SOM, providing immediate improvements in soil health and productivity. Widowati et al. (2020) applied biochar (pyrolyzed organic matter) to sandy corn field soils and saw immediate and long-lasting improvements to SOM content and overall soil fertility. Such materials are particularly useful in severely degraded soils where natural recovery processes are insufficient. However, the cost of acquiring and applying organic amendments can be high, and improper application can lead to issues such as nutrient imbalances, soil contamination, and negative impacts on water quality. For example, a study in the Ozark Highlands demonstrated that repeated annual applications of broiler litter significantly increased nutrient and metal concentrations in runoff water, highlighting the potential for environmental harm in regions with sensitive topography (McMullen et al., 2014). Price et al. (2010) demonstrated that the application of alkaline stabilized biosolids to agricultural soils contributed to the overall mineralized nitrogen pool, which could potentially lead to nitrate leaching and impact water quality in the long term.

Both passive and active restoration approaches have their merits and challenges. Passive restoration is cost-effective and relies on natural processes, but it can be slow and insufficient for severely degraded sites. Active restoration attempts to quickly provide improvements in SOM levels and soil health, but it requires careful management and can be costly. The choice between passive and active restoration should be based on site-specific conditions, restoration goals, and available resources. By understanding the strengths and limitations of each approach, practitioners can develop effective strategies to restore SOM and promote sustainable land management.

Recolonization and Hierarchical Filters

Effective ecological restoration is centered on understanding ecosystem dynamics and removing barriers that impede natural recovery processes (Gann et al., 2019). This approach advocates for restoration practices that facilitate recolonization by creating conditions where ecosystems can self-organize and recover their functionality. Restoration is not merely about replanting native species; it involves restoring the ecological processes that sustain these species. This comprehensive framework includes engaging stakeholders, utilizing diverse knowledge sources, and establishing clear, measurable goals for ecosystem recovery.

Restoration should aim to modify physical, chemical, and biological barriers that hinder natural processes – or hierarchical filters. The concept of hierarchical filters is crucial for understanding how ecosystems recover and recolonize. Hierarchical filters refer to various layers of environmental and biological factors that influence the establishment, survival, and growth of species within an ecosystem (Lavorel and Garnier, 2002). Hierarchical filters can be categorized into several types: abiotic filters, biotic filters, and anthropogenic filters. These filters operate at different spatial and temporal scales, including climatic conditions, soil properties, hydrological regimes, and biotic interactions such as competition, predation, and symbiosis. Abiotic filters include non-living environmental factors such as climate, soil texture, and hydrology. For example, soil pH, moisture levels, and nutrient availability are crucial abiotic filters that determine which species can establish and thrive in a given area. Biotic filters encompass interactions among living organisms, such as competition for resources, predation, and mutualistic relationships. For example, the presence of keystone species or dominant competitors can significantly shape community structure (Rudgers and Clay, 2008; Smith, 2006). Anthropogenic filters, stemming from human activities, impact ecosystem recovery through land-use changes, pollution, introduction of invasive species, and habitat fragmentation. Example of filter modifications can involve actions such as eliminating invasive species that compete with native flora and fauna, mitigating pollution that affects soil and water quality, restoring natural hydrology to support wetland and riparian ecosystems, or reestablishing connectivity between fragmented habitats to facilitate species migration and genetic flow (Koch et al., 2021). The ultimate goal is to create an environment where natural processes can prevail, leading to the self-sustaining recovery of ecosystems.

Understanding hierarchical filters is essential for restoration practitioners as it helps identify and address the specific barriers that need to be removed to facilitate recolonization. For instance, if soil compaction is identified as a limiting abiotic filter, restoration efforts might focus on soil aeration techniques to improve root penetration and water infiltration (Hulvey and Aigner, 2014). Similarly, if invasive species are a significant biotic filter, targeted removal or control measures may be necessary to allow native species to reestablish (Theoharides and Dukes, 2007; Teixeira et al., 2017). Effective restoration requires a multi-scale approach that considers the interplay of hierarchical filters. This involves conducting thorough site assessments to identify the key abiotic, biotic, and anthropogenic filters affecting the site, implementing adaptive management strategies that can respond to ongoing changes and new information about the filters at play, and engaging local communities and stakeholders to understand socio-economic filters and ensure that restoration efforts are sustainable and supported by those who live and work in the area. A successful example of this approach can be seen in the restoration of Dyke Marsh Preserve in Virginia, USA, where hierarchical filters were addressed to improve restoration outcomes. Soil aeration was used to alleviate compaction, and invasive species were managed to facilitate the reestablishment of native vegetation. The project also involved hydrologic modeling to restore natural water flow and extensive stakeholder engagement to ensure the sustainability of the restoration efforts. This comprehensive approach significantly increased confidence in the decision-making process by focusing on the most critical ecological, social, and economic aspects of the project (Hopfensperger et al., 2006).

Practitioners must emphasize the importance of removing barriers to natural processes to enable recolonization. The concept of hierarchical filters provides a framework for understanding the complex interactions that influence ecosystem recovery. By addressing these filters through targeted restoration actions, practitioners can create conditions that support the recolonization and long-term resilience of ecosystems.

Recolonization in the Absence of Soil Organic Matter

Succession is a fundamental ecological process that describes the progressive changes in species composition, structure, and ecosystem function over time following a disturbance (Shugart, 2013). This process occurs in a series of stages, each characterized by different communities of plants, animals, and microorganisms (Tscherko et al., 2005). Succession is driven by the interactions between species and their environment, as well as by external factors such as climate and human activities (Horn, 1974). Succession can be categorized into two main types: primary and secondary. Primary succession occurs on newly exposed or created substrates that have no prior biological legacy, such as bare rock, sand dunes, or areas left by retreating glaciers. This type of succession begins with the colonization of pioneer species, which are typically hardy, stress-tolerant organisms capable of withstanding harsh conditions. These pioneers modify the environment, making it more hospitable for subsequent species (Shure and Ragsdale, 1977). Over time, a series of successional stages lead to the development of a mature, stable ecosystem, known as a climax community. Secondary succession takes place in areas where a disturbance, such as fire, flooding, or human activities, has disrupted an existing ecosystem but left behind some biological legacy, such as soil and seed banks. Secondary succession generally proceeds more quickly than primary succession because the soil already contains the nutrients and microorganisms necessary for plant growth. Early successional species quickly colonize the disturbed area, followed by more competitive, longer-lived species that eventually lead to the formation of a climax community (Heydari et al., 2014).

Succession is driven by several key mechanisms. Facilitation involves early successional species modifying the environment in ways that make it more suitable for other species. For example, pioneer plants may fix nitrogen or improve soil structure, enabling other species to establish (Walker and Clarkson, 2003). Inhibition occurs when certain species inhibit the establishment and growth of other species through competition for resources, production of allelopathic chemicals, or other means (Muller, 1966). Tolerance is seen in species that are more tolerant of the conditions found in later successional stages and can outcompete early successional species as the environment changes (Connell and Slatyer, 1977). Periodic disturbances can also reset successional processes, maintaining diversity and preventing any one species from becoming overly dominant. For example, a study in the Pacific Northwest of the United States examined how managing disturbance regimes can help maintain biological diversity in forest ecosystems. The study found that disturbances such as fire and harvesting create functional heterogeneity, which promotes high species richness and diversity. This is achieved by preventing competitive exclusion and maintaining a mosaic of different successional stages, each supporting various species (Odion and Sarr, 2007). By understanding and applying disturbance principles, forest managers can enhance biodiversity and ecosystem resilience.

In ecosystems lacking soil organic matter, spurring succession can be particularly challenging as SOM plays a crucial role in supporting plant growth and ecosystem development (Fageria, 2012). Without sufficient SOM, the early stages of succession may be slow or incomplete, perhaps mimicking primary forms of succession. Recolonization without SOM is typically slow and limited to species that are highly tolerant of poor soil conditions (Chapin et al., 1994). The lack of SOM can prolong the recolonization process significantly, often taking several decades or even centuries for a stable plant community to develop. This slow recovery can leave ecosystems vulnerable to erosion, further degradation, and the invasion of opportunistic, often undesirable species (Lal, 2015). For instance, a study conducted in northeastern British Columbia, Canada, examined the response of a trembling aspen (*Populus tremuloides* Michx.) plant community to organic matter removal and soil compaction. The study found that removal of the forest floor and organic matter significantly altered species diversity and composition, favoring ruderal species over bud-banking species. This indicates that the absence of SOM can lead to substantial changes in plant community dynamics and further complicates the restoration efforts (Haeussler and Kabzems, 2005).

However, through active restoration efforts, such as the addition of organic amendments, restoration professionals can accelerate succession by improving soil conditions and facilitating the establishment of pioneer species (Sutton-Grier et al., 2009). Understanding and facilitating succession can significantly enhance the effectiveness of restoration efforts, particularly in environments lacking SOM. By addressing the initial barriers to succession, such as poor soil conditions, and supporting the establishment of pioneer species, restoration practitioners can promote the recolonization and long-term resilience of ecosystems.

Novel Ecosystems Emerging from Disturbance

Novel communities, or novel ecosystems, arise following significant anthropogenic disturbances that create environmental conditions differing markedly from historical or "reference" ecosystems (Hobbs et al, 2013). These disturbances, such as deforestation, urbanization, pollution, and climate change, alter the physical and biological environment in ways that preclude the return of traditional ecosystems. For instance, a study conducted in the Swiss Rhone Valley examined how historical forest uses, including forest litter collecting and wood pasture, created novel ecosystems that differ significantly from traditional forest ecosystems. These practices altered the forest structure, composition, and function, leading to long-term changes which preclude the return to historical conditions. The study highlighted the profound and lasting impact of anthropogenic disturbances on forest ecosystems, demonstrating the creation of novel ecosystems with unique characteristics (Gimmi et al., 2008). Consequently, novel communities are composed of both native and non-native species that adapt to these new conditions, forming species combinations that have not previously coexisted. These novel communities emerge because anthropogenic disturbances fundamentally change the landscape and its ecological processes. Land-use changes like urban development, agriculture, and industrial activities transform landscapes, introduce new species, and eliminate others (Barnagaud et al., 2014). Climate change shifts temperature and precipitation patterns, favoring different species assemblages. Human activities facilitate the introduction and spread of invasive species, which establish themselves and become dominant in the new conditions. Altered disturbance regimes, such as changes in fire frequency, water flow, and nutrient cycling, disrupt traditional ecosystem processes, allowing novel species to thrive. For instance, climate change has been shown to significantly influence the distribution and performance of both native and non-native species, with non-native species often benefiting more from the new conditions (Sorte et al., 2013). Additionally, human activities like deforestation, urbanization, and agriculture facilitate the spread of invasive species, which can alter forest composition and structure (Dukes et al., 2009). Changes in climate and disturbance regimes also promote the dominance of invasive species by providing favorable conditions for their growth and spread, as seen in marine ecosystems where ocean warming facilitates the invasion of non-native species (Stachowicz et al., 2002).

While novel communities are often perceived as degraded or less valuable compared to reference communities, this perspective is increasingly challenged. Novel communities can provide unique ecosystem services, which are the benefits that humans derive from ecosystems. For example, the concept of ecosystem services highlights how even modified ecosystems can offer significant benefits, such as air filtration, climate regulation, and recreational opportunities, enhancing the quality of life in urban areas (Bolund and Hunhammar, 1999). Furthermore, the recognition of nature's contributions to people emphasizes the diverse ways humans benefit from ecosystems, whether through cultural, provisioning, or regulatory services (Kadykalo et al., 2019). Novel ecosystems, therefore, should be valued for their potential to support human well-being and sustainability (Mandle et al., 2020). These services are crucial for supporting human life and well-being and are categorized into four main types: provisioning, regulating, cultural, and supporting services. Provisioning services include the production of food, water, fuel, and other resources. For example, ecosystems support and enhance human life through providing ecosystem services such as food and freshwater, which are essential for human survival (Geneletti et al., 2015). Regulating services, which include climate regulation, flood control, and water purification, are equally critical for maintaining the stability of our environment (Schowalter et al., 2018). Cultural services provide non-material benefits, such as recreation and spiritual enrichment, contributing significantly to human well-being (Hirons et al., 2016). Supporting services, such as soil formation, nutrient cycling, and primary production, underpin all other ecosystem services and are vital for ecosystem health and resilience (Udawatta et al., 2017). Novel communities can contribute to local food production and provide raw materials. Regulating services, which manage natural processes, include climate regulation, flood control, and disease regulation. Novel ecosystems can help manage stormwater in urban areas, sequester carbon, and control erosion. Cultural services encompass recreational, aesthetic, and spiritual benefits. Novel ecosystems often become valued green spaces in urban areas, providing recreational opportunities and enhancing quality of life. Supporting services are necessary for the production of all other ecosystem services, such as soil formation, nutrient cycling, and primary production. Novel ecosystems can contribute to soil health and biodiversity, supporting overall ecosystem functioning. For instance, local food production is a critical provisioning service, with urban gardening and farming helping to secure food supplies in cities (Smith et al., 2013). Regulating services like climate regulation and flood control are vital for maintaining environmental stability and mitigating the impacts of urbanization (Orwin et al., 2015). Additionally, cultural services provided by green spaces enhance urban living by offering aesthetic and recreational benefits (O'Riordan et al., 2021).

Examples of novel communities include urban green spaces, post-industrial landscapes, and regions where agriculture has been abandoned. Cities often have novel ecosystems in parks, vacant lots, and green roofs, supporting a mix of native and non-native species and providing habitats for urban wildlife and recreational spaces for residents. Former industrial sites, such as abandoned mines and factories, often develop novel communities rich in biodiversity, supporting species that thrive in disturbed conditions. In regions where agriculture has been abandoned, novel communities can form as native and non-native species colonize the fields, developing new habitats that support wildlife and promote ecosystem services like carbon sequestration and soil restoration. For instance, the development of novel ecosystems on post-industrial landscapes has shown significant increases in plant diversity and ecosystem functioning over time (Salisbury et al., 2020). Additionally, the reforestation of tropical pastures with a mix of native and non-native species has led to enhanced carbon sequestration and improved plant community dynamics (Silver et al., 2004). Similarly, in abandoned agricultural lands, the restoration of grassland biodiversity has been shown to accelerate soil carbon sequestration and support soil health (Yang et al., 2019).

Novel communities should not be discarded or viewed as inherently less valuable than reference communities for several reasons. They are often better adapted to current environmental conditions than reference communities, which may no longer be viable due to significant changes. They provide essential ecosystem services that support human well-being and ecological resilience. Novel ecosystems can support unique biodiversity, including species that may not survive in traditional ecosystems. Additionally, these communities can be more resilient to further environmental changes, providing stability and ongoing ecosystem services.

However, novel communities must still maintain elevated levels of plant diversity to maximize their ecological functions and benefits. High plant diversity within these ecosystems enhances their resilience, supports a broader range of wildlife, and stabilizes ecosystem functions such as nutrient cycling, soil formation, and carbon sequestration. Even though the species composition and plant structures in novel communities may differ from those in reference ecosystems, they can still provide similar levels of ecosystem services. For example, research has shown that plant diversity in novel forests can maintain ecosystem processes, including productivity, carbon storage, and nutrient cycling, even after the decline of native species (Mascaro et al., 2012). Similarly, biodiversity in urban ecosystems has been found to increase ecosystem functions and support services such as soil multifunctionality and organic carbon stocks (Schittko et al., 2022). In another study, enhancing plant diversity on green roofs improved ecosystem multifunctionality, providing benefits such as stormwater retention, thermal regulation, and carbon sequestration (Lundholm, 2015).

When juxtaposing an urban lawn and a novel cultivated wildflower zone, one can identify several potential differences in ecosystem service provision. An urban lawn, typically consisting of a single or few grass species, offers limited biodiversity and ecosystem services. Lawns require significant maintenance, including watering, mowing, and fertilizing, yet provide minimal habitat for wildlife, low nutrient cycling, but may provide elevated aesthetic or recreational value. In contrast, a cultivated wildflower zone in an urban setting supports a wide variety of plant species, attracting pollinators such as bees and butterflies, enhancing soil health through diverse root structures, and improving water infiltration and retention. These wildflower zones require less maintenance than traditional lawns, reduce urban heat islands, and provide aesthetic benefits to residents, but may reduce recreational opportunities. The increased plant diversity in these zones contributes to higher resilience against pests and diseases and offers more robust ecosystem services compared to monoculture lawns. For instance, a study highlighted how wildflower meadows in urban areas can significantly increase biodiversity and ecosystem services, providing habitat for pollinators and enhancing soil quality (Bretzel et al., 2016). Similarly, wildflower strips in agricultural landscapes have been shown to enhance pollinator visitation and provide ecosystem services such as erosion control and nutrient cycling (Xavier et al., 2017). Additionally, integrating wildflower zones in urban settings can improve biodiversity and ecosystem functionality, supporting a wide range of services from recreational benefits to climate regulation (Lin et al., 2015).

Maintaining elevated levels of plant diversity in novel communities not only supports the stability and functionality of these ecosystems but also ensures they continue to provide valuable ecosystem services comparable to those of reference ecosystems. Recognizing and integrating the ecological value of novel communities into conservation and restoration strategies can significantly enhance environmental resilience and human well-being in a rapidly changing world.

Characterizing Passive Colonization Through Taxonomic and Functional Means

Researchers employ a variety of statistical methods to study recolonization and succession in disturbed environments, focusing particularly on diversity indices to understand plant community dynamics. Traditional measures of species diversity, such as species richness and evenness, provide a basic understanding of biodiversity by counting the number of species and their relative abundances within a community (e.g., Shannon Diversity Index). Principal Component Analysis (PCA) and Non-metric Multidimensional Scaling (NMDS) are used to reduce the complexity of ecological data and highlight the main factors explaining variability in plant communities. These techniques help visualize successional trajectories and the relationships between species and environmental variables. Furthermore, cluster analysis and dissimilarity indices groups and quantify similar sampling units based on species composition, enabling researchers to identify distinct successional stages and novel community (e.g., k-means and Bray-Curtis Dissimilarity)

While these measures are straightforward and widely used, they do not capture the functional roles that different species play within an ecosystem, making them less informative for understanding ecosystem processes and resilience. In contrast, functional diversity considers the variety of functional traits present within a community, offering a deeper insight into how ecosystems operate and respond to changes. Plant functional traits are morphological, physiological, or phenological characteristics that influence plant performance and ecosystem processes (Pérez-Harguindeguy et al., 2013). These traits, such as leaf area, root depth, and flowering time, determine how plants respond to environmental factors and how they affect ecosystem functions like carbon sequestration, nutrient cycling, and soil formation (e.g., *response* traits). In contrast, *effect* traits such as leaf litter quality, biomass production, and canopy structure, determine how plants influence ecosystem processes, affecting functions like carbon storage, nutrient availability, and habitat formation. For example, plant functional traits play a crucial role in carbon accumulation in forest ecosystems, influencing plant carbon, soil carbon, and microbial carbon, which are integral components of the global carbon cycle (Rawat et al., 2015). Additionally, the beginnings of standardized approaches (e.g., TRY, TOPIC, and GLOPNET) to measuring these traits globally have been essential for understanding ecological and evolutionary patterns and processes, facilitating predictions about plant and ecosystem responses to environmental changes (Pérez-Harguindeguy et al., 2013). Moreover, the functional trait ecology framework has highlighted the significance of these traits in linking species richness to ecosystem functional diversity and in predicting the impact of environmental changes on ecosystem processes (Kattge et al., 2011). Common functional traits include specific leaf area (SLA) (measured as cm^2 g^{-1}), which affects photosynthetic capacity and nutrient cycling; leaf dry matter content (LDMC), which influences decomposition rates and nutrient retention; and leaf nitrogen content, which impacts photosynthesis and growth rates. Root traits, such as root length density and root diameter, affect water and nutrient uptake efficiency and soil stability. Reproductive traits, including seed size, dispersal mechanisms, and flowering time, influence plant reproduction, colonization, and species interactions. Growth traits, such as plant height and biomass allocation, determine competition, light capture, and overall productivity. These traits, such as leaf area, root depth, and flowering time, determine how plants respond to environmental factors and how they affect ecosystem functions like carbon sequestration, nutrient cycling, and soil formation (Hodgson et al., 2011; Yan, 2009; Wang et al., 2022).

Understanding these functional traits is crucial because they directly impact ecosystem functions such as primary production, nutrient cycling, and resilience to disturbances (de Bello et al., 2010). By focusing on functional traits, researchers can predict how changes in community composition will affect ecosystem processes, providing a more comprehensive picture of ecosystem health and functionality. For example, functional traits have been shown to influence multiple ecosystem services through their effects on underlying ecosystem processes (Díaz et al., 2013). Additionally, plant functional traits are useful for characterizing variation in community and ecosystem dynamics, such as nutrient cycling and primary productivity (McCary and Schmitz, 2021). The community functional composition in restored ecosystems is often influenced by the prevailing environmental conditions, which in turn affects ecosystem functioning (Zirbel et al., 2017). Functional diversity offers several advantages over traditional indices of species diversity. It is closely linked to ecosystem processes, ensuring a wider range of ecological roles and processes are maintained, promoting ecosystem stability and productivity (Mouillot et al., 2011). Ecosystems with high functional diversity are generally more resilient to environmental changes and disturbances, arising from the presence of species with different responses to stressors, ensuring that some species can maintain function under changing conditions (Mori et al., 2013). Functional diversity can better predict ecosystem responses to environmental changes, management interventions, and conservation strategies than species richness alone, providing insights into how ecosystem services might be affected by biodiversity loss or climate change (Cadotte et al., 2011).

To calculate functional diversity, researchers often use metrics such as Community Weighted Mean (CWM) and Rao's Quadratic Entropy (Rao's Q). CWM calculates the average value of a functional trait in a community, weighted by the relative abundance of each species. It provides a measure of the dominant functional traits in a community and is useful for understanding how trait distributions shift in response to environmental changes. For example, CWM has been shown to effectively summarize shifts in mean trait values within communities due to environmental selection for certain functional traits (Ricotta and Moretti, 2011). Meanwhile, Rao's Q measures the functional diversity based on multiple traits and considers both species abundance and the differences among species (Botta-Dukát, 2005). This index is particularly useful for analyzing patterns of trait convergence or divergence in a given species assemblage (Van der Linden et al., 2016). The calculation for CWM is given by:

$$CWM = \sum (p_i \times t_i)$$

where p_i is the relative abundance of species i and t_i is the trait value of species i.

Rao's Q is a more comprehensive measure that considers both the abundance and functional dissimilarity of species within a community, integrating information on species' functional traits and their pairwise differences, providing a multidimensional view of functional diversity. Rao's Q is particularly useful for comparing functional diversity across different communities and understanding the impacts of species loss on ecosystem functioning. The calculation for Rao's Q is given by:

$$Rao's\ Q = \sum_{i=1}^{S} \sum_{j=1}^{S} p_i p_j d_{ij}$$

where S is the total number of species, p_i and p_j are the relative abundances of species i and j, and d_{ij} is the functional dissimilarity between species i and j.

While traditional measures of species diversity provide valuable information about the number and relative abundance of species, they fall short in capturing the functional roles that species play within ecosystems. Functional diversity, which considers the variety of functional traits present in a community, offers a deeper and more informative understanding of ecosystem health and resilience. By focusing on plant functional traits and using metrics like CWM and Rao's Q, researchers can gain insights into the roles different species play within ecosystems and how these roles contribute to overall ecosystem resilience and stability. Understanding and measuring functional diversity is thus crucial for effective ecosystem management and conservation.

Chapter 3

Title: Functional and Taxonomic Diversity in Abandoned Borrow Pits of Northeastern Ontario: Influences of Human Disturbance and Natural Recovery

Authors: Jonathan Lavigne

Abstract:

This study examines the recolonization processes within abandoned sand and gravel pits along the Highway 17 corridor in Northeastern Ontario, focusing on both taxonomic and functional diversity. The research explores how human disturbance, microtopography, and soil quality impact the establishment and structure of plant communities. Four distinct subzones—Interface Communities (IC), Open Communities (OC), True Remnant Communities (TRC), and Recent Remnant Communities (RRC)—were identified and analyzed for species composition, soil characteristics, and functional traits. Results indicated that undisturbed subzones (TRC and RRC) supported more diverse and predominantly native plant communities compared to the frequently disturbed OC subzones, which were characterized by low diversity and the presence of stress-tolerant, often non-native species. IC subzones exhibited a gradient of characteristics influenced by their proximity to adjacent forests, demonstrating how natural interfaces can foster higher

biodiversity. The findings underscore the ecological benefits of limiting human disturbance and enhancing microtopographic variability to promote successful reclamation. Recommendations include the use of industrial residuals for soil enhancement and strategic site modifications, such as mounding and microtopographic diversity, to create conditions that support natural colonization and biodiversity. The study's insights contribute to more sustainable land management practices that balance ecological recovery with community use.

Introduction

Aggregate mines extract materials such as sand, gravel, and rock for use in construction and infrastructure development. In Ontario, Canada, the history of these mines are closely tied to the region's extensive infrastructure development as it necessitated large quantities of these materials in the construction of road and rail beds (Avis, 1984). The extraction process, however, often leaves a significant environmental footprint. The removal of vegetation and topsoil disrupts local ecosystems, leading to soil erosion, habitat loss, and alterations in hydrology (Wilk and Szarek-Łukaszewska, 2020; Gillies and Sharratt, 2008). Further, negative environmental impacts of continuous soil removal from sand and gravel pits includes landslides, erosion, flooding, and vegetation loss (Owolabi et al., 2020).

Over time, these disturbances may create challenging conditions for natural recovery and active revegetation. Passive recolonization, the process by which disturbed lands are recolonized by native and non-native species over time without direct human intervention, offers a promising approach to understanding and addressing the ecological impacts of sand and gravel pits (Hugron et al., 2011). Characterizing the recolonization process in these areas is crucial for several reasons, encompassing both ecological and practical considerations. Given the ecological impacts of these mines can be significant, studying the recolonization process helps identify successful colonizers and their environmental interactions, which is essential for restoring ecosystem functions such as soil stabilization, water filtration, and habitat provision (Hugron et al., 2011). Informed management practices are another significant benefit of understanding recolonization. Insights into natural succession patterns and influencing factors can guide management by identifying keystone species, predicting successional trajectories, and optimizing resource allocation (Montoya et al., 2012). Understanding their processes of recolonization (e.g., resource allocation) may inform restorationists seeking to regreen these disturbed sites. Indeed, successful recolonization can enhance biodiversity, contributing to the overall health and resilience of ecosystems (Benayas et al., 2009).

Passive recolonization provides a cost-effective and sustainable method for the rehabilitation of disturbed sites (Bradshaw, 2000; Tropek et al., 2012). Compared to active restoration methods, recolonization offers a cost-effective solution for land reclamation. Understanding these processes can reduce restoration costs by minimizing the need for expensive planting and soil amendments (Bradshaw, 2000). By allowing natural processes to take place, these reclaimed lands can support a variety of ecosystem functions without the high costs associated with active restoration methods (Wang et al., 2017). Passive recolonization can significantly enhance biodiversity and ecosystem services, contributing to overall ecosystem resilience (Yu et al., 2020). Additionally, colonizing ecosystems can provide valuable services such as carbon sequestration, flood mitigation, and recreational opportunities (Setiawan et al., 2021).

However, little is known of the recolonization processes in these sites – simply allowing the site to regreen may lead to unintended consequences (e.g., domination by exotic plants, arrested successional development). Gaining this knowledge allows for the efficient use of resources, focusing efforts on areas where recolonization is slow or facing significant barriers (Young, 2000). Understanding the negative impacts of disturbance is a critical aspect of studying recolonization. Here, we can assess and mitigate soil degradation by determining how well native species respond to and perhaps improve soil structure and fertility over time. This research also aids in managing invasive species by understanding their impact on recolonization and informing strategies to control their spread (Mehta et al., 2008). By characterizing recolonization, we can promote sustainable practices and advocate for policies supporting its use as a viable restoration strategy (Souza et al., 2021). Such research can also help develop standards and guidelines, establishing benchmarks for successful recolonization and guiding future reclamation projects (Smith and Sullivan, 2012).

To fully understand the dynamics of recolonization, it is important to consider not just the taxonomic diversity – the variety of species present – but also the functional traits of the plants involved. Plant functional traits are specific characteristics that influence a plant's growth, reproduction, and survival. Traits influencing drought tolerance, nutrient uptake efficiency, and sunlight capture are particularly relevant in the harsh conditions of reclaimed sand and gravel pits (Díaz and Cabido, 2001; Lavorel and Garnier, 2002). Incorporating a quantitative assessment of functional diversity into reclamation studies allows for a deeper understanding of how plant communities develop and persist in disturbed environments, providing insights into the ecological roles and interactions of different species (De Kovel and Maas, 2004).

The process of recolonization within aggregate mines in the northeastern Ontario region presents unique challenges. This region's colder climate and shorter growing season result in fewer degree days, which can slow plant growth and reduce the establishment success (Baer et al., 2002). Additionally, the siliceous, coarse-textured, glacial soil of this region generally exhibit low fertility due to poor nutrient and moisture retention, lower organic matter content, and adverse effects on microbial communities, all of which are critical for soil health and fertility, which support recolonization (Harrison et al., 1994; Harrison et al., 2003; Lazzaro et al., 2009; Meola et al., 2014; Kim et al., 2017; Zimmerman and Horn, 2020). Despite efforts by provincial agencies, such as the Ontario Aggregate Resources Corporation (TOARC), to reclaim these sites through earthworks and the hydroseeding of native grasses and legumes, many of these northern pits remain sparsely vegetated and dominated by hardy, often invasive, species many decades following such treatments (McLachlan and Bazely, 2003). In contrast, this organization has apparently had much greater success in Southern Ontario, where pits are regularly regreened to achieve a variety of post-use cases (TOARC, 2024). Understanding why these sites lag in recolonization compared to their southern counterparts is critical for improving future reclamation efforts.

This study aims to investigate the recolonization processes occurring within borrow pits of this region, focusing on both taxonomic and functional diversity. By identifying specific traits that enable species to colonize these challenging environments, we begin to understand how recolonization is occurring. Additionally, we aim to identify the factors that may be hindering recolonization, such as climate, soil quality, and ongoing human disturbance. We hypothesize recolonization is lagging in these sites due to a combination of these factors. We expect that the plant species successfully invading these sites will exhibit traits that enable them to manage or avoid stressors associated with nutrient scarcity and drought.

Understanding the processes driving recolonization in borrow pits is essential for developing effective reclamation strategies. This study not only provides insights into the specific challenges and opportunities associated with recolonization in northeastern Ontario but also offers broader implications for land reclamation in similar environments. By examining the functional traits of colonizing species, we can identify the key factors that support successful plant colonization and inform management practices that enhance ecological recovery. Ultimately, our findings will contribute to more sustainable and effective approaches to reclaiming disturbed lands, ensuring that they provide ecological, economic, and social benefits over the long term (Fischer and Lindenmayer, 2007; Palmer, Filoso, and Fanelli, 2014).

Methods

This study focuses on smaller (<10 ha) sand and gravel pits, also known as borrow pits, which are largely abandoned, privately owned, and are currently undergoing recolonization. We conducted a survey of vegetation and soil across 20 abandoned borrow pits along the Highway 17 corridor, spanning from Greater Sudbury, ON, to Sault Ste. Marie, ON. This region is characterized by a humid continental climate, typified by four distinct seasons. Summers are generally warm and humid, with average high temperatures in July ranging from 23°C to 26°C. Winters are cold and snowy, with January average lows between -15°C and -8°C. The annual precipitation is approximately 900 to 1100 mm, with a significant proportion falling as snow from November to March (Environment Canada, 2024).

There are currently 556 licensed sand and gravel pits in the Greater Sudbury and Algoma districts, disturbing a total area of 19,136.9 hectares. Additionally, 809 abandoned gravel pits are catalogued in these regions, with 98.2% showing no signs of groundwater seepage (TOARC, 2024). Site selection was based on the following criteria: TOARC designation as “legacy” (privately owned, abandoned, unable or unwilling to regreen), total disturbed area between 0.5 and 10 hectares, at least 20 years since original excavation, no evidence of recent industrial-scale excavation, no evidence of groundwater seepage, can be used recreationally or undergoing small-scale extraction, and no prior revegetation attempts. Initially, over 50 sites were visited to identify the final selection (Fig. 1).

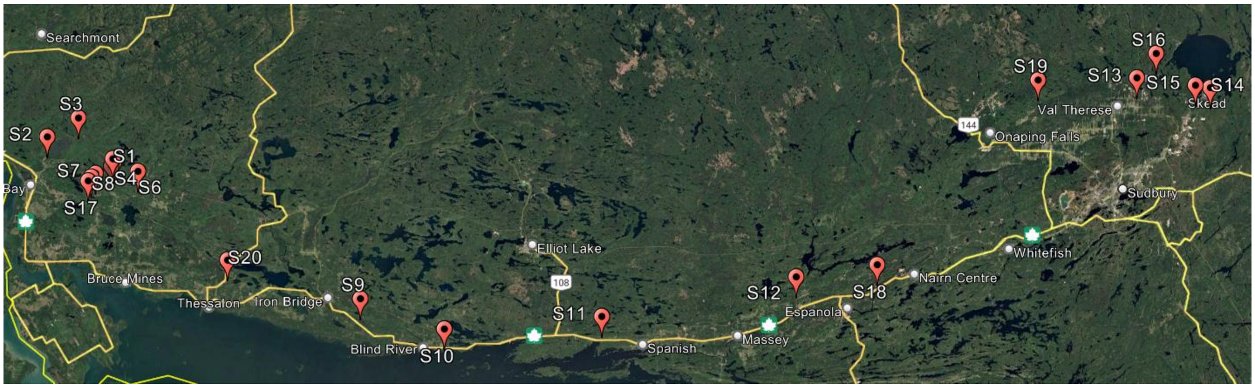

Figure 2 - Map of study sites surveyed in Chapter 2, illustrating the locations of 20 abandoned borrow pits across Northeastern Ontario, Canada, along the Highway 17 corridor from the Greater Sudbury area to the eastern shores of Lake Superior. Each site (labeled S1 through S20) represents a unique study location selected based on criteria including site abandonment duration, surrounding vegetation, and lack of recent industrial activity. This spatial distribution highlights the variation in environmental conditions and disturbance histories across the sampled sites, enabling a comprehensive assessment of recolonization and soil reclamation potential in disturbed glacial soils.

Experimental Design and Vegetation Sampling

Site sampling was conducted during the peak growing seasons of June to August (2021 and 2022). Each borrow pit was divided into three subsampling zones where applicable: the forest-disturbance interface (IC), open barren zones (OC), and undisturbed or "remnant" zones (RC) – the latter being further divided into 2 sub-zones: true undisturbed zones: (TRC) where no evidence of extraction or disturbance could be found, but was located within the overall perturbed area; and recent undisturbed zones (RRC) where the area was historically disturbed by extraction, but has largely been left to passively revegetate since. These zones were initially identified using satellite imagery and confirmed on-site. When surveying vegetation, we walked along each sub-zone in a straight line, placing a 1 m² quadrat every 5 m, using a Garmin GPSMAP 67 device with an accuracy of ± 2 me. The 5-m spacing was chosen to balance sampling effort and coverage. At each quadrat, we recorded a GPS point and assessed species richness and evenness using a modified Braun-Blanquet scale. Diversity was calculated using the Shannon index. This procedure continued until the end of the zone, or a return to the starting point for the interface zone. To equalize sample counts, parallel lines were run when needed, maintaining a 5-m distance from the original line. Relative abundance was calculated for each species and sub-zone by dividing the total observations per species by the total sampling area.

Soil samples were collected from each subzone when present: IC, TRC, RRC, and OC. The sampling methodology paralleled the protocol employed for vegetation surveys, with some modifications in spacing and collection techniques. Soil surveys were conducted concurrently with vegetation surveys, with samples taken every 5 m along the transect. Each soil sample was extracted using a standard metal soil probe to a depth of 10 cm, collecting approximately 70 cm^3 of soil. When soil texture was too coarse for the probe, a hand trowel was used to manually reach the required depth. Composite samples were created by combining parallel samples in sets of 4 (20 m). In larger plots, the number of individual soil samples could be substantial, making compositing a practical approach to reduce labor and laboratory costs (Fig. 2).

For IC subzones, an additional perpendicular transect sampling approach was employed. Perpendicular transects were systematically established every 20 m or, at a minimum, in four cardinal directions (North, South, West, and East) per site, ensuring a comprehensive representation of the soil conditions across the study areas. Sampling began 3 m within the undisturbed stand, extending to the edge of the IC zone. Samples were collected at 1-m intervals along these transects. In the TRC, RRC, and OC subzones, the soil sampling methodology was consistent with the approach used for the IC subzones, with the exception of the perpendicular transect sampling (Fig. 3)

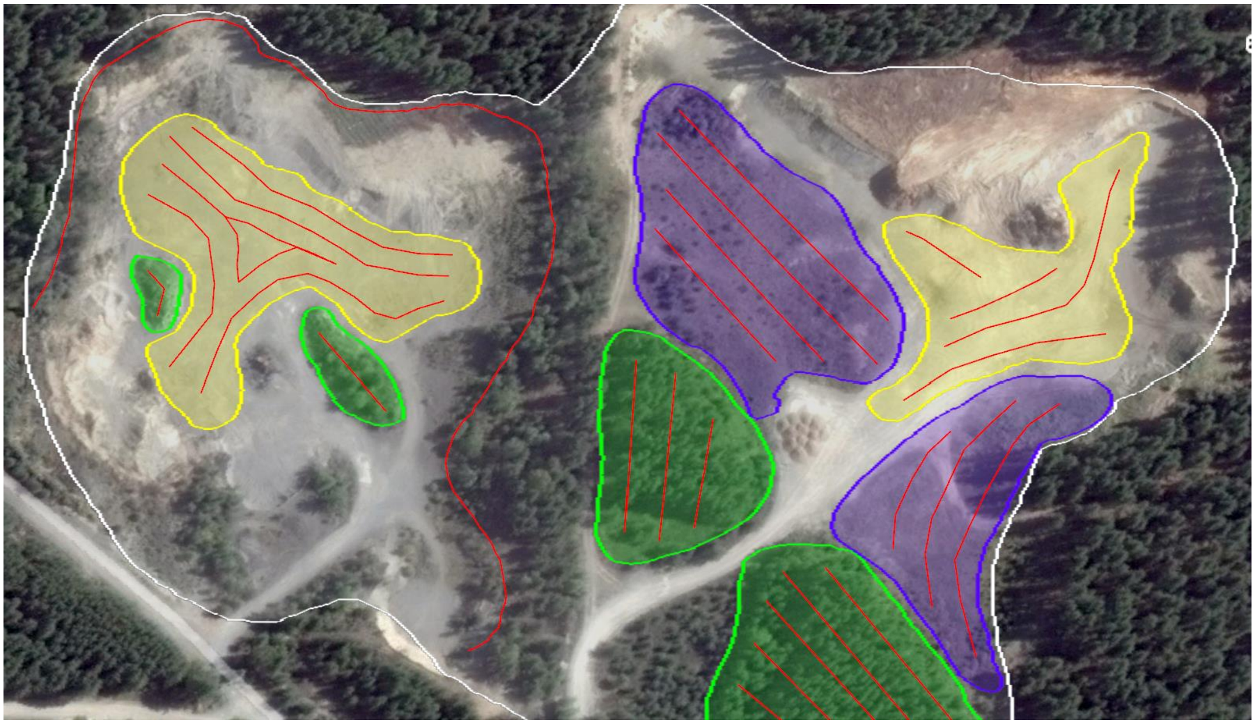

Figure 2 - Map of site zones and microhabitat delineations for vegetation sampling of a borrow pit. The colored polygons represent distinct microhabitat zones: yellow for OC subzones, purple for RRC subzones, and green for TRC subzones, the white area roughly representing an IC subzone as well as the site as whole. Red lines within each zone indicate the orientation of transects for sampling quadrats

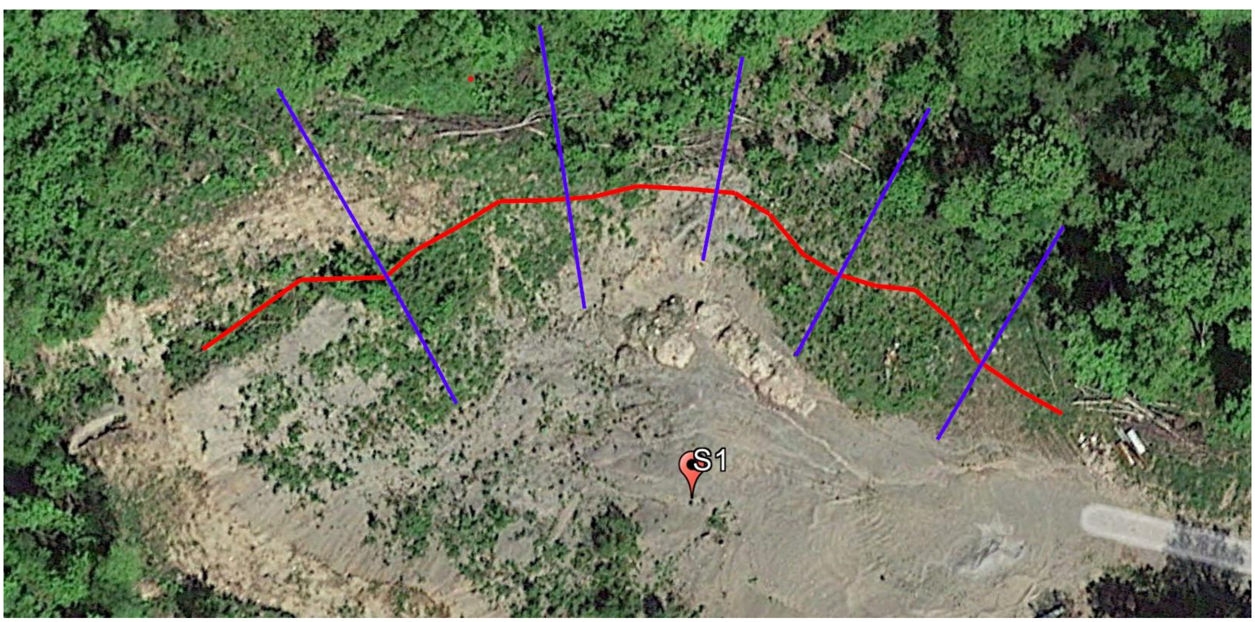

Figure 3 - Site S1 showing the composite sampling procedure an IC subzone. The red line marks the disturbance interface, separating the densely vegetated surrounding forest from the exposed pit area. Purple lines indicate the transects along which sampling quadrats were placed, extending from the disturbance interface into the barren zones of the pit.

Soil Assessments

Field analysis of soil texture was conducted using the hand-texture method, a quick and practical technique for estimating the proportions of sand, silt, and clay. The procedure began with moistening a small sample of soil to achieve a workable consistency. The soil was then pressed between the thumb and forefinger to form a ribbon. The ability to form a ribbon and its length provided an initial indication of the clay content; soils that formed longer, more cohesive ribbons indicated higher clay content, while soils that formed shorter, crumbly ribbons indicated a higher sand content. Further tactile assessment was conducted by rubbing the soil between the fingers to discern the texture. A gritty feel indicated a higher sand content, while smooth feel suggested silt, and a sticky feel indicated a higher clay content. These field observations provided preliminary classifications, such as sandy, silty, or clayey textures. The results from the hand-texture method were recorded and later confirmed through laboratory analysis, ensuring accuracy in the characterization of soil texture across the study sites. To determine texture quantitatively, composite samples were air-dried over the course of a week. Then, texture was determined using the hydrometer method (sodium hexametaphosphate settling) as described by Bouyoucos (1962). 10 replicates (maximum) per subzone and site had their texture determined using the above protocol.

Surface soil temperature and volumetric water content (%) were measured at each soil sampling location using an Accumet TDR150 probe calibrated for sandy soils. These measurements were performed using the same sampling intervals (5 m). Additionally, soil was excavated to form a pit (30 cm diameter, 100 cm depth) using a trowel and shovel. Within the pit at each 20 cm depth increment, the soil was re-analyzed for temperature and moisture content using the same probe, providing a vertical profile of these parameters. This was done once per subzone (4 pits per site).

Bulk density of surface soil was measured using a soil ring sampler following the 20-m interval set prior. This cylindrical tool is designed to extract undisturbed soil cores, with dimensions of approximately 10 cm in diameter and 10 cm in height. The sampler was inserted into the soil to collect the cores, ensuring minimal disturbance and compression. The extracted soil cores were then weighed on-site using a portable scale. The mass of each core, combined with the known volume defined by the sampler, was used to calculate the bulk density of the soil. This method was applied every 20 m, uniformly across all sampling locations to determine the physical characteristics of the soils within each subzone.

Soil carbon content was determined using the Loss on Ignition (LOI) method, employing a Thermolyne FA1730. Triplicate samples of 5 g of soil, pre-dried in a drying oven at 150°C for 24 hours to remove moisture, were placed in ceramic crucibles. The crucibles were then positioned inside the furnace. A propane torch was used to heat the furnace, starting at the lowest possible setting. The temperature was increased at a rate of 5°C per minute until reaching 700°C. The samples were held at this temperature for 2 h to ensure complete combustion of organic material. These triplicates were repeated 5 times per subzone for each site.

The mass of each soil sample was recorded before (pre-ignition dry) and after (post-ignition) the LOI process. The loss in mass, corresponding to the amount of organic matter burned off, was calculated using the formula:

$$LOI\ (\%) = \left(\frac{Mass_{pre-ignition} - Mass_{post-ignition}}{Mass_{pre-ignition}}\right) \times 100$$

This percentage represents the organic matter content, which was used to estimate the soil carbon content.

The above value is multiplied by 0.58 (to isolate fraction of C in SOC) then the soil carbon content per unit area (kg C/m^2) was calculated using the formula:

$$Soil\ Carbon\ = Bulk\ Density \times Soil\ Depth \times \left(\frac{Soil\ Carbon\ Content\ (\%)}{100}\right)$$

This method provides a standardized measure of soil carbon, allowing comparisons across different sites and soil types. The procedure ensures accurate representation of the organic carbon stored in the soil profile, essential for assessing soil health and carbon sequestration potential.

We also estimated Total Kjeldahl nitrogen of our composite soil samples. Approximately 1-2 g of air-dried, ground soil was digested in concentrated sulfuric acid with potassium sulfate as a catalyst. Following digestion, the samples were neutralized with 40% NaOH and subjected to steam distillation. The distillate was collected in 4% boric acid solution and titrated with standardized 0.1 N HCl to determine the nitrogen content. The procedure followed established guidelines (Bremner, 1965), with modifications as noted.

Total phosphorus content in soil samples was determined using an acid digestion followed by the molybdenum blue colorimetric method (Murphy and Riley, 1962). Approximately 0.5 g of air-dried and ground soil was digested with 5 mL of concentrated sulfuric acid (H_2SO_4) on a hot plate. After the initial reaction subsided, 2 mL of concentrated perchloric acid ($HClO_4$) was added, and heating continued until the digest became clear. The digested samples were then allowed to cool to room temperature before being diluted to a final volume of 50 mL with distilled water. For colour development, 10 mL of the diluted digest was transferred to a 50 mL volumetric flask, and the following reagents were sequentially added: 2 mL of ammonium molybdate solution (5% w/v), 1 mL of potassium antimony tartrate solution (0.25% w/v), and 1 mL of ascorbic acid solution (1% w/v). The flask was then filled to the 50 mL mark with distilled water and mixed thoroughly. The solution was allowed to develop for 15-30 min, resulting in a blue color that indicated the presence of phosphorus. Absorbance was measured at a wavelength of 880 nm using a spectrophotometer. The phosphorus concentration was quantified by comparing sample absorbance values to a standard curve prepared from known concentrations of prepared potassium dihydrogen phosphate. Blanks and standards were included with each batch of samples to ensure accuracy and consistency in the results.

Data Analysis

To assess whether species compositions differed across the 20 study sites and their respective subzones, we applied a suite of multivariate statistical analyses using Hellinger-transformed relative occurrence data. This transformation was chosen as it is well-suited for ecological community data, effectively reducing the influence of rare species while maintaining the Euclidean properties needed for subsequent analyses.

We first employed a Permutational Multivariate Analysis of Variance (PERMANOVA) to statistically test for differences in community composition among the sites. PERMANOVA evaluates whether the centroids of species composition differ significantly across groups, using permutation to assess statistical significance. The analysis was performed using the "adonis" function in the R package "vegan," with 999 permutations to ensure robust inference. Next, we conducted a Principal Component Analysis (PCA) on the Hellinger-transformed data to visualize patterns of community composition among the subzones. The PCA generated principal components that capture the maximum variance in species composition, facilitating the identification of clustering patterns among sites. Additionally, we calculated Bray-Curtis dissimilarity values using the raw species abundance data to quantify compositional differences among the subzones. This dissimilarity matrix was generated with the “vegdist” function from the "vegan" package, allowing for the assessment of pairwise dissimilarities and reinforcing the findings from the PCA. Together, these complementary analyses provided a comprehensive evaluation of compositional differences across the 20 study sites.

For the functional diversity assessment, we exported data from the Traits of Plants in Canada (TOPIC) database, specifically of the following traits: maximum height, seed weight, seed persistence, specific leaf area (SLA), leaf dry matter content (LDMC), water preference, drought tolerance, ability and diversity of vegetative propagation, shade preference, moisture preference, growth rate, and root depth. This provided 61.6% of the data for all species, with the remaining data sourced from literature pertaining to the same biome or interpreted personally. The collated data were then weighted by abundance and the Community Weighted Mean (CWM) formula was applied:

$$CWM = \sum (p_i \times t_i)$$

where p_i is the relative abundance of species i and t_i is the trait value of species i.

Rao’s Q was calculated for each sub-zone by determining the Euclidean pairwise distances of species and their traits, with greater distances indicating higher functional diversity:

$$Rao's\ Q \ = \sum_{i=l}^{S} \sum_{j=1}^{S} p_i p_j d_{ij}$$

where S is the total number of species, p_i and p_j are the relative abundances of species i and j, and d_{ij} is the functional dissimilarity between species i and j. This sum was then averaged by sub-zone then log-transformed to improve interpretability.

To investigate the relationship between plant community composition and measured soil metrics, we employed Canonical Correspondence Analysis (CCA) using Hellinger-transformed relative occurrence data. The Hellinger transformation standardizes species occurrence data, reducing the influence of rare species and making it suitable for ordination methods based on Euclidean distances. CCA was chosen to identify how much of the variation in plant community composition could be explained by environmental variables, given the linear properties of the transformed data. The soil metrics used as explanatory variables included temperature, moisture, moisture and temperature at depth, bulk density, carbon content, total Kjeldahl nitrogen (TKN), and total phosphorus (P) – combined with a suite of functional plant traits. Prior to analysis, these variables were standardized to ensure comparability. To quantify the influence of explanatory variables on community composition across the subzones, we developed an influence metric that integrates both the magnitude of the loading vector and the correlation of each loading with the respective subzone. The magnitude of the loading vector, calculated as the length of the vector in the ordination space from CCA, reflects the contribution of each explanatory variable to the variability in species composition. Larger magnitudes indicate a more substantial contribution to the observed community structure. The magnitude is calculated using the formula:

$$Magnitude = \sum_{i=l}^{n} (loadings_i)^2$$

where *loading* represents the individual loadings for each variable.

The correlation coefficient quantifies the strength and direction of the relationship between each loading variable and community composition for the specific subzone. Positive coefficients suggest that an increase in the explanatory variable correlates with increased species abundance, while negative coefficients indicate a decrease. The influence metric is derived by multiplying the magnitude of the loading vector by the corresponding correlation coefficient. Higher influence scores indicate that the variable plays a critical role in shaping community structure, while lower scores suggest minimal influence. Positive values denote a beneficial influence, whereas negative values reflect a suppressive effect on community composition. The CCA was conducted using the "cca()" function in the R package "vegan", and significance was assessed using permutation tests (999 permutations) to determine the statistical significance of the overall model and individual variables.

Results

The primary objective of this study was to investigate the recolonization status in abandoned sand and gravel pits located along the Highway 17 corridor in northeastern Ontario. Specifically, we aimed to examine both the taxonomic and functional diversity of plant communities that have established in these disturbed sites. The study also sought to understand the factors influencing recolonization, such as soil quality, microtopography, and human disturbance, and how these factors affect the composition and structure of plant communities. The results presented here are intended to inform land management practices and guide future reclamation efforts, ensuring that these disturbed sites can be restored to provide ecological, economic, and social benefits.

<u>Site Characteristics and Environmental Conditions</u>

Plant communities were organized in 4 distinct groups: i) interface communities (IC); ii) true remnant communities (TRC); iii) remnant communities (RRC); and iv) open communities (OC). IC zones occurred along the interface of the undisturbed stand and were observed in all sites. These zones could extend between 1 and 12 m into the disturbed area. RC is classified into 2 subgroups: i) those belonging to truly remnant communities largely left undisturbed during the original extraction period but are not in direct interface with the adjacent forest; and ii) those belonging to recently revegetated patches. In contrast to IC, these communities are not shaded and only appear in larger sites (>2.5 ha). Lastly, OC are regularly disturbed by recreational human activity, extractive processes, and erosion – either in concert or individually. While they are predominantly void of vegetation, small communities do scatter this zone.

This trend was broken by few sites. In Site 2, points of ingress were not readily apparent. Here, plant community structure was unique, and the site was entirely vegetated. There were no signs of recent extraction or other forms of disturbance since the original perturbation (sometime before 1985). In contrast to Site 2 and all other sites, Site 1 was hydric and entirely vegetated by early, yet very productive hardwoods. Indeed, while the legacy effects of extraction were visible in certain areas, it would be difficult to identify this site as being historically perturbed.

Each sub-zone was characterized by unique microtopography. TRC zones were larger mounds which were either composed of dumped overburden (36%), or the original soil prior to extraction (64%). In the former, these dumped mounds were typically small, ranging 5-15 m^2, and were roughly circular or polygonal in shape – consistent with dumping. The latter were quite large (typically 100-1000 m^2, again polygonal in shape, but usually more elevated as well, with abrupt slopes and visible soil horizons showcasing exposed organic layers undergoing a gradient of decomposition. Sources of human disturbance, specifically those mechanical in nature, were not observed here. IC zones ranged from flat to heavily sloped (>20°), as it followed the natural topography of the area, as well as historical grading or extraction. Small (~2.5 m^2) dumped mounds were present at this interface as well, often organized in rows. RRC and OC zones ranged from flat to gently sloped (3-4°), again as a result of extraction and grading.

Soil texture was virtually identical across RRC, outer IC, and OC sites – comprising a high fraction of sand (typically greater than 90%) with larger stones intermixed. In all but one site, these soils would be considered gravelly regosols, or perhaps brunisols in zones of limited horizontal development (according to the Canadian System of Soil Classification, 2025). Only Site 1, which lay directly adjacent to a well populated lake, was primarily silty. Here, the soils contained elevated rates of volumetric water content which were repeatedly measured during multiple site visits – registering mean volumetric water content readings of 45.5 ± 1.5%, 41.1 ± 4.9, and 43.1 ± 3.1% (± indicating SEM). Indeed, gleying (bluish banding) was observed in these soils, confirming their long-term saturation. These soils would be best described as a silty, gleyed brunisol. In contrast, soil moisture of the remaining sites was quite variable given the acute effects of the subzones. TRC sites were largely in-line with the moisture content of undisturbed stands (14.5% ± 5.1%). IC rapidly dried with increasing distance from the interface – as it transitioned from the undisturbed stand edge (where moisture was slightly lower than TRC 11.1 ± 3.2%) to the OC. OC sites were especially dry, typically being unable to register a reading with the instrument. RRC sites were quite variable in soil moisture but usually averaged somewhere between the TRC and OC sites (8.1 ± 3.6 %). Moisture reserves were present in the soil, but typically at a depth of 20 cm or more. Saturated zones (seepage) were never reached during these excavations – even at 1 m depths. When analysed, the VWC (%) of these excavated soils were consistently above 15-20%.

Compaction was also near universally observed, especially in IC zones (75.13%) and flat OC zones (64.12%), the former exhibited an apparently mosaic effect, as a quasi-cemented layer of variably sized particles present in the first 3-5 cm. This mosaic effect was most likely driven in flat surfaces where mechanical activity was clear (e.g., tire tracks, excavation laydowns) but was evidently not present in the eroding soils of heavy slopes. Erosion was common in the latter, and as a result, the margins of the pits appeared to expand with time as the slope sought balance. This was observed in all pits with a slope angle greater than 30 degrees and confirmed with historical satellite imagery. Bulk density was variable but generally much greater than undisturbed soils, especially in OC zones, which appeared to have a massive structure; bulk density was higher (1.81 ± 0.42 g/cm^3). RRC soils were similarly elevated (1.68 ± 0.28 g/cm^3). There was a distance effect in IC soils, with samples nearest the perturbation being most similar to recent RC and OC soils (1.65 ± 0.21 g/cm^3), with bulk density decreasing as we moved towards the undisturbed stand (1.01 ± 0.20 g/cm^3) (r=0.78). True RC soil bulk density was similar to those found in undisturbed stands (0.91 ±0.18 g/cm^3). Bulk density was also largely negatively correlated with silt and clay fractions, as expected following logarithmic transformation ($r^2 = 0.61$).

Soil organic matter depth and content, including the litter (L), fermented (F), and humic (H) layers were expectedly most elevated in and TRC soils. In TRC soils, SOM depth and content (%) matched those of the undisturbed soil profile, ranging from 1.4 to 7.7 kg C/m^2. From the 30 cm deep soil cores retrieved along this interface, a thin eluviated mineral horizon was reached in no more than 15 cm before transitioning to gravelly parent material. RRC soils were dominated with gravelly mineral soil but heavy in fresh (L) and fermenting litter (F) – humic (H) matter was also observed, but rarely so. Carbon had not yet accumulated in the mineral soils at elevated rates (0.7-1.8 kg C/m^2) but rather concentrated in the LFH layers (3.6 to 8.1 kg C/m^2). In IC soils, the surface soils are exclusively described as sandy and gravelly and are almost always covered with primarily fresh (L) but less commonly decaying (F) litter (1.8-3.5 kg C/m^2). Carbon content in IC soils were therefore much lower than those found in TRC soils, especially in samples taken further towards the disturbed zone (0.5-2.8 kg C/m^2), where C levels were often analysed to be below minimum detectable limits. This occurred typically in samples greater than 1m from the interface. Soil C content was much more clearly delineated in true RC sites as it quickly plummeted once having reached its immediate vegetative boundary, especially having reached the OC zone. In OC soils, carbon content was negligible or undetectable, similarly to the mineral layers of recent RC (~0.1 kg C/m^2).

TKN levels varied across community types. TRC exhibited the highest TKN values, ranging from 9100 ± 1200 mg/kg. RRC had TKN levels ranging from 6600 ± 800 mg/kg. In RRC zones dominated by the nitrogen fixing *Comptonia peregrina*, TKN % rose significantly to 18700 ± 1200 mg/kg. In IC, TKN levels ranged from 7500 near the forest edge and decreased to 250-6000 mg/kg with increasing distance from the edge. OC exhibited the lowest TKN values, with a range of 100 to 3000 mg/kg. TP concentrations were generally low across all subzones. TRC had TP values ranging from 131.5 to 254.9 mg/kg. RRC exhibited TP levels between 81.7 and 147.8 mg/kg. In IC, TP values ranged from 41.5–164.3 mg/kg near the forest edge, tapering to 36.9–79.8 mg/kg with increasing distance. OC exhibited the lowest TP concentrations, with a range of 28.4 to 55.1 mg/kg.

Vegetation Survey

Species Richness and Diversity

Effective Species Number (ESN), or the *e* transformed Shannon-Wiener Index, highlights the lowest possible number of species which are equally distributed of the surveyed area. Differences in ESN were statistically significant in all zones ($p<0.01$): the highest being in IC (11.5 ± 5.1), followed by true RC (10.1 ± 2.3), then recent RC (5.1 ± 4.1), and finally OC (1.1 ± 0.5). Species richness followed similar patterns with IC and true RC being similarly rich (34.1 ± 17.4 and 24 ± 16.1) ($p=0.14$), recent RC being moderately lower (8.9 ± 4.1), while OC sites were typically very low (3.5 ± 2.1). Site scale richness averaged 23.6 ± 9.9 and was positively correlated with size ($r^2=0.554$) with a regression slope (β) of the log-transformed site area of 5.44 which was significant ($p=0.00026$).

Community Composition and Structure

The analysis of community composition revealed distinct patterns across the four subzones—Interface Communities (IC), Open Communities (OC), Recent Remnant Communities (RRC), and True Remnant Communities (TRC). The 20 most influential species were identified for each subzone, based on their relative occurrence and cosine similarity to subzone centroids (Fig. 4).

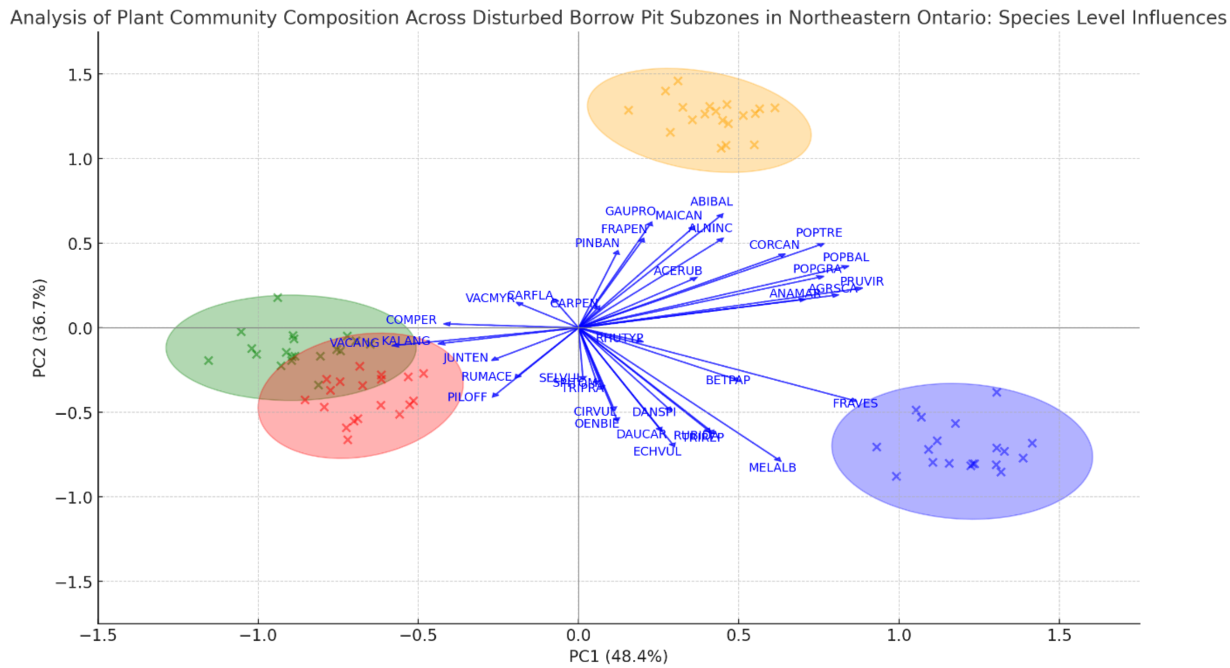

Figure 4 - Principal Component Analysis (PCA) of plant community composition across subzones in disturbed borrow pits in Northeastern Ontario. Each point represents a site subzone, while colored ellipses indicate distinct plant community clusters within different microhabitats: green (RRC), red (OC), yellow (TRC), and blue (IC). Species labels point toward specific directions of influence along the two primary principal components (PC1 and PC2), which account for 48.4% and 36.7% of the variance, respectively. This analysis highlights species-level influences on community structure, with certain species clustering in specific microhabitats, providing insights into ecological gradients and the successional dynamics within disturbed pit landscapes.

Interface Communities (IC) were characterized by significant contributions from *Arctium lappa*, *Agrostis gigantea*, and *Waldsteinia fragarioides*, each demonstrating strong associations with the community structure. Other key species included *Salix bebbiana*, *Rhus typhina*, and Betula papyrifera, indicating a diverse composition that incorporates both early-successional and stress-tolerant species. Open Communities (OC) exhibited a different profile, with *Juncus tenuis* emerging as the most influential species. This was followed by *Pilosella officinarum*, *Agrostis capillaris*, and *Selene vulgaris*, highlighting a community adapted to open, disturbed conditions. The prevalence of *Danthonia spicata* and *Rumex acetosella* further emphasized the dominance of species with high tolerance to nutrient-poor environments.

Recent Remnant Communities (RRC) were notably influenced by *Vaccinium angustifolium*, *Danthonia spicata*, and *Kalmia angustifolia*, suggesting a community influenced by species typically found in heathlands or early-stage regeneration. Populus grandidentata and Betula papyrifera also featured prominently, reflecting an intermediate successional stage with a mix of shrubs and pioneering tree species. True Remnant Communities (TRC) demonstrated a composition marked by species such as *Agrostis capillaris*, *Solidago canadensis*, and *Achillea millefolium*, indicative of communities that retain characteristics similar to adjacent undisturbed areas. *Betula papyrifera* and *Cornus canadensis* contributed significantly, along with stress-resilient species like *Anaphalis margaritacea* and *Rubus idaeus*.

With regards to the status of species colonizing in these, both TRC and RRC were exclusively dominated by native species (94.6% and 96.7%) – while OC, though its species counts were generally low, typically contained a handful of truly exotic or noxious weeds, such as *Echium vulgare*, *Pilosella piloselloides*, and *Artemisia vulgaris*. In contrast, IC sites contained many "roadside" species often considered invasive or noxious, particularly *Melilotus albus*, *Dacus carota*, and *Cichorium intybus* (though many of these species are considered to be widely naturalized and tend to colonize similarly disturbed environments like roadsides or abandoned farm fields). Agricultural grasses such as *Agrostis capillaris*, *Agrostis gigantea*, *Phleum pratense*, and *Poa compressa* were also common in IC sites.

Overall, the PCA analysis corroborated these findings by showcasing clear separations among subzones based on species composition, with the most influential species providing insight into the functional strategies and ecological pressures characteristic of each subzone. These results reflect adaptations ranging from pioneering species in nutrient-poor, disturbed environments to more stable, late-successional assemblages. The Bray-Curtis dissimilarity analysis revealed distinct variations in community composition across the four subzones (TRC, RRC, OC, and IC). The highest dissimilarity was observed between TRC and OC (0.896), indicating substantial differences in species composition between these subzones. Similarly, TRC showed considerable dissimilarity when compared to RRC (0.733) and moderate dissimilarity with IC (0.534), suggesting that while TRC retains unique characteristics, it shares some compositional overlap with IC.RRC and OC displayed a moderate dissimilarity (0.605), indicative of partial community resemblance, which aligns with their ecological positioning and successional characteristics. The IC subzone exhibited notable dissimilarity with RRC (0.647) and OC (0.625), highlighting the distinct yet moderately overlapping species assemblages that may reflect the influence of both proximity to undisturbed areas and ongoing disturbances. PERMANOVA shows the subzones to be statistically distinct from each other, and in pairwise comparison as well ($p=<0.001$). However, it again highlighted some similarity between RRC and OC (Pseudo-F = 25.41) while TRC and IC are noticeably unique (Pseudo-F > 150 for all pairwise values). Again, between site community composition was hardly differentiable – indicating the repeated presence of the 4 observed subzones as well as their species. Overall, these pairwise comparisons underscore the gradient of ecological divergence from the most established subzones (TRC) to those under persistent disturbance (OC), providing insights into the impact of disturbance regimes and successional processes on plant community structure within these sand and gravel pit environments.

Functional Diversity Assessment

Community Weighted Means (CWM)

The analysis of community-weighted mean (CWM) trait values revealed distinct patterns across the four subzones (TRC, RRC, OC, IC), each representing unique plant community structures and adaptations.

In TRC, the CWM values were characterized by high levels of Leaf Dry Matter Content (LDMC) (1.35) and Height (ht) (1.50), suggesting a community dominated by taller, structurally robust species that likely contribute to enhanced competition for light. Traits associated with lateral and vegetative spread, such as Lateral Extension (LE) (0.37) and Vegetative Spread (VP) (0.36), were positive, indicating moderate capacity for horizontal growth and clonal propagation. The Seed Weight (SDWT) (1.44) was notably high, implying an investment in larger seed sizes that may enhance seedling establishment under more stable environmental conditions.

In contrast, RRC exhibited a more balanced distribution of trait values. Slightly negative CWM values for Drought Tolerance (DROTOL) (-0.55) and Reproduction Mode (REP) (-0.43) suggest a community with lower drought resilience and less emphasis on reproductive spread, potentially reflecting species composition adapted to intermediate disturbance regimes. LDMC (-0.06) hovered near neutral, indicating diverse leaf structural strategies. The Growth Rate (GROW) (-0.60) was moderately negative, signifying slower-growing species that may contribute to gradual successional development.

The OC subzone displayed a distinctly negative profile across most traits. The low CWM values for Drought Tolerance (DROTOL) (-0.81), Seed Weight (SDWT) (-0.41), and Growth Rate (GROW) (-0.66) point to a community composition predominantly made up of stress-tolerant species adapted to resource-scarce conditions. The notable negative value for Vegetative Spread

(VP) (-1.08) aligns with a low presence of species capable of clonal expansion, and the Moisture Preference (WP) (-0.91) reflects adaptations to drier, more exposed habitats.

IC demonstrated significant positive CWM values for key traits, including Drought Tolerance (DROTOL) (1.43), Lateral Extension (LE) (1.22), and Moisture Preference (WP) (1.38). These results indicate a community adapted to variable moisture conditions, capable of enduring environmental stress and rapid lateral growth. The high CWM for Seed Persistence (SDPER) (1.47) suggests a composition favoring species with long-lasting seed banks, enhancing resilience in fluctuating environments. Additionally, the Growth Rate (GROW) (1.47) was markedly positive, indicating species with rapid growth potential that could facilitate competitive colonization and resource acquisition.

Overall, the CWM analysis highlighted distinctive functional trait distributions across subzones, suggesting that plant communities are structured to optimize survival and performance according to their specific environmental contexts. These findings provide a basis for understanding community-level adaptive strategies in relation to ecological gradients and disturbance regimes within the studied subzones.

Rao's Q

Rao's Q is an index used to measure functional diversity within ecological communities by assessing the distribution of traits among species. It quantifies how species with different functional traits are dispersed in a community, with higher values indicating greater functional diversity and potential for ecosystem resilience. By incorporating both species richness and the functional differences between species, Rao's Q provides insights into the ecological processes that may influence community structure and stability.

Rao's Q values matched the expected outcomes from field observations for each subzone across all plots. Site effects were minimal (Permutation test, $p = 0.45$) when controlled for size, while significant subzone effects were observed ($p=<0.001$), as anticipated, with TRC and IC exhibiting high functional diversity scores of 6.64 ± 1.61 and 7.4 ± 1.28, respectively. RRC demonstrated much greater variability but lower overall diversity with a score of 4.99 ± 1.89, while OC consistently displayed low functional diversity, reflected by a score of 3.41 ± 1.22. When functional diversity is calculated at the site level, Rao's Q was directly proportional to the number of subzones present (e.g., TRC and RRC were not always present), and the plot. This was expected given Rao's Q is simply the product of the CWM and the quantity of pairwise comparisons which potentially introduce unique functional traits from these "new" species. As shown in figure 5, there was a strong positive correlation between these factors and functional diversity – with the largest sites containing all subzones demonstrating the greatest overall functional diversity.

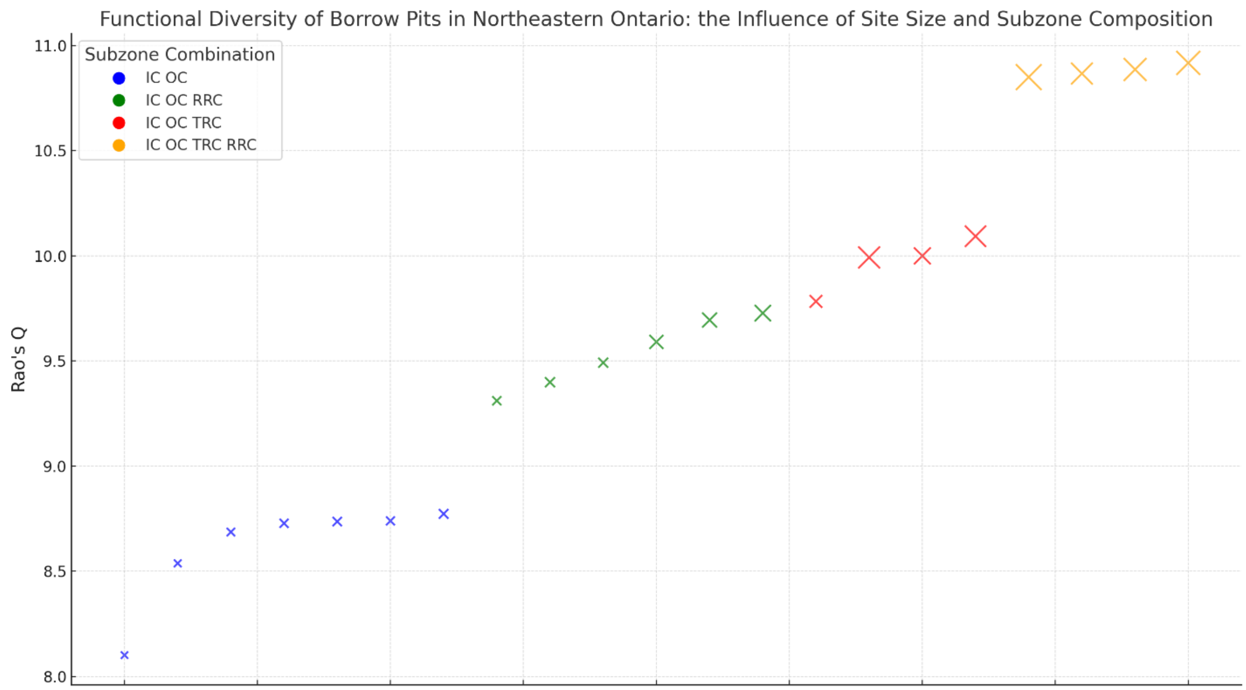

Figure 5 - Functional diversity (Rao's Q) of plant communities across different subzone combinations in borrow pits in Northeastern Ontario, as part of Chapter 2. Each color represents a distinct combination of subzones: blue (IC OC), green (IC OC RRC), red (IC OC TRC), and orange (IC OC TRC RRC). The x-axis represents the sorted ascending increasing in Rao's Q values (y-axis) for each configuration. This plot illustrates the influence of site size and subzone composition on functional diversity, with a clear trend of increasing diversity (Rao's Q) in sites with more complex subzone structures, highlighting the role of habitat heterogeneity in supporting diverse functional traits within plant communities.

Soil and Trait Interactions

Canonical Correspondence Analysis (CCA) revealed distinct relationships between plant community composition in subzones (TRC, RRC, OC, IC) and the explanatory variables comprising plant traits and soil properties.

In the plant community structure of TRC subzones, there were strong positive influences associated with several factors, including greater maximum height, deeper root systems, higher clay content, larger seed weight, increased soil carbon content, elevated leaf dry matter content, higher total Kjeldahl nitrogen (TKN), and an enhanced ability and diversity of vegetative propagation. Conversely, community structure was associated with low bulk density and low sand content, along with a weak negative influence reflected in slightly lower seed persistence. Additionally, TRC was weakly associated with warm and moist soil, increased prevalence of drought tolerant species, and a slight preference for shade.

In the RRC plant community structure, strong negative influences were observed with much lower specific leaf area (SLA) values, as these communities were not readily disturbed and occurred in cooler soil temperatures. This subzone also exhibited lower growth rates. Weak negative influences included slightly lower drought tolerance, a slight preference for sunlight, and a slight preference for drier soils.

The Open Communities (OC) subzone showed a strong positive influence from elevated bulk density and sand content, indicating a preference for these soil characteristics. There was also a weak positive influence related to slightly enhanced seed persistence. However, OC had strong negative influences from lower moisture rates, lower TKN, lower leaf dry matter content (LDMC), lower silt content, lower seed weight, lower soil carbon content, shallow root systems, and shorter plant height. Additionally, weak negative influences were noted, with a preference for drier soils, low ability to spread vegetatively, and low diversity in spreading mechanisms, favoring seed reproduction.

Lastly, the Interface Communities (IC) subzone exhibited strong positive influences from frequent disturbance and warmer soil conditions, with species characterized by very high SLA values compared to other subzones, as well as faster growth rates. A weak influence was observed in the context of low TKN soils, characterized by low silt and low moisture content. IC was uniquely influenced by aspect and shade. When the plant community structure of IC sites was alone ordinated (CCA) with these factors included, shaded, south facing communities were remarkably similar to those of TRC – being dominated by trees and shrubs of moderate LDMC and more elevated seed weights. In contrast, those north-facing, full-sun communities were expectedly unique, composed primarily of highly drought tolerant species with low seed weights, elevated LDMC values, and propensity for vegetative spread. Similar changes in south facing communities were observed as we moved away from the forested zone. Here, BD and soil temperature increased, SOM, TKN, TP, and soil moisture decreased, generating a gradient from TRC similar communities (though still regenerating), "true" IC communities, to OC-similar (or north-facing-similar) communities – with distance to interface being a key loading here.

These patterns reflect how various environmental traits influence community composition and structure across different subzones, providing insights into the ecological dynamics present in these habitats.

Discussion

Borrow pits experience a rush of colonization by a diverse set of species following disturbance (Day et al., 2017; Dawe et al., 2021). Plant recolonization was observed in all subzones, occurring in different ways based on influences such as forest proximity, disturbance intensity, and microtopography. Comparable studies in various environments support this, indicating perturbed sites will eventually progress towards stable ecosystems, albeit potentially novel or suboptimal ones, as a function of the disturbance profile. Doley and Audet (2013) discuss how radically disturbed sites, such as former aggregate mines, can develop into hybrid or novel ecosystems that provide acceptable levels of stability and functionality, incorporating both native and non-native species. Northeastern Ontario's sand and gravel pits exhibit slower ecological development compared to similar pits in southern Ontario, where recolonization appears to occur at a much faster pace (TOARC, 2024). This disparity may largely stem from climatic differences, as the warmer and wetter conditions in southern Ontario are more conducive to rapid plant growth. Additionally, southern Ontario's limestone-rich soils offer more nutrient benefits than the silica-based sands and gravels prevalent in the north, further accelerating vegetation establishment in the south.

Ultimately, while this slower regeneration process in the north may not fundamentally hinder natural succession, it does imply that these sites will take longer to reach a more advanced stage of development compared to their southern counterparts. However, this extended recovery time introduces a significant risk regarding human disturbance. The longer these sites remain in early stages of succession, the more vulnerable they are to disturbances from activities like ATV use, which are capable of resetting ecological progress in areas with sparse vegetation. Without thick ground cover or, ideally, a closed canopy, these sites are at higher risk of continual disturbance that could delay or prevent them from reaching a stable, resilient state.

Human Disturbance and Its Impacts

Despite recolonization occurring, the extent and consistency of human disturbance in these sites is perhaps underestimated. Human activity appears to significantly limit the progression of these sites, almost exclusively so. All-terrain vehicles (ATVs) are particularly destructive, causing soil compaction, vegetation uprooting, and soil erosion, especially near slopes. Ploughe and Fraser (2022) support this in their review of the impacts of ATVs, highlighting significant ecological impacts on soil, vegetation, and wildlife, though current research is mainly focused on short-term responses. Furthermore, urban borrow pits often served as makeshift landfills, where household garbage, including hazardous materials like cleaning agents, batteries, paints, and electronic waste, was dumped. This not only harms plant and animal life (Vaverková et al., 2019) but may also introduce invasive plant species. These invasives can severely disrupt local ecosystems by displacing native species and altering ecosystem functions (Kulmatiski, 2006; Martin et al., 2009; Cushman and Gaffney, 2010; Erhenfeld, 2023). This dumping behaviour was observed consistently within IC subzones, where garbage appeared to be piled in this zone mechanically. Additionally, low-volume aggregate extraction by local residents generates disturbances that reset the recolonization process by removing all vegetation.

Undisturbed Sites: Potential Reference Models

Of the 20 sites surveyed, only two sites (S1 and S2) did not have any publicly available points of ingress and displayed no evidence of recent human activity. These sites were functionally and taxonomically diverse, containing species and assemblages not observed in the readily accessible sites. Here, the entire disturbed areas (2.1 and 4.2 ha) were covered in layers of vegetation, while being excavated only decades prior: S1 soils, being quite moist and silty, was dominated by a mix of shrubs (e.g., *Amenlanchier alnifolia*, *Salix bebbiana*) and pioneering trees (particularly *Populus tremuloides*), with a developed graminoid and herbaceous layers – somewhat resembling a cross between IC and TRC sites; S2, being more xeric and heath-like, was dominated by colonies of rather prostrate *Juniperus communes* and *Juniperus horizontalis*, species not observed in any other sites, while containing elevated fractions of heaths and drought-tolerant shrubs, herbs, and grasses – effectively being an "model" RRC site rather than sub-zone. While unique, and undoubtedly affected by site-specific properties, these sites may provide practitioners with a snapshot of future assemblages when left truly undisturbed following the original perturbation.

Distinct Plant Communities and Influencing Factors

In contrast, we repeatedly observed the 4 distinct plant communities within the remaining 18 sites: TRC, RRC, IC, and OC. These were distinct, both taxonomically and functionally, as confirmed by PERMANOVA and Bray-Curtis Dissimilarity values. These sites did not resemble their "undisturbed" counterparts (SX and SY), at least not at site scales. Interestingly, the taxonomic and functional diversity observed in IC was notably higher than RRC, even when the latter was only meters away from the former. This suggests communities are responding to and affecting the environment in distinct ways, potentially highlighting the strong beneficial influence of the adjacent forests.

Several mechanisms may explain this pattern. Adjacent forests, particularly at their interface with the disturbed environment, can significantly influence the community composition of colonizing zones. A study in the Choszczno Forest Inspectorate, NW Poland, demonstrated that the proximity of different ecosystems, such as forests, built-up areas, and grasslands, influenced the richness of flora in adjacent forest patches (Gamrat et al., 2019). The same process has been shown to influence wetland communities as well – a common resultant ecotype of closed aggregate mines experiencing significant seepage (Houlahan et al., 2016). Forests provide shade, reducing evapotranspiration rates, which allows species less tolerant of full sun and drought conditions to establish near its interface (Holmes and Cowling, 1993). Shade generated by an adjacent canopy can significantly influence the recolonization process in disturbed environments by favoring shade-tolerant species, altering plant community composition, and impacting ecosystem dynamics (Modrý et al., 2004; Valladares et al., 2016; Powers et al., 2020). This was observed in our study, as north-facing IC communities (shaded) were more resource-competitive, featuring traits such as larger leaves and higher growth rates, while south-facing IC communities were woodier and drought-tolerant. Forests also contribute organic matter through litterfall and roots, enriching the soil with carbon and nutrients, potentially enhancing plant growth near the forest edge (Attiwill and Adams, 1993). There appears to be a distance-dependent relationship with soil benefits such as soil organic matter (SOM) diminishing with increased distance from the forest. Johnson et al. (2009) observed this as well, where forest edges often served as sources of organic inputs, such as leaf litter and root exudates, which enhanced SOM levels in nearby soils. Plant communities were distinguishable from high to low organic matter zones regardless of equal shading. Drought is especially detrimental in these coarse-textured mineral soils, and therefore plants appear to be filtered based on their ability to withstand or avoid it (Wright et al., 2020). The elevated levels of SOM nearest the forest edge appear to lessen the negative effects of drought (Udding et al., 2008; Buttler et al., 2019).

Soil and environmental factors were critical in shaping these observed community patterns. Soil moisture emerged as a pivotal determinant of plant community composition, with TRC and IC subzones exhibiting higher moisture levels, thus potentially supporting more diverse and functionally rich plant assemblages (Winkler et al., 2016). In contrast, OC subzones displayed extremely low moisture retention, which constrained plant establishment and growth (Richardson et al., 2010). Bulk density was another influential factor; the elevated compaction observed in OC and certain IC subzones correlated with limited root penetration and reduced vegetative cover. In contrast, TRC subzones featured lower bulk density, facilitating the establishment of deeper-rooted, more competitive species. Soil organic matter (SOM) and carbon content were highest in TRC subzones, aligning with their complex plant communities and indicating a robust capacity for nutrient cycling and carbon sequestration. IC subzones exhibited a gradient of SOM, diminishing as the distance from forest boundaries increased, while OC subzones demonstrated negligible organic content, underscoring their limited ecological development. While litter production was readily observed in RR zones, SOM formation was limited and accumulated – mostly likely due to consistent "resets" occurring in these sites following human disturbance.

Nutrient availability, particularly Total Kjeldahl Nitrogen (TKN) and Total Phosphorus (TP), further differentiated the subzones. TRC and specific areas within RRC showed higher nitrogen content, conducive to supporting diverse plant communities and facilitating successional progression. In contrast, OC subzones exhibited minimal nutrient concentrations, reinforcing the prevalence of species adapted to resource-scarce environments.

<u>Adaptations in Disturbed Zones</u>

In zones furthest from the forest edge, plant species may be selected for their rooting depth. Deep rooting species can access greater moisture reserves, circumventing extended periods of drought (Padilla and Pugnaire, 2007). However, this requires significant resource investment and availability (Borden et al., 2016). Such behaviour was somewhat observed in this study as roots were often shallow but expansive, a common trait associated with rapid colonizers represented in our results. Above-ground vegetative growth was extensive and the main pathway of colonization, particularly from species like *Fragaria virginiana*. This is expected given these soils, while primarily coarse-textured, exhibited severe compaction in nearly all sites, limiting stoloniferous spread. Soil compaction is known to significantly reduce root penetration, resulting in shallow and expansive root systems (Sinnett et al., 2008). For instance, compaction can cause shallow roots and increase lateral branching as a response to reduced soil porosity and increased soil strength, as observed in our study (Gilman et al., 1987). Additionally, localized soil compaction has been shown to reduce total root length, which in turn limits shoot growth and overall plant health (Montagu et al., 2001). This is further supported by findings that soil compaction often leads to the development of short, thick roots that are inefficient in exploring the soil profile (Atwell, 1990). This may explain the contrasting RSD results between TRC (high RSD) and the remaining subzones (low RSD). These adaptations help individuals establish and thrive in challenging soil conditions.

Human disturbance appeared to limit the spread of IC, where ground-spreading species abruptly ended, and transitioned into an annual herb community whose primary method of reproduction was seed based. Furthermore, the exposed mineral soils (particularly of OC subzones) are often disturbed from consistent extraction and recreational use, hindering seed germination and emergence, and favoring vegetative spread (Hyatt et al., 2007). However, one noteworthy exception was consistently observed: *Oenothera biennis*. This species appeared to transitorily dominate OC zones, with exceptionally deep roots (stem length would match root length at ~30 cm – though this data collection was not standardized or originally part of the experimental design). This species would appear for approximately 4 weeks following Spring's arrival, then all perish simultaneously near the beginning of August. Martínková et al. (2006) notes this as well, with *Oenothera biennis* displaying the ability to sprout from buried roots consistently year over year in similarly sandy soils. This ability (root budding) could be of particular interest when attempting to regreen pit soils. Overall, the tendency of plant species to spread vegetatively or by seed were a result of these soil and anthropogenic filters. Community composition appeared to shift towards to Eurasian "roadside" species at the interface between IC and OC gap, whose seed weights are exceptionally low, and its inverse seed production rate, being exceptionally high (Moles and Westoby, 2006). By filling this niche IC/OC gap, these "roadside" species are improving the short-term diversity of the sites overall (as seen by increased Rao's Q values when IC and OC are considered as one) but may yet reduce the overall potential diversity and integrity of the sites given their propensity to dominate disturbed zones. Again, these communities appear to establish as a result of anthropogenic activity, as RRC, TRC, and the innermost zones of IC, are primarily composed of native species.

RR Communities and Mosaics

RR communities, being more isolated, may not fully benefit from these interface interactions, explaining the predominance and patchwork of heath and grass species adapted to infertile and full sun conditions. Here, spontaneous vegetation establishment occurred fairly quickly, within a decade, even after complete soil profile removal (as shown by satellite imagery). This indicates a persistent biological legacy and perhaps avoidance by residents – leading to less severe and continuous disturbance. Indeed, site visitors tend to follow preferential paths and set aside specific zones for recreational activities – nearly always avoiding RR communities (Trip and Wiersma, 2020). Our analysis showed that RRC zones, like OC, were dominated by species associated with traits with elevated seed persistence, and may exhibit lower leaf dry matter content, reduced seed weight, and potentially lower specific leaf area. This can imply faster growth cycles or adaptations to disturbance, as species with low LDMC and SLA often have shorter life spans and higher turnover rates (Wilson et al., 1999; Poorter and Remkes, 1990). These communities tended to form mosaics leading to low diversity at smaller quadrat scales but greater values at site scales. This was not observed in IC communities, which remained largely heterogeneous even at quadrat scales. Plant communities commonly organize themselves in mosaics, perhaps as a result of competitive exclusion, given that early stages of succession often see broad niche overlaps and intense competition, contributing to a dynamic mosaic structure (especially given our results which suggest rapid species turnover). Over time, this leads to the emergence of patches dominated by species that can best exploit local conditions, creating a pattern of community differentiation (Parrish and Bazzaz, 1982).

Certain heath species observed in RC communities are believed to be allelopathic (e.g., phenolic compounds of *Kalmia angustifolia*), or exhibit inhibiting behaviors through their litter (Mallik, 1987; Inderjit and Mallik, 2002; Joanisse et al., 2007). Heath species are also less palatable than species found in IC communities as they invest in defense mechanisms to deter herbivores, removing an additional barrier to their flourishing (Aerts, 1993; Cates and Orians, 1975). Heath species also thrive in acidic, nutrient-poor soils, saturating their growth layers with vegetation. They contribute to and reinforce these soil conditions through their leaf litter and root exudates, further excluding other species and potentially contributing to their tendency to form mosaics (Graaf et al., 2009). For example, studies have shown that heath vegetation is often found on highly acidic and nutrient-poor soils, which support the growth of sclerophyllous shrubs that are well-adapted to such conditions (Specht and Rayson, 1957). The soils in these environments are low in essential nutrients such as nitrogen and phosphorus, and the organic matter from heath species further acidifies the soil and maintains these nutrient-poor conditions (Proctor, 1999). Additionally, the addition of nutrients and acidifying agents has been shown to decrease species diversity in heathlands by altering soil pH and nutrient availability, which favors certain dominant species like *Molinia caerulea* and excludes others (Roem et al., 2002). This dynamic further promotes the formation of mosaic patterns in plant communities, as different species dominate different microhabitats within the same area. RRC-heath dominated sites were observed throughout the experimental corridor, but most frequently in the Greater Sudbury region. Swaths of this region (~80000 ha) have acidified following nearly a century of elevated sulphuric acid deposition. While soil pH was not exclusively examined in this study, the Greater Sudbury plots, while not especially near zones of acid deposition, may have been acidified to an extent, promoting the establishment of acid tolerant species. However, studies mapping the gradient of acidification show our sites to be largely outside this range (Keller et al., 2019). The reinforcement of acidic and nutrient-poor conditions by heath species' litter and root exudates plays a significant role in maintaining these mosaic landscapes and excluding less adapted species.

IC Communities and Homogeneity

IC communities were surprisingly homogeneous between sites which spanned a 400 km experimental range, especially given their heterogeneity at quadrat or sub-zone scales. The spatial homogeneity in IC plant community structure is likely due to similar regional hierarchical filters, including seed banks, vegetative spread, and inputs from animals such as birds (Elsey-Quirk and Leck, 2015). The biome (interface of Boreal and St. Lawrence forests) and soil conditions remained quite similar across this range, contributing to the similarity. The dimensions of IC are perhaps more diffuse than those of RRC, OC, or TRC, given our experimental design. As we reported in our results, our IC findings were strongly influenced by disturbance and distance to adjacent stand gradients, as well as aspect, suggesting this subzone could be further divided and therefore perhaps artificial increased functional and taxonomic readings. Assemblages did not appear to be influenced by the original excavation date; nearby sites exhibited taxonomic and functional similarities despite being separated by decades since their initial extraction. This was similarly observed in RRC zones; however, we may be limited by the resolution of our longitudinal satellite and aerial imagery. The most recent confirmed RRC to be observed fully vegetated was 5 years after disturbance. Therefore, given nearly all sites (save S1 and S2) are consistently disturbed from human activity, that is the most likely explanation for a lack of correlation between assemblage type and original excavation date.

Variable microtopography plays a significant role in regenerating disturbed sites by creating diverse microhabitats that influence soil properties, hydrology, and, in the case of our study, vegetation patterns (Simmons et al., 2011). Large mounds within both IC and RC communities showed advanced development, with productive saplings, and shade tolerant forest herbs – essentially developing as micro-TRC zones. Similar effects were observed by Simmons et al. (2011) where induced microtopographic variability had significant beneficial effects on the richness and survival of forest species. Again, these mature mound communities highlight the significance of human disturbance in these sites – and how directed and planned “disturbances” may yet be beneficial. Here, the physical barriers of these mounds discouraged and redirected forms of human disturbance towards more accessible areas of the site, like those of OC and flat IC communities. These mound communities were quite similar to those found in TR zones. Here, TR communities behaved somewhat as “reference” islands, where, for reasons unknown to us, especially large areas of the pit were not extracted, or perhaps lightly so. These TR communities largely matched those found in the surrounding forest, though edge effects were significant in shifting the ground layer community composition towards more shade intolerance as it transitioned into its own version of IC (e.g., *Solidago* sp., or *Aster* sp. dominated).

These findings collectively underscore the complex interplay between soil properties, environmental context, and plant community dynamics, highlighting the significant impact of proximity to undisturbed forest areas, microtopography, and historical disturbance on the recolonization processes within these reclaimed landscapes.

Recommendations for Future Reclamation Work

The results of this study underscore that abandoned borrow pits, like any ecosystem with available solar energy, moisture, and nutrient reserves, naturally attempt to revegetate. This process, however, results in a range of community structures with varying levels of ecological benefit, including increased biodiversity and enhanced functional diversity. These attributes contribute to the functional integrity of emerging ecosystems and support resilience in the face of environmental challenges.

One of the most tangible insights from this research is the significant opposing force posed by human disturbance. Although these sites are labeled "abandoned" or "disused," our findings reveal that they are frequently impacted by human activity, primarily through recreational use. While such activities—ranging from off-road vehicle use to informal extraction—offer recreational value and community engagement, this value must be weighed against the ecological advantages of allowing these landscapes to undergo natural reclamation.

Our study highlights that in areas where human disturbance is minimal, site development appears to follow a more typical ecological trajectory, favoring the establishment of native plant communities with minimal encroachment by non-native species. Though this paper does not make definitive claims about the long-term sustainability of these communities, current observations suggest that in the absence of continual disturbance, recolonized areas progress toward vegetation structures that are predominantly native, though potentially novel. Additionally, the intense ecological pressure exerted by adjacent forests suggests that some of these colonizing species, particularly exotic ruderals, may be outcompeted and shaded out over subsequent decades, contributing to a dynamic succession process.

Presently, standard reclamation practices involve mechanically grading sites for stability and safety, followed by hydroseeding with grasses and legumes to encourage vegetative cover and soil stabilization. While these measures are important for site safety and immediate ecological restoration, we recommend that future reclamation strategies incorporate approaches that support and maintain the development of Recent Remnant (RR) and Interface Communities (IC). Our results also highlight the negative influence of eroding slopes on recolonization, effectively rendering the entire zone barren, so reductions in slope angle present dual benefits. Observations from this study indicate that these areas, characterized by microtopographic variability and structural diversity, support higher biodiversity. To mimic these successful patterns, we suggest that reclamation efforts include the deliberate mounding of Open Community (OC) zones. Mounding can reduce direct human access, serving as a deterrent to recreational disturbances, while simultaneously fostering diverse microhabitats that promote colonization by a broader range of plant species - in accordance with our results. A study by Ewing (2002) on using mounding for prairie restoration on a capped landfill in Washington, USA, found that mounds helped create diverse microhabitats, enhancing plant establishment and reducing human interference by limiting access. This study demonstrated how mounding can effectively promote varied plant communities while minimizing recreational disturbances on restoration sites. Overall, the primary limiter to the recolonization of these sites is human disturbance. If any recommendations are acted upon, limiting community access is key. However, there are societal and legal considerations, given these pits are often enjoyed by the community and the land is privately owned.

If the goal for a particular site is to rapidly establish vegetated cover, further enhancements to soil quality may be required to support plant establishment. The use of waste organic material such as soil amendments should be explored – materials such as compost and biochar, which can often be sourced through community programs, offer vital organic matter and nutrient inputs that improve soil structure and moisture retention (Liu et al., 2021; Kammann et al., 2015). Additionally, industrial-scale residuals like pulp mill sludge or boiler ash, though heavily regulated by Provincial authorities, could provide innovative solutions for nutrient deficits and improve soil conditions in these nutrient-poor, compacted areas (Gallardo et al., 2012).

Reclamation strategies should also incorporate more varied microtopographic features beyond simple mounding, such as pits, ridges, and terraces. These modifications contribute to site entropy, creating "rough and loose" conditions that have been associated with higher potential for new species colonization and increased biodiversity (Zeeuw, 2020; Kappes et al., 2012). Studies indicate that such topographic complexity can enhance habitat heterogeneity, supporting niche differentiation and promoting plant establishment by providing varied moisture regimes and reducing competition through sheltered microhabitats (Polster, 2009).

Implementing these combined strategies—enhancing soil conditions with organic and industrial residuals and incorporating complex microtopographic features—could lead to more effective and sustainable reclamation practices. This approach may promote native biodiversity, improve ecological resilience, and harmonize the needs of human recreational use with the ecological recovery of these landscapes.

Recommendations for Further Research

To gain a deeper understanding of the recolonization processes in abandoned sand and gravel mines and to develop more effective restoration strategies, several areas warrant further investigation. First, the long-term ecological impacts of human disturbances, particularly those caused by all-terrain vehicles (ATVs) and recreational activities, require comprehensive study. Longitudinal research should focus on the sustained effects of these activities on soil compaction, vegetation damage, erosion rates, and the overall recovery timelines of disturbed sites. Controlled experiments could help isolate specific impacts, allowing for the development of targeted mitigation strategies that balance recreational use with ecological restoration.

Second, the potential benefits of microtopographic modifications in enhancing plant diversity and ecosystem stability in disturbed sites should be explored. Research could investigate how induced microtopographic variability influences soil properties, hydrology, and vegetation patterns. This line of inquiry may reveal ways to create diverse microhabitats that support a wider range of plant species, thereby increasing biodiversity and promoting more stable ecosystems. Additionally, the role of soil amendments, such as the addition of organic matter, in mitigating drought effects and promoting plant establishment in nutrient-poor, compacted soils merits further investigation. Studies should evaluate the effectiveness of different types and quantities of organic amendments in improving soil structure, increasing soil moisture retention, and enhancing nutrient availability. This research could lead to practical recommendations for land managers aiming to restore fertility and support plant growth in degraded mining sites. Moreover, examining the mechanisms behind the observed homogeneity in interface communities (IC) across a broad geographical range is essential. Research should focus on understanding the factors driving seed dispersal, vegetative spread, and the influence of regional climatic conditions. Investigating these processes could provide insights into the resilience and adaptability of these communities, guiding restoration efforts in similar environments. Lastly, the impact of invasive species introduced through illegal dumping and other human activities on local ecosystems should be thoroughly studied. Research should further quantify the extent to which invasive species displace native plants and alter ecosystem functions in such passively colonizing sites. Understanding these dynamics is crucial for developing effective management and eradication strategies to preserve native biodiversity.

By addressing these research areas, we can develop a more nuanced understanding of the recolonization processes in disturbed sites and create informed, effective restoration practices that enhance ecological stability and biodiversity.

Conclusion

This study highlights the complex interplay of natural and anthropogenic factors influencing the recolonization process in abandoned sand and gravel mines of Northeastern Ontario. While recolonization is occurring, the extent and pace are heavily moderated by human activities and proximity to forested areas. Undisturbed sites provide valuable insights into potential future plant assemblages, serving as reference models for restoration efforts. Further research into mitigating human disturbance and enhancing soil conditions will be crucial for promoting ecological stability and biodiversity in these disturbed landscapes.

Chapter 4

Title: A Greenhouse Study for the Potential Reclamation of Borrow Pits Using Industrial Residuals: Enhancing Soil Properties and Tree Seedling Growth

Authors: Jonathan Lavigne, Patrick Levasseur, Peter Beckett, Nathan Basiliko, Marc Hebert, Olivia Baudet

Abstract:

This study investigates the application of pulp mill sludge (PMS), lime-stabilized municipal biosolids (LSMB), and biomass boiler fly ash (BBFA) for the potential reclamation of borrow pits that are characterized by nutrient-poor, coarse-textured parent material substrates. Conducted in a controlled greenhouse environment, the research evaluates the impact of these residuals on soil physico-chemical properties and the growth responses of trembling aspen (*Populus tremuloides* Michx.) and yellow birch (*Betula alleghaniensis* Britt.) seedlings. Results indicated that PMS significantly enhanced soil organic matter, moisture retention, and overall seedling performance, while LSMB and BBFA presented challenges that appeared to be related to elevated soil pH and limited moisture retention. The findings suggest that PMS holds significant potential for borrow pit reclamation, though careful optimization of LSMB and BBFA application rates is necessary to mitigate adverse effects. The study emphasizes the importance of balancing nutrient enhancement with physical soil improvements to achieve effective revegetation and sustainable land reclamation.

Keywords: Borrow pits, Industrial residuals, Soil reclamation, Pulp mill sludge, Tree seedling growth

Implications for Practice

- The use of pulp mill sludge (PMS) as a soil amendment significantly enhances soil fertility and moisture retention, suggesting it should be prioritized in reclamation efforts of nutrient-poor, sandy aggregate substrates.
- Application rates of lime-stabilized municipal biosolids (LSMB) and biomass boiler fly ash (BBFA) must be carefully managed to prevent adverse effects on soil pH and nitrogen mineralization, emphasizing the need for customized application protocols.
- Incorporating organic-rich amendments like PMS can markedly improve the survival and growth rates of tree seedlings, crucial for the successful revegetation of disturbed sites.

Introduction:

Borrow pits are sand and gravel deposits excavated for use at a nearby location, typically for construction or infrastructure development, and are widely used when a region is rapidly industrializing (Avis, 1984). Globally, borrow pits, along with sand and gravel extraction sites, cover extensive areas and are widespread due to the high demand for these materials in construction and infrastructure projects, leading to significant environmental impacts across diverse regions. In 2024, there were 5873 licensed sand and gravel mines in the province of Ontario, Canada, disturbing a total area of 177 km^2 (Government of Ontario, 2024). Additionally, an estimated 8000 privately owned, abandoned borrow pits pockmark the landscape (TOARC, 2024). Borrow pits are typically small (<5 ha) but elevated in density given their function to quickly provide nearby aggregate resources for local infrastructure (TOARC, 2024). Once the immediate need for aggregate is met, the pit is typically abandoned or continues to be lightly used.

As opposed to quarries or larger sand and gravel pits, borrow pits are less intensely mined and therefore do not typically penetrate the water table (Government of Alberta, 2024). Once the borrow pit is closed the disturbed area is barren with exposed parent material and irregular topography (Owolabi et al., 2020; Tavares et al., 2021).

Environmental damage associated with borrow pit activities are immediate, yet rarely extending past the extraction area (Langer and Arbogast, 2003). To access the aggregate, topsoil is mechanically removed and usually stockpiled. Following the complete removal of biologically active soil horizons, loss of habitat and ecosystem functions (e.g., carbon and nutrient cycling, transpiration, altered albedo) are the most apparent above-ground disturbances (Bobrowsky, 1998). Soil instability is also a concern as erosion can increase the disturbed area, potentially impacting downslope ecosystems and damaging infrastructure and posing safety risks (Carter, 1995; Smith and Sullivan, 2012). Many borrow pits, especially in Canada, are glacial in origin; these siliceous soils have low cation content and are expected to have limited soil biota activity following disturbance (Borgegard, 1990; Walker and Syers, 1997; Peltzer et al., 2010; Damptey et al., 2020). The gravel substrate in borrow pits and their irregular topography pose challenges to water retention, microbial activity, and nutrient availability creating an inhospitable environment for plant growth (Hugron et al., 2011). The struggle for borrow pits to naturally recover post-abandonment stems from these inherent limitations. Indeed, borrow pits are often compared to areas of glacial retreat and may be undergoing a form of primary succession (Kershaw and Kershaw, 1987; Bradshaw, 1997; Bradshaw, 2000; Řehounková and Prach, 2006; Sheoran et al., 2010).

Enhancing the physical structure and nutrient content of the substrate is likely needed to initiate passive or active recovery in abandoned borrow pits. Pulp mill sludge (PMS), lime-stabilized municipal biosolids (LSMB) and biomass boiler fly ash (BBFA) are residual materials with extensive use in agricultural lands and could be valuable tools in borrow pit restoration (Zvomuya et al., 2006; Larney and Angers 2012). Turner et al. (2022) attributes the success of industrial residuals as soil amendments to their capacity for creating enduring improvements in the chemical, physical, and biological properties of soil. The nutrient-rich composition of certain residuals directly addresses the nutrient scarcity typical of poor sandy substrate found in borrow pits. Moreover, residuals can significantly improve water retention and soil structure, mitigating issues of rapid drainage and susceptibility to drought – both commonly observed in borrow pits (Freeze and Cherry, 1979; Turner et al., 2022). Examples of residuals being used in borrow pit restoration are sparse; however, the potential use of low-value or waste residuals from mill and municipal wastewater treatment systems and biomass boilers for pit reclamation is intriguing and could also offset landfilling of these materials.

Lime-stabilized municipal biosolids (LSMB) have been shown to improve soil pH, enhance nutrient availability—especially nitrogen, phosphorus, and potassium—and increase organic matter content, which collectively boost soil fertility and promote plant growth. The application of LSMB has been found to significantly increase soil pH, which helps to neutralize acidity and create a more favorable environment for plant growth (Wong et al., 2001). Research in Eastern Canada demonstrates that the application of lime-stabilized municipal biosolids is an effective strategy for ameliorating acidic, nutrient-poor forest soils. Field trials and controlled greenhouse experiments indicate that this amendment significantly elevates soil pH and increases exchangeable calcium, thereby reducing aluminum toxicity in both the forest floor and the upper mineral layers (Keys et al., 2018). Additionally, LSMB enhances the availability of essential nutrients such as nitrogen and phosphorus, which are crucial for plant development and yield (Silva-Leal et al., 2021). The biosolids also contribute beneficial nutrients such as potassium and phosphorus and add organic matter that improves soil structure and water-holding capacity (Keyes et al. 2019). The increase in organic matter from LSMB further contributes to improving soil structure and fertility, leading to better water retention and nutrient availability, which are vital for sustainable plant growth (Dad et al., 2018). Vegetation growing in biosolid amended plots have exhibited significant increases in foliar concentrations of calcium, potassium, and phosphorus in white spruce needles (Keys et al., 2018). However, LSMB may introduce trace elements such as lead and chromium, leading to their accumulation in the soil and potential leaching into groundwater (Lasley et al., 2008). The elevated pH levels associated with LSMB can also cause nutrient imbalances, particularly affecting micronutrients like zinc and manganese (Shaheen et al., 2014). However, recent field-based leaching analyses further indicate that nutrient losses are primarily restricted to beneficial cations, with negligible nitrate leaching and minimal heavy metal accumulation in both soil and leachate (Keys et al., 2018)

Similarly, pulp mill sludge (PMS) is rich in organic matter and has been found to improve soil structure, water retention, and microbial activity (Alvarenga et al., 2019). These primary sludges and biosolids may also provide essential mineral nutrients such as calcium, magnesium, and potassium, however this is dependent on mill wastewater management processes, for example if lime mud and/or biomass boiler ash are also introduced to the wastewater treatment plant influent. The application of PMS significantly enhances the chemical properties of soil, including increased organic matter and nutrient content, leading to improved plant biomass production (Gallardo et al., 2012). Additionally, PMS has been shown to improve water retention and support microbial activity in soils, which further contributes to enhanced soil fertility and plant growth (Camberato et al., 2006). Despite these advantages, PMS can contain trace amounts of heavy metals, including manganese, iron, and zinc, which may accumulate in the soil and negatively impact plant health (Undurraga et al., 2017). The high organic content of PMS might also increase the biological oxygen demand in leachates, posing a risk to water quality, and low macronutrient (N, P) contents may lead to temporary immobilization of nutrients by soil microbes (Quintern, 2014) Biomass boiler fly ash (BBFA) offers benefits such as high calcium and potassium content, improving soil pH and fertility while acting as a liming agent to neutralize acidic soils and enhance nutrient availability (Park et al., 2012; Ondrašek et al., 2020; Cherian and Siddiqua, 2021). However, BBFA can introduce trace metals like arsenic, cadmium, and mercury, which carry risks of contamination and potential leaching into water sources (Zhang et al., 2008). Furthermore, excessive application of BBFA may lead to overly alkaline soil conditions, adversely affecting nutrient uptake and microbial function (McCarthy et al., 2012). Therefore, managing the application of these residuals is crucial to prevent these adverse effects on water quality and public health. Nevertheless, research suggests that aligning application rates with anticipated plant productivity can mitigate this effect, resulting in an ephemeral spike in nutrient and metal loss which is expected to rapidly taper below critical levels (Kardos et al., 1979; Sopper and Kerr, 1981; Drie et al., 1982; Seaker and Sopper 1984).

A greenhouse-based investigation was conducted in two phases to evaluate the effects of three industrial residuals (LSMB, PMS, BBFA) on the physical and chemical properties of borrow pit substrates and their subsequent impact on tree seedling performance. I hypothesize that the application of these residuals will lead to significant improvements in specific soil properties of aggregate substrates, particularly soil organic matter (SOM), moisture retention, cation exchange capacity (CEC), and nutrient availability (especially nitrogen and phosphorus). In turn, these improvements should lead to comprehensive enhancements to planted and sown seedling productivity (e.g., growth rates) and overall health metrics (e.g., survival rates, leaf chlorophyll content).

In the first phase, we predict that residuals with higher organic content (PMS and LSMB) will show greater improvements in moisture retention and nutrient availability, leading to better seedling growth and survival. However, these changes will be assessed alongside potential risks of leachate contamination, where we hypothesize that residuals with higher soluble salt content (LSMB and BBFA) may lead to elevated leachate concentrations of specific metal ions. The metals present in biosolids – notably Cd, Zn, Cu, Ni, Pb, Cr, and others – can under certain conditions leach into groundwater or surface water. The extent of this leaching is highly dependent on factors like soil pH, application rate, and soil properties (Stehouwer et al., 2006; CIELAP, 2008). Furthermore, there may be significant loss of N and P ions immediately following the incorporation of the nutrient rich materials – potentially at rates damaging to ground and surface waters. In the second phase, under simulated drought conditions, we expect seedlings in substrates amended with PMS to exhibit the longest survival times due to enhanced moisture retention and SOM content. The interdependence of chemical and physical soil properties is anticipated to play a critical role, with comprehensive improvements in both domains leading to the most favorable plant health outcomes.

Materials and Methods:

<u>Treatment Materials</u>

Four industrial residual solids were collected from industrial plants in Northeastern Ontario, Canada in May 2020.

i) Lime-stabilized municipal biosolids are treated sewage sludge that has been mixed with quicklime (CaO) for sterilization and stabilization purposes, resulting in a nutrient-rich soil amendment which has been approved for agricultural use (Walker Environmental, Greater Sudbury, Ontario). Lime-stabilized municipal biosolids are granular, nutrient-rich, pH-elevated organic amendments that provide essential macronutrients like nitrogen (N) and phosphorus (P), along with trace elements, while improving soil structure and water retention (Environmental Protection Agency, 2000; Walker Environmental, 2024). The high pH (~12.0) from lime treatment in LSMB helps pathogen reduction and immobilizes heavy metals (Bean et al., 2007). Materials were collected from a municipal waste-water treatment plant in the City of Greater Sudbury, ON.

ii) Blended pulp mill sludge from a nearby multi-line sulphite and thermomechanical pulp and paper mill is a N rich byproduct composed mainly of lignin, cellulose, and other organic waste fibers (primary sludge), combined with secondary sludge, a product of secondary aerobic microbial treatment, rich in microbial biomass and other suspended solids that flocculate and are removed during clarification steps (Soucy et al., 2014). The nutrients in the PMS stem from the organic feedstocks at the mill and microbial biomass, however in contrast to many other pulp mill sludges and biosolids, the use of ammonium (NH_4) in the pulping process leads to material with relatively high total N contents (37600 mg/kg of soil). The material is elevated in TOC (45.4%) and moisture (70.1%), while being slight acidic (6.7) (Exova Canada, 2020)

iii) Biomass boiler fly ash is a powdery, alkaline material with elevated cation concentrations, especially calcium (Ca) which readily forms alkalizing hydroxides. The material does not contain N as it is volatilized during the combustion process (Giuntoli et al., 2010). The material was amended with a blend of ammonium nitrate and urea (sourced from a local farm supply vendor). Residuals were collected from a regional biomass boiler combusting bark, hog fuel, and ground stemwood with primarily softwood feedstock.

iv) Dolomitic limestone ($CaMg(CO_3)_2$) and synthetic fertilizer (6-24-6) as used in the City of Greater Sudbury Regreening protocol. This treatment has successfully reclaimed 3500 hectares of similarly coarse textured but acid and metal damaged soils (Gunn et al., 1996; Munford et al., 2024).

Greenhouse Trial

The experiment was carried out in greenhouse conditions at Collège Boréal in Greater Sudbury, Ontario, Canada. The growing environment was controlled for temperature, light availability, and precipitation. Daytime greenhouse temperature ranged 6°C to 26°C and luminosity was near constant at 28000 lux (which was ~36000 lux less than outdoors). Aggregate substrate was sourced from an active local borrow pit (46.65, -80.77) with texture fractions of 90%

sand, 5% silt, and 5% clay, characterizing it as a sand. The substrate was slightly acidic with a pH of 6.6 and was devoid of organic matter (0.0%). The gravel contains low amounts of P, K, and plant-essential micronutrients, and undetectable levels of total N.

Gravel was sieved using a 2 cm metal screen to remove larger stones prior to producing the amended substrate. The materials were blended with amendments using a 60 L cement mixer for 60 minutes to promote homogeneity. The mixer was rinsed with water between treatments to reduce cross-contamination.

We selected yellow birch (*Betula allegheniensis* Britt.) and trembling aspen (*Populus* tremuloides Michx.) for this experiment. The former representing tree species belonging to mature forests, with developed soils. The latter representing an earlier seral forest stage, where soils may lack organic matter, or may have been recently perturbed. Trees were either sown with the goal of being planted as seedlings or were sown directly into the growing medium. In the former, seedlings were germinated in-house and grown for 10 weeks prior to use in experiment. Here, the seeds were pre-stratified by the collector (see below) and simply placed in the sowing cavity of a standard jiffy plug. Seedling germination followed a standard greenhouse germination protocol developed by Collège Boréal: newly germinated seedlings follow a 16-hour, full spectrum LED lighting regime and are kept moist with water. Once the true leaves emerge the seedling is amended with fertilizer to support growth until it is planted in the growing medium. Here, the seedlings were given nutrient water (20-20-20) with concentration increasing weekly (25 ppm up to 200 ppm). Trembling aspen seeds were acquired from Sheffield's Nursery (Hamilton, Ontario), which were collected from Upstate New York, USA. Yellow birch seeds were acquired from Ontario Seeds, which were collected from Southern Ontario.

The greenhouse experiment was conducted using styroblocks. Each styroblock contained 24, 700mL cavities (15 cm deep; 10 cm diameter) (Beaver Plastics, Oregon, USA). 114 styroblocks were placed together in a rectangular orientation to allow for 2736 individuals. Treatment, species, and growing techniques were assigned to evenly distribute edge effects. Species were assigned equal halves (57 styroblocks). Growing technique alternated by block, with even blocks being sown and odd blocks planted. In total, each combination of treatment, species, and growing technique was represented by 76 individuals. Due to the size of trembling aspen seeds, sowing was done via mini sampling spoon (0.10 mL volume). One scoop containing approximately

25-30 seeds was spread near the centre of the cavity. The larger yellow birch seeds allowed for a single seed to be sown in the centre of the cavity.

The experiment ran in two phases for a total 20-week period. Phase 1 lasted 15 weeks where seedlings were grown in 16 hours/day of full spectrum light and received 60 minutes of precipitation beginning 2 hours after the lights were turned off (~50 $mL \cdot individual^{-1} \cdot day^{-1}$). During Phase 1 seedling height, survival, and chlorophyll content (mg/cm^2) were measured weekly. The former was analysed using CHL BLUE Chlorophyll Pen using manufacturers guidelines (atLEAF, Delaware, USA). To account for differences in starting height (X_1) in planted individuals we calculated the final logarithmic relative growth rate using:

$$RGR = \frac{ln\, ln\, (X_2)\ - ln\, ln\, (X_1)}{t_2 - t_1}$$

Once sudden changes in leaf colour were observed during the 3rd week of the trial, a qualitative but standardized colour gradient (deep green to deep red) was used to track colouration weekly. This was converted to a "health status" with the healthiest and most vigorous individuals scoring a 5, and descending as signs of stress (leaf discolouration, loss of turgor, desiccation) increased, ultimately reaching 0 if the individual expired. Germination rate and the approximate percent cover of sown trembling aspen individuals was visually determined daily during the initial 2 weeks of the trial. Nine leachate collection systems were installed per treatment (plastic tubing directing leachate from bottom of growing cavity to sterile 500 mL glass bottles). Leachate was collected weekly, or when enough leachate was produced (~50 mL).

Phase 2 occurred for the final 5 weeks where the lighting regime remained the same, but precipitation was halted to simulate drought. During Phase 2, seedlings were tracked daily for signs of wilting and desiccation. Once Phase 2 ended, 9 surviving individuals from each treatment were randomly selected and excavated to determine root and shoot mass. The root zone was separated from the substrate manually and lightly rinsed with water, measuring wet length and mass. Roots were then left to air dry for 48 hours then reweighed. Shoot length was measured and shoots were weighed, then re-weighed after 48 hours of air drying.

<u>Soil and leachate analyses</u>

During phase 1, the substrates were tested for volumetric water content (VWC) and temperature (°C) of every individual (n=2736) on a weekly basis. Analysis was done in-situ, using an Accumet TDR150 unit with 6 cm probes installed (Massachusetts, USA). Throughout phase 2, one Onset (Massachusetts, USA) EC5 Soil Moisture Smart Sensor was installed for each treatment, wired to a HOBO U30 USB Weather Station Data Logger. The probes recorded every 5 minutes at a 5 cm depth to gain a higher resolution of changes in substrate conditions. Air temperature was determined using a 12-Bit Temperature Smart Sensor and hung in the middle of the greenhouse.

Prior to treatment construction, unamended substrate was collected from the bulk of the sieved material to form a composite (~1 kg). Once the substrate was amended with the residual, approximately 1 kg of material per treatment was taken directly from the cement mixer. Post-trial, composite samples were created by collecting the treatment layer from the same 9 individuals selected for root excavation, with approximately 1 kg of material collected per treatment. Pre and post trial aggregate substrate were analysed for base cation concentration, particle size and texture, macro and micro plant essential nutrients, trace metals, and soil organic matter content. Particular trace metals of concern were arsenic (As), lead (Pb), chromium (Cr), cadmium (Cd), and mercury (Hg). Analyses were completed by TestMark Laboratories (Greater Sudbury, Ontario, Canada) in accordance with standard operating procedure. Leachate samples were analysed for a collection of anions (total and available forms of N, total and available forms of P, DOC, DC, DIC, and DN) and a suite of metals (totals). Analyses were completed via ICP-OES and were conducted by the Natural Resources Analytical Laboratory (NRAL) of the University of Alberta.

Data analysis and visualization

Before conducting analyses, all data were tested for normality (Shapiro-Wilk), and if the data were found to be non-normally distributed, they were standardized using Box-Cox transformation. The effects of industrial residuals on seedling growth and chlorophyll content were assessed using a one-way ANOVA, with significance confirmed by Tukey's HSD test ($a = 0.05$). Effect size was determined using Cohen's D. Germination and survival rates were analyzed using a chi-square ($\chi2$) test, with significance confirmed via Cramér's V. To quantify the daily moisture loss in treatment substrates, an exponential decay model was employed. Soil moisture content was monitored over a specified period under controlled environmental conditions. Moisture readings were taken using an Accumet TDR 150 (Massachusetts, USA) to measure the percentage of moisture content remaining in the substrates. The observed moisture loss over time was modeled using an exponential decay function, defined as:

$$M(t) = M_0 \times e^{-kt}$$

where: $M\ (t)$ is the moisture content at time t, M_0 is the initial moisture content at t = 0, k is the decay constant representing the rate of moisture loss per day, and t is the time in days. The decay constant k was determined by fitting the model to the observed data using non-linear regression techniques, specifically the least squares method. This model was then used to estimate the rate at which moisture was lost from the substrates over the observation period, providing insights into the moisture retention characteristics of the different substrate treatments.

Redundancy Analysis (RDA) was used to identify the relationships between substrate properties and plant response across the different experimental treatments. Prior to analysis, the data were standardized (z-score) to ensure all variables contributed equally to the analysis, regardless of their original units or scales. The analysis first examined how substrate properties were influenced by the treatments, and then it identified which of these properties most explained the observed differences in plant response. To further interpret the results, canonical coefficients were calculated to identify the importance of each property in explaining the variance in plant response. Additionally, permutation tests were incorporated to assess the statistical significance of the RDA outcomes. This approach was chosen to ensure that the observed relationships were not due to random chance, thereby enhancing the robustness and reliability of the findings. We performed a cluster analysis to identify and group the effects of different industrial residual soil treatments on the growth of trembling aspen and yellow birch seedlings, allowing us to determine which treatments produced similar impacts on soil properties and plant growth, and to distinguish distinct patterns of response across the treatments and species.

We also generated soil fertility and plant performance indices (SFI and PPI respectively) to better visualize the multivariate response to soils and plants following industrial residual application. The Plant Performance Index is calculated by standardizing each measurement ($\frac{X_{ij}-\mu_i}{\sigma_i}$), summing the standardized values for each parameter ($\sum_{j=1}^{m}$), and then weighting these sums by the inverse coefficient of variation ($\frac{\mu_i}{\sigma_i}$). The final PPI is the sum of these weighted values for all parameters:

$$PPI = \sum_{i=1}^{n} \left(\frac{\mu_i}{\sigma_i} \cdot \sum_{j=1}^{m} \left(\frac{X_{ij} - \mu_i}{\sigma_i} \right) \right)$$

Soil texture and pH are non-linear values. Therefore, we calculated their Euclidean distances (D) from an "ideal" then assigned a score based on its inverse ($S = \frac{1}{D}$). We chose a pH of 6.5 (converted H^+ concentration) which we believe best mimics the soils of the region while maintaining low metal mobility risk. For texture we assigned the model to improve scores with decreasing sand content (up to 40%) and increasing silt and clay content (up to 20%).

$$D = \sqrt{([H^+]_{ideal} - [H^+]_{treatment})^2}$$

The SFI is similar to the PPI, but with the nutritional, physical, and chemical properties of the soil equally weighed:

$$SFI = (0.5 \times \sum_{i \in Nutrients} \left(\frac{X_i - \mu_i}{\sigma_i} \right)) + \sum_{i \in Structure} \left(\frac{X_i - \mu_i}{\sigma_i} \right) + \sum_{i \in Chemistry} \left(\frac{X_i - \mu_i}{\sigma_i} \right)$$

Analyses were conducted using the "vegan" package and visualizations using "ggplot2" in R-4.2.2 (R Core Team, 2024). Data management was conducted using Microsoft Excel (version 2403).

Results

Chemical and physical properties of substrates

Prior to amendment, the unamended substrate (CON) was largely infertile, with micro and macro nutrient levels well below those commonly found in the podzol and brunisolic soils of boreal forests (e.g., Rutkowski and Stottlemyer, 1993; Brais et al., 1995; Gower et al., 2000). Cation exchange capacity (CEC) was 2.9 meq/100g and pH was 6.6. Metals of concern included arsenic (As) (8.6 µg/g) and cadmium (Cd) (0.29 µg/g), while all other measured metals were below MDL. Organic matter was not detected (0.0%). Textural analysis classified the substrate as sand, composed of 91% sand, 4% silt, and 5% clay – though it did contain larger gravel stones as well prior to screen filtering.

Minimal organic matter content (0.4%) could be detected in the CON soil after the 20-week experiment. Organic matter content increased most in treatments amended with PMS: 12.2% (PPF), 11.1% (PP), and 10.9% (PPA). Unamended LSMB (NRICH) increased OM content to 3.5%, BBFA to 1.4%, and SUD to 1%. STOCK contained negligible (0.4%) SOM. Modifications in soil texture were observed following residual application. Following treatment with PPF, soils showed a decrease in sand to 74%, an increase in silt to 11%, and an increase in clay to 15%. Similar changes were observed following application of NMC, PP, and PPA. SUD, AF, while NRICH did not appreciably change soil texture (Table 1). The addition of industrial residuals significantly improved the fertility of the aggregate substrate. In all treatments, plant-essential macronutrient levels increased significantly, as did essential base cations (particularly Ca) and CEC ($p<0.001$). Increases were greatest in PMS amended soils, followed by LSMB and BBFA.

Table 1 - Results of a comparative analysis of nutrient enrichment in soil treated with various industrial residuals (t=20 weeks).

Parameter	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 addition of industrial residuals was tied to improvements to soil moisture retention in both phases of the trial. When compared to CON, the PPA treatment significantly improved water retention throughout the first phase of the trial (15.7 +/- 0.3%) ($p<0.001$), with VWC remaining above or near the standard permanent wilting point (PWP) of sandy soil (~5-10% VWC) (Wiecheteck et al., 2020). Similar trends were observed with the remaining PMS and BBFA treatments. All remaining treatments struggled to retain moisture, consistently sampling near or below 5% VWC for the entirety of the phase 1 trial. Overall, significant differences in soil moisture were observed across three groups—decreasing in the order of: A) PPA > B) PP, PPF, AF > C) NMC, NRICH, CON, SUD (Fig. 1) ($p<0.001$). In group C, NMC moisture rates averaged 4.07 +/- 0.14% for the first phase of the trial. This was marginally greater (but still statistically significant) than SUD (2.58 ± 0.09%), NRICH (3.01 ± 0.10%), and CON treatments (3.10 ± 0.12%) (p=0.041). No significant differences were observed within group B (p=0.54). In phase 2, a decay model determined the relative rate of exponential moisture loss. Here, we see slight but statistically significant differences in weekly moisture loss rate between PPF, PP, PPA, AF treatments (16.5% loss/wk) and remaining treatments (17.8% loss/wk) (p=0.002). In the PMS and BBFA treatments, we estimate a 10–12-day window from the onset of drought where moisture rates remain adequate for plant growth (above permanent wilting point) (Fig. 6).

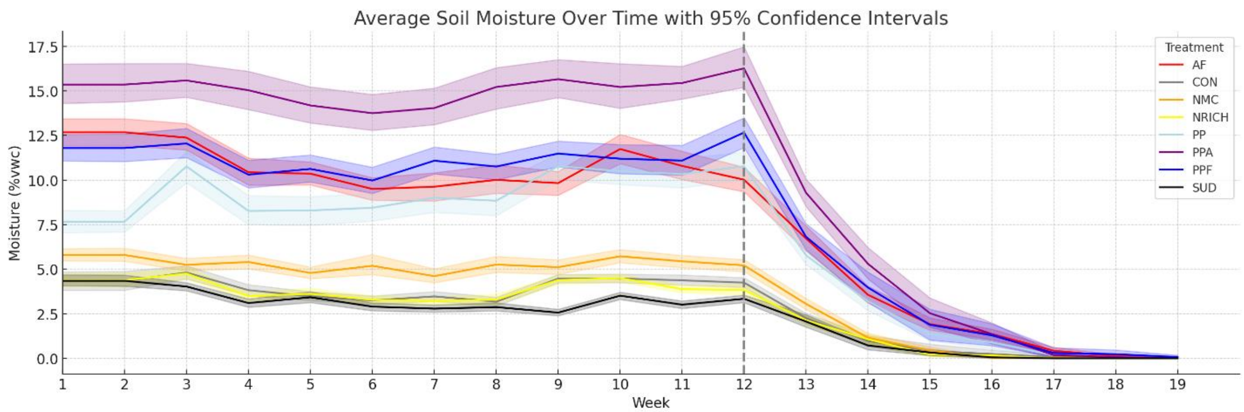

Figure 6 - Temporal variation in soil moisture content across different treatments with 95% confidence intervals. Soil moisture content is expressed as a percentage of water by volume (vwc%) and was monitored over a 19-week period. Treatments indicated by the color key. The vertical dashed line at week 12 denotes the onset of an experimentally induced drought period, illustrating the response of soil moisture levels to the cessation of watering across all treatments. Note the varying degrees of moisture retention and the rates of decline in moisture content post-drought induction among the different treatments.

The Soil Fertility Index (SFI) highlights improvements in all aspects of the soil following PMS amendment, with more moderate improvements in those amended with LSMB and BBFA (Fig. 7). In the latter, we see improvements in the chemical and nutrient fractions, but little improvement in structure. We see similar trends in SUD amended soils, where nutrient fractions have improved moderately, chemistry minimal so, with no improvements to structure.

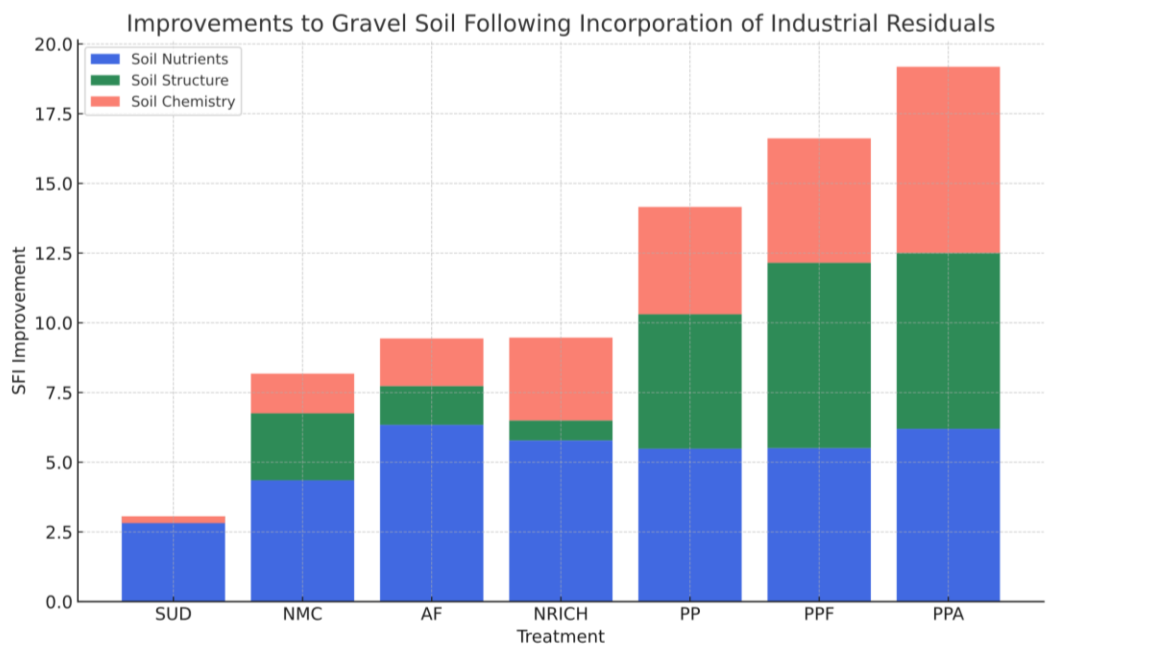

Figure 7 - Normalized contributions of nutrient availability (blue), soil structure (green), and chemical properties (red) to the overall Soil Fertility Index (SFI) for each treatment, with the control (CON) set as a baseline (0).

Arsenic was present in all treatments, but As concentrations did not differ between treatments ($p>0.05$) (Fig. 8). When compared to CON soils, Cd levels increased across all treatments, with the highest increase in PPF (2.26 µg/g), followed by slight increases in PPA (1.64 µg/g), PP (1.51 µg/g), NRICH (0.62 µg/g), AF (0.57 µg/g), and NMC (0.32 µg/g) (p=<0.05). For Cr, all treatments showed an increase, with NMC exhibiting the most substantial rise (10.8 µg/g), followed by NRICH (7.5 µg/g), PPF (6.2 µg/g), PPA (4.4 µg/g), PP (3.1 µg/g), and AF (2.7 µg/g) ($p<0.05$). Lead concentrations were higher in all treatments, notably in NRICH (41.4 µg/g), NMC (22.4 µg/g), PPF (2.8 µg/g), AF (2.0 µg/g), PP (1.6 µg/g), and a smaller increase in PPA (0.1 µg/g). Mercury was not detected in any treatment (MDL = 0.05 µg/g) (Fig. 8).

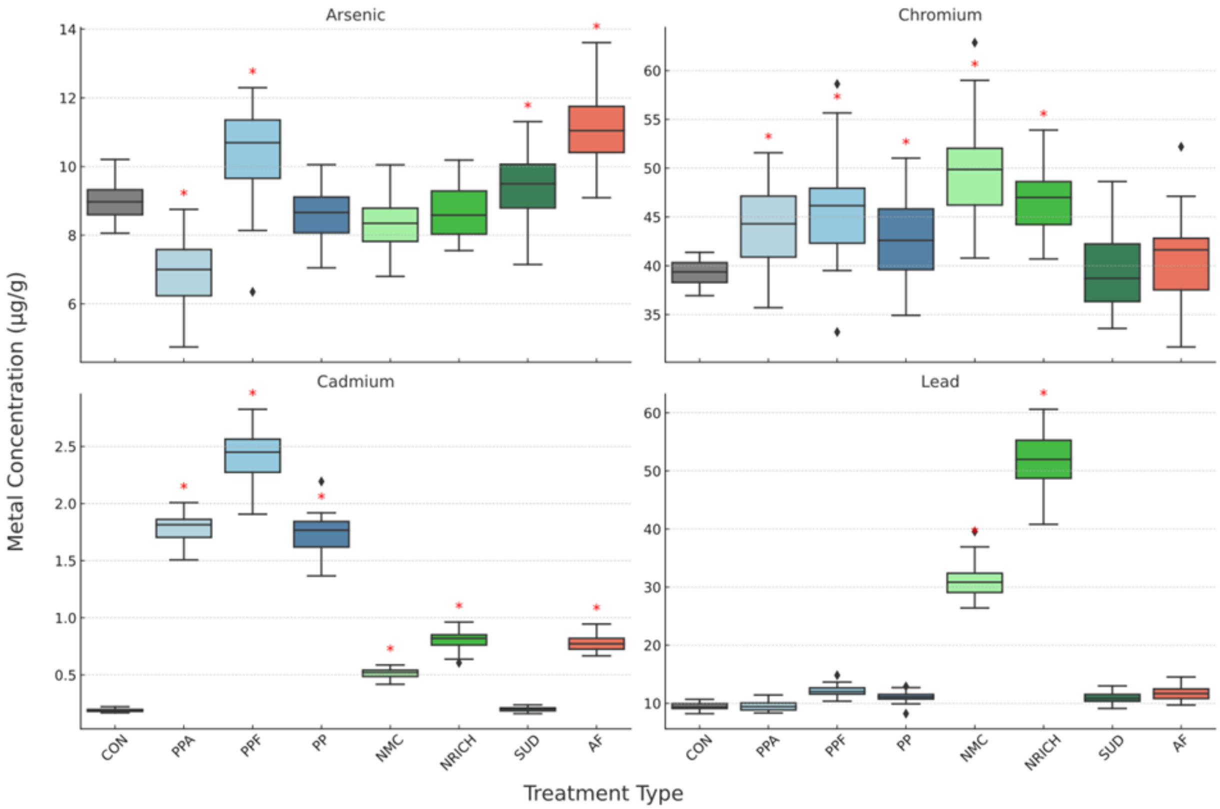

Figure 8 -Box plots illustrating the concentrations of four heavy metals (Arsenic, Chromium, Cadmium, and Lead) in soil samples across various treatment types. Each subplot shows the distribution of metal concentrations (in µg/g) for different treatment groups, labeled along the x-axis. Red asterisks (*) denote statistically significant differences in metal concentration between treatment types. The black diamonds represent outliers within each treatment. This comparison highlights how different treatments affect the accumulation of heavy metals in soil, with notable variability across metals and treatments.

<u>Leachate Composition</u>

The addition of industrial residuals generated leachate which largely did not contain metal concentrations in excess of CCME guidelines with respect to aquatic health. The exception being Cu, which maintained leachate concentrations above the recommended guideline of 4 µg/L in all treatments for the duration of the trial (CCREM, 1987). This was not observed in CON, where Cu content was found at MDL in all but 1 sample from the initial sampling period. Total P losses were observed in all treatments and often breached the Canadian Trigger Range for long-term risk of hyper-eutrophication (100 µg/L) (CCME, 2004). Losses in exceedance of CCME guidelines were observed during the entire sampling period but were temporally variable across treatments. Total P losses were greatest in SUD amended soils, which decreased from 987 µg /L to 610 µg/L, and finally 137 µg/L by the end of the trial. Total P losses were lowest in LSMB amended soils, with only 1 of 18 samples exceeding the threshold (117 µg/L). BBFA total P increased with time, ranging from 73.5 µg/L to 134 µg/L but generally remained below the guideline.

PMS treatments hovered near the guideline but generally remained above it, averaging 135.9 µg/L by the end of the trial. Orthophosphate (PO_4-P) followed similar patterns to total P, however exceedance is difficult to quantify as turnover is rapid (CCME, 2024). Nitrate losses were ephemeral, and only so in PMS treated soil where losses averaging 25.2 µg/L in PP and PPF, and 15.1 µg/L in PPA – slightly in exceeding of the 13 µg/L threshold (CCME 2024). All other treatments were well below the exceeded threshold. CCME quantifies NH_4 risk to aquatic bodies along a temperature and pH gradient, where cool and acidified freshwater bodies are at the lowest risk. Similar trends were observed for NH_4, where we observed initial losses in PMS followed by a significant decline. Assuming spring lake temperatures of 5°C and a pH of 6.5 the NH_4 threshold is 48.3 µg/L. Initial exceedances occurred in SUD, AF, NMC, and all PMS treatments. These were most elevated in PMS treatments, with PPA registering 332.2 µg/L. By the end of the trial only PMS values exceeded the threshold averaging 61.1 µg/L (Fig. 9).

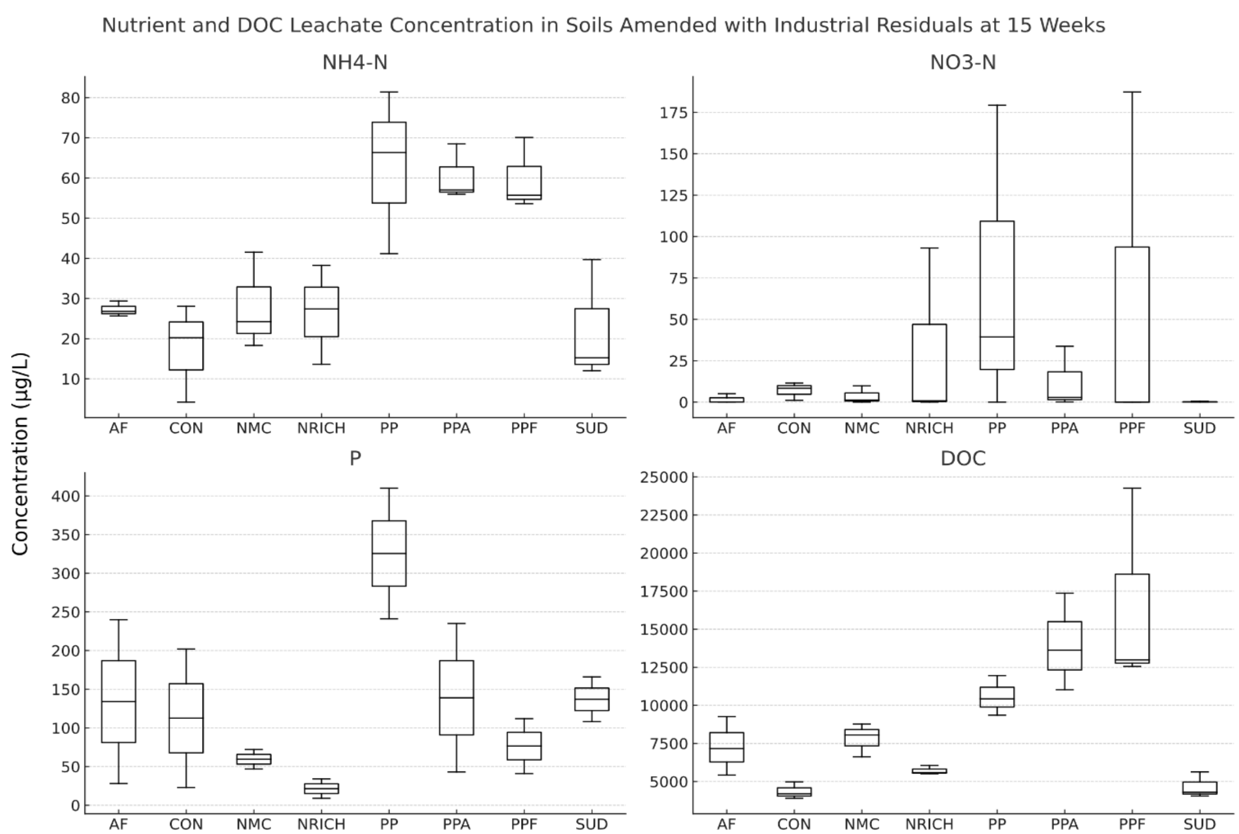

Figure 9 - Box plots of nutrient (NH4-N, NO3-N, and P) and dissolved organic carbon (DOC) leachate concentrations in soils amended with industrial residuals at 15 weeks. The treatments are compared to evaluate the impact on soil leachate composition. Concentrations are presented in µg/L, highlighting variations among different soil amendments.

Survival and Germination Rate

Trembling aspen seeds sown directly into gravel saw 40.7% successful germination. In contrast, germination rose in gravel amended with PPA to 80.8%. NMC (75.9%), AF (75.4%), PPF (72.4%), and NRICH (57.1%) saw significant improvements to germination rate as well ($p<0.001$). SUD (49.1%) and PP (44.4%) showed slight but significant improvement to germination rates compared to controls ($p<0.05$). In gravel soil (CON), 18.2% of sown individuals exhibited percent cover values equal or greater than 20%, with the remaining only covering between 1% to 5%. In contrast, all other treatments saw significant improvements in percent cover. The combination of PMS and BBFA (PPA) had especially beneficial results with 74.4% and 64.4% of individuals exhibiting equal or greater than 20% cover ($p<0.001$). NMC, AF, PP, and PPF saw similar improvements (>35%) ($p=<0.01$). The expanse of vegetated cover in SUD and NRICH amended individuals were within 5% of CON. Once germinated, 85.7% of CON seedlings survived until the end of the first phase of the trial. Only BBFA had significant beneficial effect (93.0%), while SUD and PPA had negative effects (78.6% and 61.9%) ($p=<0.05$). All other treatments had no significant effects.

The survival rate of successfully germinated seedlings varied across treatments. Control seedlings (CON) had a survival rate of 85.7%. The highest survival rate was observed in AF (93.0%), suggesting a positive effect of this amendment ($p<0.001$). NMC (86.4%) performed similarly to the control, while PP (80.6%), PPF (80.0%), and SUD (78.6%) exhibited slightly lower survival rates – though significance was detected in the latter ($p<0.01$). The most pronounced reductions in survival were seen in NRICH (71.9%) and PPA (61.9%), indicating that these treatments may have negatively impacted seedling establishment ($p<0.001$).

Yellow birch exhibited consistently high germination rates across all treatments. The control (CON) had a germination rate of 96.0%, the highest among treatments. The most improved germination occurred in PPA (97.8%), slightly surpassing the control. Other treatments that maintained high germination rates included PP (94.1%), AF (90.6%), and PPF (90.0%). Lower, but still relatively strong germination rates, were observed in NRICH (89.4%), SUD (84.7%), and NMC (84.4%), suggesting some moderate reductions compared to the control.

Regardless of the treatment, all successfully germinated yellow birch seedlings survived to the end of the study. This suggests that survival was not impacted by the applied treatments and that once germinated, yellow birch seedlings exhibited 100% survival across all conditions (Fig. 10).

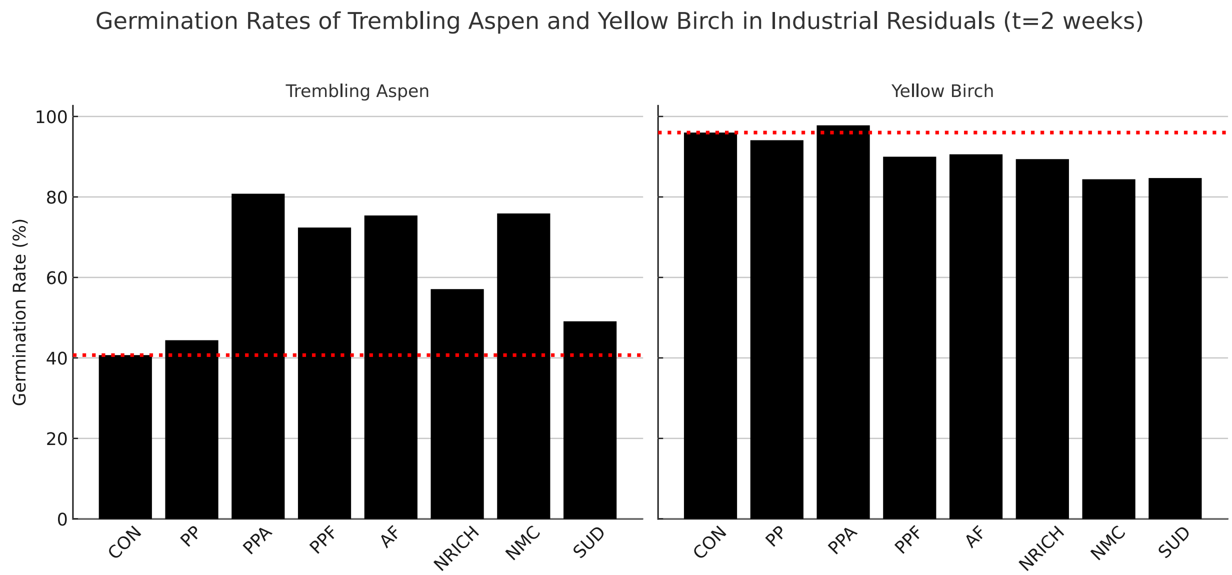

Figure 10 – Rate of successfully germinated individuals tracked 2 weeks from experiment start date. Horizontal red dotted line is included to compare the germination of species sown in the unamended aggregate substrate (CON)

<u>Plant Growth</u>

Seedling productivity was severely inhibited in CON soils, registering the lowest final heights in both sown and planted individuals of either species. Industrial residuals generally had a very positive effect on both above and below soil growth – especially in sown individuals.

In unamended aggregate substrate (CON), sown trembling aspen average daily increases in stem slightly greater than 2.5 ± 0.9% - being quite variable. Overall, PMS treatments (PPF>PPA>PP) improved growth rates (daily increases in stem height) significantly against all other treatments – growing an average of 5.9 ± 0.4 % every day for sown trembling aspen ($p<0.0001$). SUD and NRICH treatments were also moderately beneficial, but variable and statistically significant – averaging 4.1 ± 0.9% and 3.9 ± 0.7% every day ($p<0.0001$). AF and NMC offered similarly mild gains but were again highly variable – averaging 3.2 ± 0.9% and 3.5 ± 0.9 respectively while retaining significance ($p = 0.0007$). These treatment effects were most clearly visible in sown species, as well as planted yellow birch – e.g., where mean PMS gains over CON were >6000% consistently. Only in planted yellow birch were stem length increases muted (as seen in Fig. 11), though relative increases against CON were still significant (Fig. 11).

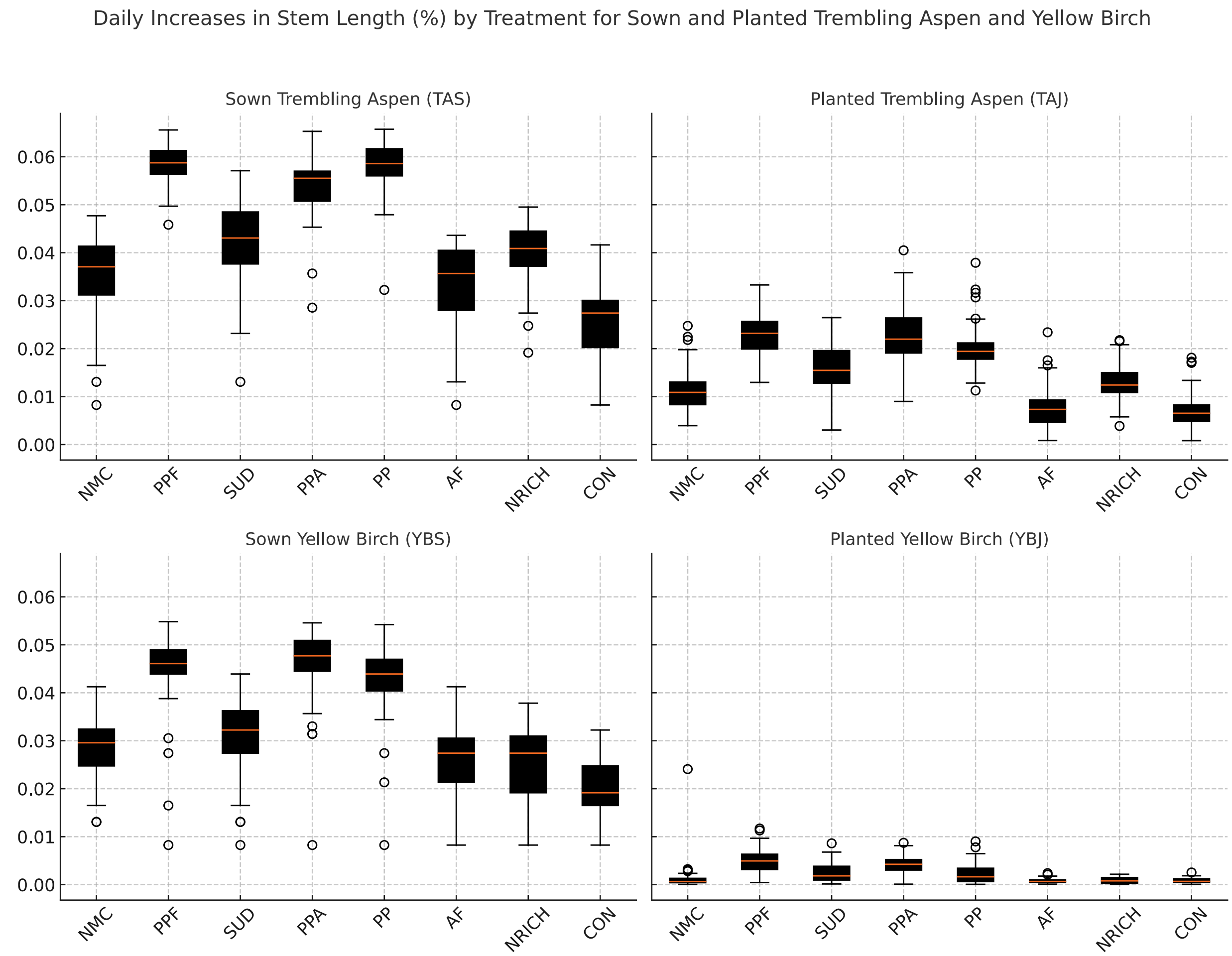

Figure 11 - The above graph represents the average daily increases (%) in stem length from t=0 to t=12 weeks. Orange bars indicate the median.

PP, PPA, and PPF were again beneficial to stem diameter growth, exhibiting increases of 288%, 329%, and 362% over CON (P=<0.0001). SUD had similar but more mild effects (174%) ($p<0.01$), while AF, NMC, and NRICH had more mild effects (24.9%, 63.0%, 59.1%). Sown trembling aspen showed similar patterns, with PP, PPA, and PPF treatments increasing RGR by compared to controls ($p<0.001$). Again, remaining treatments did improve growth, but moderately so ($p<0.05$). Leaf chlorophyll content matched growth rates well, with coefficients of determination of 0.62 and 0.49 for planted yellow birch and trembling aspen seedlings. Here, PMS, LMBS, and BBFA treatments resulted in twice the leaf chlorophyll content seen in controls in both planted species ($p<0.001$) while SUD showed statistically insignificant increases ($p=0.24$). Planted trembling aspen leaf chlorophyll content (LCC) was low in CON soils – registering an average of 0.11 g/m^2 (± 0.02). In contrast, LCC was raised 0.41 g/m^2 (±0.16), 0.32 g/m^2 (±0.11), and 0.35 g/m^2 (±0.07) in seedlings planted in PP, PPA, and PPF soils (p=<0.001). AF and NMC improved LCC as well (0.27 g/m^2 ±0.12) (0.25 g/m^2 ±0.07), while NRICH had significant but very mild positive effects (0.21 g/m^2 ± 0.06 and 0.19 g/m^2 ± 0.04) (p=<0.05). SUD had no effect (0.15 g/m^2 ±0.06) (p=0.26).

Leaf colouration and general stress responses were collected as well. The outward health status of both planted and sown yellow birch generally benefited from PMS amendments. Here, >95% of all individuals were described as being in "excellent" health – with no leaf discolouration or loss of turgor by the end of phase 1 of the trial. AF, NRICH, NMC, and SUD were similarly beneficial with 88.3%, 75.9%, 91.5%, and 76.6% of individuals labelled as being "excellent" or "good" health. Chlorosis and light green colouration were common sources of stress here. In contrast, 58.9% of those planted or sown in CON soils were of "poor" (10.9%) or "fair" (48.1%) health. Sown trembling aspen had often expired or showed significant discolouration for most treatments. Here, PPF, NMC, and AF exhibited appreciable fractions of individuals of "good" or "excellent" health (27.7%, 32.6%, and 40.0% respectively) when compared to CON (14.3%). SUD (11.4%), NRICH (11.1%), and PPA (11.5%) which indistinguishable from CON individuals. Planted trembling aspen responded much more positively. Here, only 32.9% of CON individuals were considered of "excellent" or "good" health. In contrast, AF, NRICH, NMC and PPA were significantly healthier (74.2%, 58.7%, 57.4%, 56.7%). PP and PPF individuals were also healthier overall (48.9% and 40.0%). Planted trembling aspen did not respond well to SUD however, with only 12.2% of individuals reporting as being of "good" or "excellent" health. Here, reddening of leaf tissues was common, while necrosis was the most stressor response observed in other treatments.

Root growth and habit was also investigated. PPA had particular benefits on root length and mass for both species. Here, the inclusion PPA increased yellow birch root mass by 15.3% and root length by 27.4% when compared to CON ($p<0.01$). PP and PPF similarly improved yellow birch root growth. The remaining treatments often negatively impacted root growth, though insignificantly. NRICH saw significant decreases in root length (27.5%) ($p<0.01$). Similar patterns were observed in planted trembling aspen individuals as well. In PMS and NMC treatments, root mass was concentrated in the treatment layer (<7.5 cm depth), with a smaller number of exploratory roots delving into deeper soils. The latter was seen in all other treatments, with root growth focused entirely on long individual roots reaching towards the gravel layer (>7.5 cm depth). This occurred in both species. These values have been normalized, weighed, and summed to produce the below Plant Performance Index for both planted and sown yellow birch and trembling aspen trees (Fig. 12.)

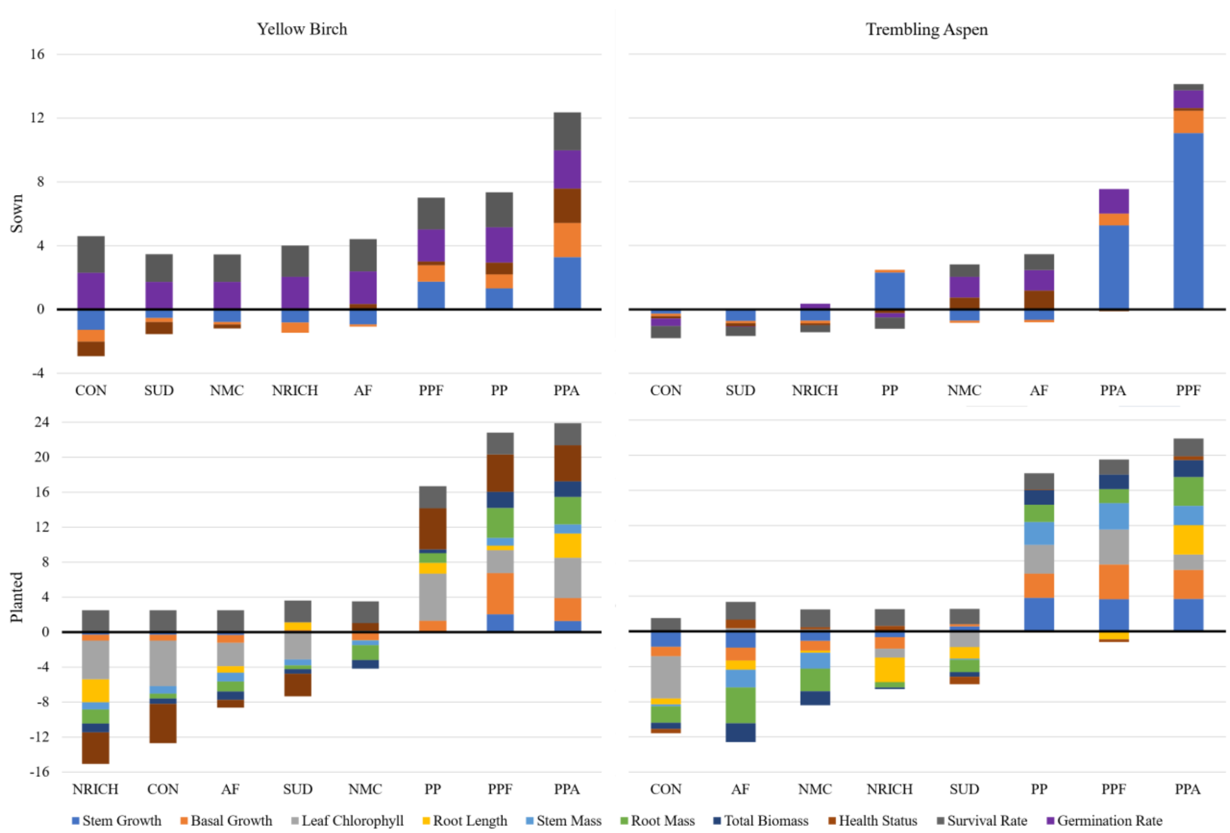

Figure 12 - Comparative Plant Performance Index (PPI) of standardized growth and health responses of seedlings grown in industrial residuals (t= 12 weeks). Each coloured bar segment of the stacked column represents its weighted contribution. Any values above 0 are considered greater than the overall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

Drought symptoms were delayed in yellow birch and trembling aspen seedlings planted or sown in PMS treatments. Here, plants remained turgid for 6 days and began to desiccate in 6 days. NMC individuals maintained turgidity for 36 hours then rapidly expired. In contrast, individuals in NRICH, SUD, and CON soils lost turgidity within 8 hours, and began to desiccate within 24 hours.

There was a strong beneficial effect of PMS treatments to overall plant growth and health. In planted individuals of both experimental species, every metric of plant performance in PMS treatments was much greater than the mean of the dataset, while also retaining low coefficients of covariance. In sown trembling aspen individuals, unamended PMS (PP) performed more poorly than expected. While stem and basal growth was improved, survival and germination rates struggled, leading to a standardized lower sum. In sown individuals, stem growth was exceptionally greater in PMS amended with BBFA or forest floor inoculum, mirroring earlier results. LSMB treatments performed poorly, typically displaying lower than average growth rates (stem and root), with leaf tissues high in discolouration and stress indicators. Similar trends were observed in SUD treatments: lower than average growth, survival, and germination rates with poor overall health.

The beneficial linkages between improved soil fertility and plant growth and health indicators are further confirmed through a redundancy analysis (Fig. 13). Here, we see exceptionally strong ties between the PMS treatments and measured soil variables. Furthermore, the explanatory power of the analysis is significant, with both axes explaining 89.6% of the variability in plant data. Additionally, we see strong linkages between plant response variables (e.g., CHLO for leaf chlorophyll content) and NO_{3-} concentrations, indicating the latter strongly influences the former. Furthermore, we see the relative growth rate of the plant stem and basal diameter is strongly linked to total P (ppm). Similar relationships were observed in planted trembling aspen seedlings as well, where above and below ground growth was positively correlated with NO_3^-. Here, 90.9% of the variation in plant parameters was explained with soils properties.

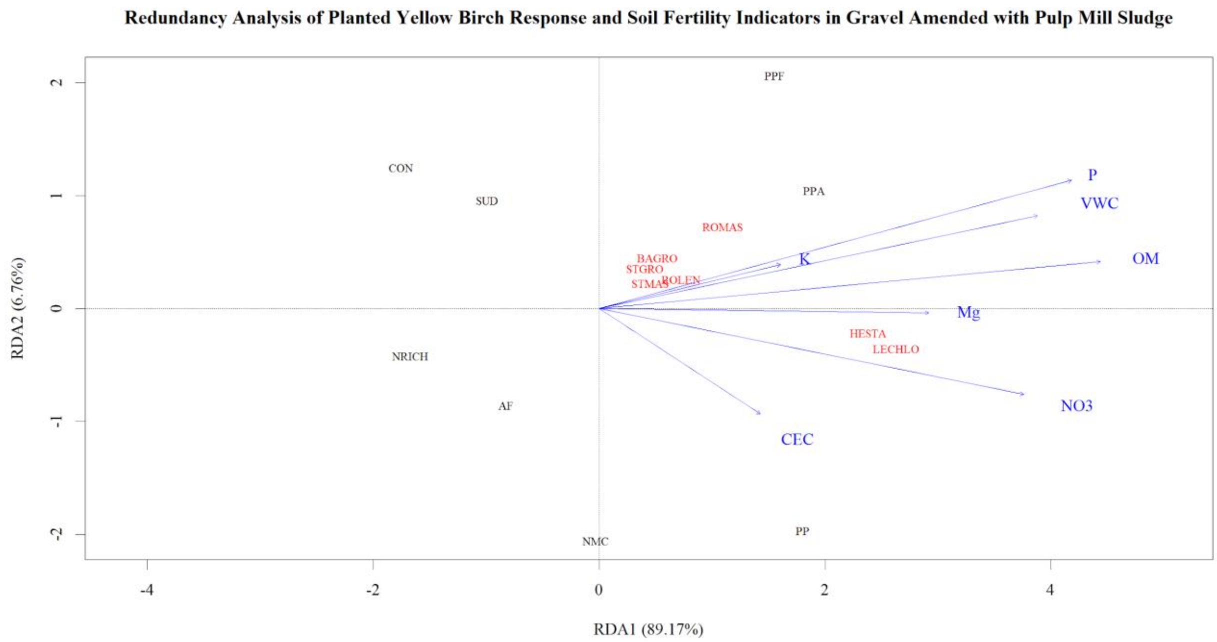

Figure 13 - RDA biplot showing the associations between soil fertility indicators (blue vectors) and plant response variables (red labels) of planted Yellow Birch following the amendment of gravel with industrial residuals. The proximity of plant response variables to soil fertility vectors suggests a correlation with the respective soil properties. PMS treatments (PPF, PPA, PP) indicate distinct clustering, reflecting their beneficial influence on both soil fertility and plant responses.

The canonical loadings reveal that organic matter (OM) (0.93) and volumetric water content (VWC) (0.87) are indeed highly influential in determining yellow birch and trembling aspen growth outcomes – though these were collinear with a Pearson coefficient of 0.84. These factors, along with phosphorus (P) (0.79) cation exchange capacity (CEC) (0.72), significantly contribute to the overall soil fertility and plant health. Permutation tests with 9999 permutations confirmed the significance of this axis ($p < 0.001$), indicating a strong relationship between the soil properties and the plant response that is unlikely to be due to random chance.

Cluster analysis further highlights the effect of industrial residuals on soil parameters and plant outcomes (fig. 14). Here, we observe 3 distinct groups: a) CON and SUD; b) AF, NRICH, and NMC); and c) PP, PPA, and PPF (Figure 14). Clusters were fairly tight and separate, with a within cluster sum of squares (WCSS) score of 101 and a between cluster sum of squares (BCSS) of 124. Moderate overlap was observed with a mean silhouette score of 0.28. Score clusters were significantly separated along both principal components ($p=0.0000501$ and $p=0.00235$). Specifically, clusters a) and b), and b) and c) were significantly separated along PC1, and clusters a) and b) retaining significance along PC2.

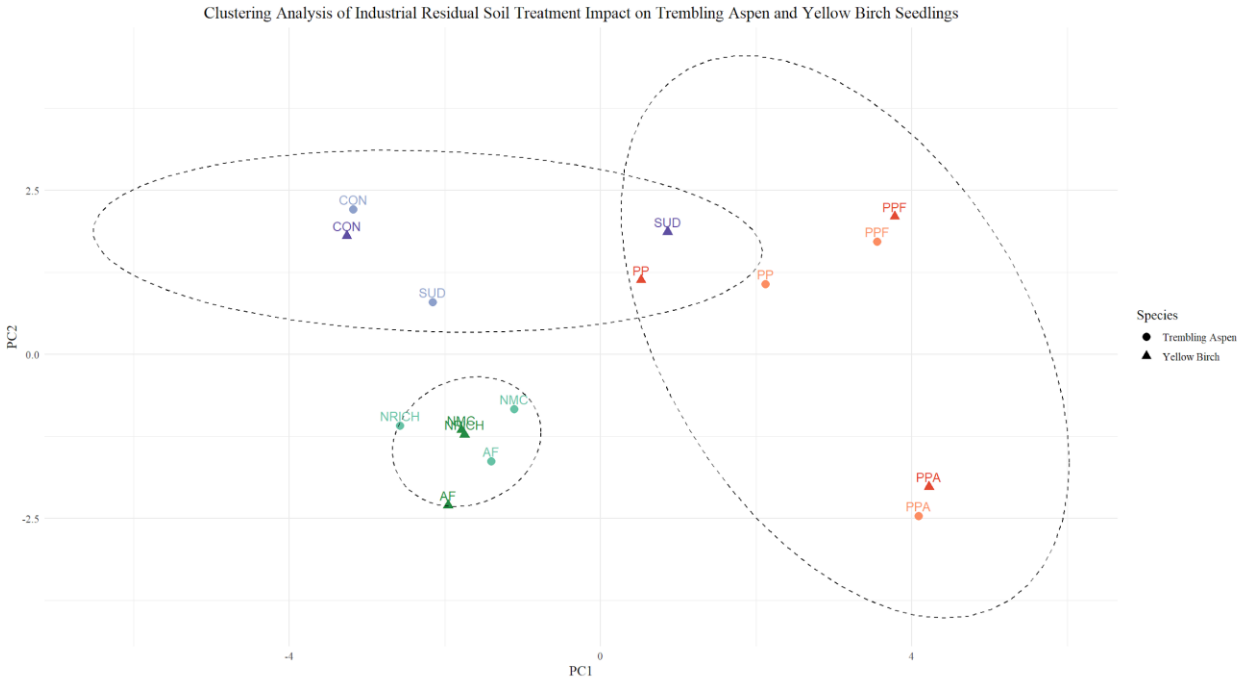

Figure 14 - K-means clustering reveals 3 distinct groups based on their soil and plant properties: A) Control (CON) and Sudbury Regreening Treatment (SUD); B) Lime stabilized biosolids (NRICH) with municipal compost (NMC), biomass boiler fly ash (AF); and C) blended pulp sludge (PP) with BBFA (PPA) or forest floor inoculum (PPF). This figure also highlights the species effect as well.

Discussion

Soil Structure and Nutritional Response

The aggregate substrate used in this experiment lacks essential plant nutrients, organic matter, clay fractions, moisture, and nutrient retention capacity to support higher forms of plant growth. Plant communities struggle to recover when these soils are left to passively recolonize, even up to one century following abandonment (Rehounková and Prach, 2010). Consequently, it is imperative for reclamation efforts to enhance the physical and chemical characteristics of these disrupted soil-precursors prior to revegetation.

The industrial residuals used in this study were expected to elevate the levels of plant-essential nutrients given their nature and manufacturing processes. As expected, we observed comprehensive improvements in the nutritional status of the amended gravel for all treatments. However, we observed treatment-specific effects of N availability. The blended PMS used was elevated in total N because of ammonium used in one of the mill's pulping processes. Ammonium ions from ammonium sulfite primarily end up in the process water and are subsequently carried into the mill's wastewater stream. In the wastewater treatment plant, these ammonium ions are typically partially converted to nitrate through biological treatment processes and taken up by microbial biomass. Nitrate, ammonium, and TKN were therefore perhaps unsurprisingly elevated throughout the trial. Given secondary sludges from WWTPs also may contain active N mineralizing and nitrifying bacteria, and considering the specific pulp mill at hand, we expect both mineralization and nitrification to have actively occurred and contributed to our result of higher levels of multiple forms of N (Harms et al., 2003; Figuerolo and Erijman, 2010).

However, we noticed a significant decrease in nitrate content in the PMS variant amended with BBFA (PPA). The addition of BBFA increased soil pH moderately in PPA soils (7.7) compared to the unamended (PP) (6.6) and inoculated (PPF) (6.8) counterparts, which remained neutral. This aligns with studies showing that nitrate amendments can influence soil pH, with nitrate additions often decreasing pH while ammonium-based amendments can lead to acidification (Zhang et al., 2017). The enzymes responsible for the mineralization of organic nitrogen, such as proteases, ureases, and amidases, are primarily produced by soil bacterial communities, including genera like Bacillus, Pseudomonas, and Actinobacteria (Wang et al., 2023). These bacteria secrete these enzymes to break down complex organic nitrogen compounds into simpler forms, such as ammonium (NH_4^+) and nitrate (NO_3^-), which are essential for plant uptake. Both the bacterial communities and their associated enzymes are highly sensitive to pH, which directly impacts their activity, growth, and overall metabolic function (Olaya-Abril et al., 2021).

In neutral to slightly acidic conditions (pH 6.0 to 7.5), these enzymes operate efficiently, and the bacteria thrive, leading to optimal nitrogen mineralization. However, in acidic environments (pH < 5.5), the activity of these enzymes declines significantly as excess hydrogen ions (H^+) disrupt their structure, while the bacterial cells themselves experience membrane stress and reduced growth (Geng et al., 2020). Conversely, in highly alkaline conditions (pH > 8.5), both the bacteria and their enzymes face challenges; the enzymes may lose functionality due to the disruptive effects of hydroxide ions (OH^-), and the bacteria may experience inhibited growth and activity (Saghaï et al., 2023). In extreme alkaline environments (pH > 10), enzyme activity may nearly cease, and bacterial populations can decline sharply, severely limiting the conversion of organic nitrogen into plant-available forms. This pH-induced stress on both the enzymes and the bacterial communities can lead to reduced soil fertility and impaired plant growth (Zhang et al., 2017).

Previously reported effects of BBFA on microbial nutrient cycling are variable. Long-term studies indicate that wood ash may stimulate net N mineralization in Norway spruce stands following the neutralization of acid soils (Jansone et al., 2020). Oldare and Pell (2009) observed a decrease in the conversion of organic nitrogen or nitrate following wood fly ash application to agricultural soils, potentially as a result of toxic metal accumulation but more likely linked to significant soil alkalinization. BBFA is a highly alkaline product rich in calcium oxides which are concentrated during combustion. It is possible the addition of BBFA to PMS generated alkaline conditions unfavourable to nitrification, explaining our observed results. Wong and Wong (1986) speculated that BBFA may create alkaline "hotspots" which could stress microbes, reducing overall nitrogen turnover rates. While nitrate levels were indeed lower in PPA, the elevated nitrogen stocks present mitigate any negative impact on plant growth. This lowered rate of accumulation may be due to an initial pH-driven "lag" – where initial alkaline soil conditions could decrease mineralization rates, which would eventually recover as the ash would interact with the slightly acidic sludge. In fact, the reduced nitrate turnover may help decrease nitrate loss through leaching. Though the pH of this treatment was slightly higher than those not amended with BBFA, these "hotspots" may not be fully captured by our bulk sampling efforts. Indeed, a similar study has shown that alkaline-treated sludge with fly ash initially inhibited organic nitrogen mineralization during the first 90 days of application. However, after 360 days, the inhibition effects disappeared, and mineralization was enhanced, suggesting an initial pH-driven lag in mineralization recovery (Topaç et al., 2008).

Organic nitrogen and ammonia are the primary forms of nitrogen found in LSMB (Wang et al., 2003; Castillo et al., 2010). These require transformation to NH_4 or NO_{3-} for plant uptake. Although TKN levels were elevated at the beginning and end of the trial, nitrification was apparently slow, and by the end of the trial, nitrate comprised only 2% of TKN, compared to 50% in PMS. This outcome was anticipated due to the neutralization of biologics in the substrate by liming (CaO) raising pH to >12, which stabilizes the residual for long-term storage. Consequently, it can be inferred that the microbial nitrification potential of the gravel soil is also low. Again, the mineralization potential of any remaining bacterial communities is expected to be severely disrupted by elevated pH – which averaged 8.8 but regularly reached >12. There is likely to be a lag in plant uptake and overall site revegetation efficiency as a result. Given BBFA was directly amended with plant-available forms of synthetic nitrogen to form our "AF" treatment, NH_4^+ and NO_3^- accounted for nearly 100% of TKN.

Following the incorporation of the PMS amendment to gravel, SOM increased from 0 to an average of 11%. This was expected given the elevated presence of carbon rich, ped forming fibres and microbial biomass in the residual. The organic, porous, humus-like fibres absorb water at elevated rates (Camberato et al., 2006). Organic matter is critical in the proper functioning of soil-plant interactions, especially in disturbed substrates such as those affected by aggregate mining. It helps regulate soil temperature, promotes gas exchange in the rooting layer, and increases nutrient and moisture holding capacity (Fageria, 2012). Furthermore, organic soil layers foster healthy and diverse biological communities, which are crucial for successful land reclamation efforts. These communities enhance soil structure, improve nutrient availability, and increase resilience against erosion and degradation, making them essential for restoring and maintaining the health of reclaimed gravel landscapes (Thiele-Bruhn et al., 2012). The restoration of SOM in these disturbed environments is critical not only for improving soil physical properties but also for preventing further degradation and ensuring long-term sustainability (Cotrufo et al., 2010). Upper mineral soil horizons of boreal forest soils (e.g., Ae) are typically 3-5% SOM, lower than our experimental PMS soils (Sanborn et al., 2011). However, we expect SOM levels matching our experimental results to be better suited for the revegetation of borrow pits given its importance in our results, and that the aggregate substrates also lack mineral horizons and Ah horizons commonly observed under north temperature and boreal forests even when growing on very coarse mineral soil parent material substrates.

Perhaps most critical are continued inputs and plant material to these soils. Plant inputs, particularly leaf litter, contribute significantly to SOC accumulation in post-mining landscapes. Research on bauxite mine rehabilitation in Australia indicates that litter accumulation is higher in restored forests than in native reference sites, suggesting that litterfall plays a key role in organic matter input and nutrient cycling (Tibbett, 2010). However, the stability of this newly accumulated carbon remains uncertain, as much of it exists in labile particulate organic fractions susceptible to rapid mineralization and loss as CO_2.

In coarse-textured soils, litter chemistry influences carbon stabilization. Huys et al. (2022) found that high-lignin-content litter enhances SOC stabilization, whereas nitrogen-rich litter promotes rapid decomposition and potential carbon loss (Huys et al., 2022). These findings underscore the importance of species selection in reclamation efforts, as plant functional traits directly affect long-term soil carbon dynamics. Aggregate formation is essential for improving soil structure, water retention, and nutrient availability in degraded substrates. The decomposition of plant inputs facilitates aggregate stabilization, as demonstrated in studies of tree litter decomposition in lignite mine spoil heaps. Horodecki and Jagodziński (2017) found that tree species selection significantly influenced litter decomposition rates and, consequently, the efficiency of soil restoration. Rapid decomposition promoted faster nutrient cycling and soil aggregation, supporting the hypothesis that afforestation strategies should incorporate species that optimize these processes.

Further supporting this, Bucka et al. (2020) examined soil organic matter accumulation in post-mining soils and found that the addition of fresh plant litter greatly enhanced microbial activity and aggregate formation (Bucka et al., 2020). The study concluded that plant inputs drive the formation of macroaggregates (0.63–30 mm), which store over 80% of total soil organic carbon, further reinforcing the role of LFH in soil stabilization. Soil microbial communities play an essential role in organic matter decomposition and nutrient cycling, yet many post-mining soils lack the microbial diversity necessary for these functions. The decomposition of leaf litter fosters microbial biomass accumulation, influencing microbial succession and soil functionality. Research on gold mine tailings in Queensland found that nutrient cycling capacity improved rapidly in reclaimed sites with significant litter decomposition, though microbial biomass accumulation remained a limiting factor, requiring up to a decade for full recovery (Grigg, 2002). This finding emphasizes the need for sustained organic matter inputs to support long-term microbial colonization in reclaimed soils.

Conversely, in LSMB, BBFA, and SUD treatments SOM either did not increase, or increased only marginally. This was somewhat expected as BBFA is a combustion product (where much OM has been lost) and not designed to deliver broad-spectrum improvements to the physical structure of the soil. In Boreal Forest soil, BBFA is typically used to amend specific plant growth inhibitors such as acidity or low base cation content (Pugliese et al., 2014). However, given the elevated fraction of fine sized particles, BBFA can fill in the spaces between soil particles, increasing the soil's overall surface area and its capacity to hold water (Adriano and Weber, 2010; Skousen et al., 2013), potentially mitigating the water stress plants experience in sand and gravel soils. Gorgolewski et al., (2015) similarly noted that wood fly ash improved soil moisture retention in a field addition trial in a managed Central Ontario forest.

Organic matter contents of wood ashes can vary widely depending on boiler type and feedstock (Pugliese et al., 2014). In our study BBFA amended soils retained moisture at rates similar to PMS soils, with only a tenth of volume applied. However, water stress symptoms were observed in BBFA plants (e.g., dry leaves, less of turgor) potentially indicating that while water was being retained, plants had difficulty accessing it. This limited moisture accessibility may be the result of the fine fraction of BBFA particles clogging or hoarding root available soil pores (Elliot et al. 2022).

LSMB, and other forms of municipal biosolids, are believed to provide physical and nutritional benefits to gravel soil. Our experimental LSMB material is elevated in OM (18%), however unlike PMS, we observed marginal improvements to moisture retention. While LSMB undoubtedly improves soil carbon content following application, the material is granular and does not mimic topsoil when incorporated into gravel as PMS has in this study. Our results show moisture retention was comparable to the SUD treatment where no organic matter was applied. Potentially using a much higher application rate, such those employed by Jin et al. (2015) (60 Mg ha^{-1} yr^{-1}) and Shu et al., (2016) (42 Mg ha^{-1} yr^{-1}), may have improved the moisture retention abilities of our aggregate substrate (as observed in those studies). However, our application rate was informed by the recommended guidelines provided by the manufacturer, as well as insights from other studies utilizing the same material, both aimed at minimizing nutrient losses while maximizing plant growth (Kuchtaruk et al., 2018; Walker Environmental 2024).

Plant Response

In this study, we comprehensively examined the physiological responses of trembling aspen and yellow birch tree seedlings planted in soils amended with industrial residuals. Plants require suitable levels of soil moisture, oxygen, temperature, and plant essential nutrients to thrive. However, gravel soils in the region struggle to retain moisture as they have little organic matter or clay fractions, are often mechanically compacted (reducing aeration), and are typically poor in nutrients given their glacial and siliceous nature.

Beneficial plant outcomes were strongly co-reliant on physical improvements, regardless of the nutritional status of the soil: namely, immediate improvements to the water and nutrient holding capacity of the substrate following SOM increases. This was expected as the control substrate had minimal water and nutrient holding capacity and was particularly salient given the elevated moisture requirements of productive pioneering trees like trembling aspen (Ayres et al., 2009; Snedden, 2013; Pinno and Errington, 2015). Pulp mill sludge (PMS) significantly enhanced these properties, resulting in the most favorable plant growth and health responses observed in this study. This was observed in both species and planting methods – highlighting the comprehensive benefits of this material to root growth. PMS seedlings exhibited a developed rhizome layer where root length and mass were significantly greater than all other treatments. Here, we also observed significant physical differences between roots growing in treated vs untreated layers of the growing cavity. In the upper treated layer, roots grew densely around the larger soil peds, forming aggregates along their length, maximizing nutrient and moisture absorption. Such root behaviour highlights the substantially improved physical structure of the amended soil. Untreated layer roots were fine, and exploratory – a standard moisture acquisition strategy (Bauhus et al., 1999; Weemstra et al., 2012; Laclau et al., 2013). Our results suggest generating a fertile soil layer when amending gravel soil is critical to a rapidly developing root system. Indeed, plants utilizing both of these rooting strategies are expected to better weather droughts (Comas et al., 2013). These benefits have been observed in similar studies where tree root growth was similarly enhanced by amending gravel soils (Padilla and Pugnaire, 2007; Ovalle et al., 2015).

Above ground tissue responses were similarly positive, highlighting the critical co-dependence of root and stem systems. Here, the PMS provided the nutritional and moisture requirements of the seedling throughout the trial. This is further evidenced by leaf chlorophyll content being significantly greater in PMS soils than all other treatments. In fact, yellow birch and trembling aspen LCC matched or were greater in PMS soils than those found in undisturbed forest stands (Simic et al., 2011). Leaf chlorophyll content in tree seedlings is a key indicator of their photosynthetic capacity and overall health, reflecting vital factors such as nutrient availability and environmental stress levels (Talebzadeh and Valeo, 2022). Higher chlorophyll levels, such as those observed in PMS, generally signify greater growth vigor and a healthier state, allowing seedlings to efficiently convert light energy into chemical energy for growth (Smith et al., 2000; Agathokleous et al., 2020). Both species of tree seedlings planted in soils amended with PMS exhibited the most elevated growth rates in this experiment, indicative of its positive impact on their overall health and vigor. The PMS amendment enhanced soil moisture and nutrient retention, significantly improved soil structure, and thereby supported more robust and competitive growth in the seedlings. We also used a colour scale to estimate leaf colouration in a standardized manner. Both planted and sown yellow birch seedlings, as well as planted trembling aspen, were often deep green, with rare instances of yellowing, browning, or other signs of stress. We suspect yellowing, and perhaps the deep green colouration, to be a result of overfertilization of plant available nitrogen, with the former leading to the displacement of other chlorophyll critical nutrients like manganese, zinc, and magnesium (Hüttl 2004). While PMS improved the health status of sown trembling aspen when compared to CON soils, these individuals were often stressed. Here, leaves were often light green, with necrotizing black spots. It is difficult to identify the direct cause of necrotic spotting - the most common being metal toxicity, nutrient imbalance, or physical stressors such as temperature fluctuation, burning, or pathogenic activity (Ivanova 2015). Pathogenic activity is most likely as the warm, humid, and crowded conditions of greenhouses are known to be conducive to microbial growth (Bains and Mirha, 2002; Reddy, 2016). However, spotted individuals (which were removed from the dataset) were found in this study at elevated rates within the sown trembling aspen population (36.1% of total population). It is possible some of the necrotic tissue was due to unidentified cases and was erroneously kept in the dataset. Regardless, sown PMS seedlings were exceptionally productive when compared to CON, LSMB, and BBFA, and generally demonstrated strong health.

Our results support the growing body of work highlighting the beneficial use of PMS when regreening sand and gravel soils. Carpenter and Fernandez (2000) used alkaline blended pulp sludge from a Kraft process mill to create a manufactured topsoil in the reclamation of an abandoned gravel pit (Maine, USA). At an application rate of 170 Mg ha^{-1} and incorporation depth (25 cm) similar to our study, the authors noted significant and sustained increases in tree (hybrid *Populus* spp.) and grass growth. Battaglia et al., (2007) observed similar results, where blended pulp sludge significantly improved root growth and lowered stress indicators of barley (*Hordeum distichum*) when applied to Pb and Zn polluted sandy soil. In a recent review by Turner et al., (2022), PMS is consistently observed to improve soil fertility and can be specifically tailored to meet the unique physico-chemical properties of diverse soil types through composting processes or additional amendments. This adaptability suggests that PMS can effectively target and mitigate specific soil deficiencies, making it a valuable tool for sustainable soil management and the revegetation of sand and gravel mines.

In contrast, BBFA and LSMB plant outcomes were often statistically indistinguishable, or had even worsened when compared to unamended controls (CON). Without adequate moisture, the root systems of these plants were significantly less developed. Here, roots were fine and exploratory which did not encourage aggregation as seen in PMS soils and weighed significantly less. Without a developed root system, above ground productivity plummeted. LSMB and BBFA stems were therefore much shorter and thinner than PMS counterparts. Leaf chlorophyll content had improved over controls, indicative of nitrogen availability and uptake, but only moderately so and significantly below values of similarly aged individuals found in undisturbed forest stands of the region (Simic et al., 2011). This highlights the critical need to improve the physical properties of aggregate substrates as well as its nutritional status.

We observed significant increases in soil and leachate pH following both BBFA and LSMB amendment. It is well understood that elevating soil pH (up to 12 in some of our samples) can lead to caustic and ionic stress and stoichiometric imbalances (Mooshammer et al., 2014; Tripathi et al., 2018). Indeed, we observed clear signs of phosphate deficiency in plants growing in LSMB and BBFA amended soils, regardless of the elevated phosphate levels observed in these treatments. In high pH environments, calcium phosphate can precipitate from solution, depriving plants of the macronutrient. This exact mechanism was observed by Cerozi and Fitzsimmons (2016) in an aquaponic environment. This may further explain the poor growth observed given phosphate is critical to plant metabolism.

We observed species-specific effects on germination and survival. In sown trembling aspen individuals, industrial residuals generally had a positive effect – raising germination from 40.7% in controls to 80.8% in PPA amended soils, with other industrials following similar patterns. Trembling aspen seeds have typically low germination rates. Causse (2006) observed a 22% germination rate in exposed mineral soils in a northwestern Quebec aspen stand and a positive correlation with soil temperature, but not moisture. This was not observed in our study, though

PPA rose soil temperature 4.6°C, while all other treatments had no significant difference from control. Wolken et al., (2010), and Lafleur et al., (2015) agree that trembling aspen seeds best germinate in exposed mineral soils as well, with the former observing topsoil (specifically Ae) improved these rates. Our results generally agree with studies as the artificial topsoil like conditions generated by the industrial residuals were observed to improve germination. We highlight the significant improvements to germination following the incorporation of PMS.

Once germinated, industrial residuals had a slight impact on trembling aspen seedlings while planted individuals benefited from industrial residuals, raising survival by an average of 7.7%. Howe et al. (2020) and Cortini and Comeau (2019) both found that soil moisture plays a significant role, with higher moisture levels leading to increased trembling aspen survival. This is in contrast to our phase 1 results, as soil moisture did not correlate with survival. This was expected given our experimental design attempted to minimize moisture stress during phase 1. However, we observed a 6-day delay in plant drought symptom appearance between control and PMS and BBFA soils when drought was simulated, indicating an improved ability to retain moisture are beneficial in such conditions. Furthermore, trembling aspen are especially vulnerable to transplant shock following planting in droughty soils, furthering the importance of an organic rich surface soil when reclaiming borrow pits (Van den Driessche et al., 2003; Martens et al., 2007).

In sown yellow birch, industrial residuals had a slight negative effect – though germination rates were above 80% in all treatments. Godman and Krefting (1960) discuss mineral soil elevated in humus provides optimum conditions for yellow birch germination – conditions similar to those generated by PMS. It is therefore surprising to observe controls to have had the most elevated germination rates, though this may be spurred by continuous precipitation. In field conditions we would not expect germination rates in bare gravel to match our experimental results. Inversely, the elevated moisture retention ability of PMS, and its rich microbial community, could potentially create temporary anerobic conditions, preventing successful germination and establishment. Survival within germinated populations was not affected by industrial residual type, nor its absence. Again, given the plants were provided with precipitation daily, we may have artificially lowered moisture stress during this period.

<u>Soil Leachate</u>

Given their acute toxicity to local freshwater ecosystems, this study was particularly interested in the importation of 5 metals of concern following the application of industrial residuals: Cd, As, Pb, Hg, Cr (Al Taee et al., 2020; CCME, 2024). Global anthropogenic activities are known to deposit these metals to Boreal Forest soils, where they can accumulate plants and concentrate in PMS and BBFA (Johnson et al., 2003, Lidman et al., 2014, Fältmarsch et al., 2007). However, modern mills (such as the sulfite thermomechanical pulp mill in our study) have improved significantly in operational and environmental performance, particularly in chemical management, resulting in minimal external chemical import into waste materials like sludge. These improvements include better sulfidity control, reduced chemical loss, and enhanced pulp washing techniques, leading to significantly lower environmental impact (Robinson et al., 1994). Additionally, modern mills have adopted low-dosage sulfite treatments to enhance fiber quality while reducing environmental discharge (Nelsson et al., 2015). These advancements ensure that the chemical composition of pulp sludge is more reflective of the original feedstock, largely devoid of hazardous industrial residues (Gontia & Janssen, 2016).

These risks can apply to lime-stabilized municipal biosolids (LSMB) as well, since the treatment of domestic sewage may contain a mix of household, industrial, and commercial waste. This can lead to elevated levels of heavy metals in biosolids due to the concentration of these contaminants during the sewage treatment process (Healy et al., 2016). Studies show that while lime stabilization can reduce pathogen loads and increase pH to mitigate metal bioavailability, long-term applications of LSMB may still contribute to heavy metal accumulation in soils, affecting plant uptake and soil chemistry (Asemaninejad et al., 2020). Risk assessments indicate that surface runoff from LSMB applications can introduce trace metals into water systems, though levels often remain below regulatory thresholds (Clarke et al., 2016).

We observed that industrial residuals do import Cr and Pb (the former in LSMB only), but were not sources of Hg, Cd, or As. We did not measure any leaching events which would trigger CCME guidelines – the exception being for Cu. This could be due to copper lined drinking water pipes – especially in acidic, or chlorine treated waters as seen by Fabbricino and Panico, (2006). Considering the historical industrial pollution which occurred in this region (100 years of uncontrolled ore smelting), we were concerned Ni, Cu, and platinum group metals may have contaminated our samples and concentrated into our leachate.

The fate of soil ions can generally be categorized into three broad pathways: leaching with percolating water, adsorption to soil components such as clay and soil organic matter (SOM), or absorption by biota within the soil (Essington ,2004; Brown and Calas ,2011). Without addition of SOM, the study soils are dominated by organic poor, largely electrostatically neutral sands, and the former is favoured. Here, charged particles tend to enter soil water solution and percolate to ground or surface waters rather than adsorb to soil particles. Practitioners should select amendments elevated in organic rich materials when attempting to improve gravel fertility as they may play an outsized role in the adsorption of metals (Fan et al., 2015). It is clear in this study that imported metals favoured adsorbing to the strong negative charge of the organic matter particles rather than leaching with percolating water. Although, organic amendments can accumulate metals in soils, potentially impacting microbial community function (Chander and Brookes, 1991; Chodak et al., 2013). However, the application of combined amendments can decrease heavy metal bioavailability and improve soil physicochemical characteristics, with both positive and negative effects on microbial diversity and composition (Cui et al., 2021). Smenderovac et al., (2022) observed no detrimental effects to soil microbial community structure following BBFA application. Similar risks can apply to planted seedlings, as metals are believed to concentrate in plant tissues following industrial residual application, at detriment to their physiology (Gagnon et al., 2013; Gagnon et al., 2014). However, a relatively recent study has shown plants, specifically their roots, to accumulate metals in BBFA amended soils at rates matching controls (Deighton et al., 2020). Furthermore, industrial residuals would ideally be applied once, which would prevent any metal loading. While these residuals generate conditions which favour adsorption rather than mobility to water resources, their benefits to metal immobilization only extend until they are biodegraded. Therefore, practitioners should take great care to ensure plant productivity establishes rapidly following the application of industrial residuals in order to replenish organic matter stocks.

CON soils contained higher than typical levels of Cu for Boreal Forest soils (Rabow et al., 2022). This is expected given the industrial Ni-Cu smelting legacy of the region. However, differences in soil Cu content between CON and PMS and BBFA soils was insignificant, with LSMB results uniquely indicating importation was occurring. However, we observed significantly elevated Cu content in collected water of all treated soils when compared to CON and SUD. This indicates industrial residuals had disproportionately leached Cu. Cu has a strong tendency to sorb to organic soil particles, suggesting that high organic treatments like PMS should have lower Cu leachate content. These treatments also elevated CEC significantly, furthering the purported rate of Cu adsorption. Furthermore, BBFA and LSMB treatments generated alkaline conditions, which favour copper oxide or sulfide precipitates, again lowering its leaching potential. However, these materials are rich in other cations and Cu may have been displaced from the soil matrix, increasing its likelihood to leach. Cu can also form soluble organic complexes as well which readily leach. Ecke and Svensson (2008) observed a strong positive correlation between metal leaching rates and dissolved organic carbon concentration (DOC). The addition of industrial residuals increased DOC rates significantly compared to controls (CON), and the transport and fate of Cu may have followed the same mechanism.

Nitrate and phosphate losses were also of concern given the nutrient-rich nature of the experimental residuals and the proximity of borrow pits to surface and ground waters. The application of industrial residuals such as pulp sludge and biosolids can contribute to phosphorus and nitrogen leaching, particularly when applied in high concentrations or on poorly drained soils (Meyer, 2022). Studies show that biosolids and combustion ashes, while valuable as fertilizers, can increase soluble phosphorus levels in soil, potentially leading to runoff and eutrophication risks (Kumaragamage et al., 2011; Kumpiene et al., 2016). The release of nitrate and phosphate into freshwater bodies can accelerate eutrophication, promoting excessive growth of algae and aquatic plants that deplete oxygen levels, harming aquatic life (Ma & Rosen, 2020). Additionally, the morphology of residual-based ash particles, such as those from biosolids, can influence phosphorus mobility and interactions with soil and water, potentially affecting its transport and leaching behavior (Strandberg et al., 2021).

Additionally, nitrate contamination poses a risk to human health when it affects drinking water sources, potentially leading to conditions like methemoglobinemia in infants (Pierzynski & Gehl, 2005). We observed significant initial NO_3 losses in all PMS samples. However, these were ephemeral and quickly fell below the CCME guideline for long-term exposure of nitrate for the protection of aquatic freshwater life (13 mg $NO_3^-\cdot L^{-1}$). NO3- losses did not cross the short-term risk threshold in any treatments (500 mg $NO_3^-\cdot L^{-1}$). Nitrate losses were below this threshold for all other treatments. Similar patterns were observed for total organic nitrogen (TON-N) and dissolved nitrogen (DN), though there are no specific guidelines here. Nitrate is notoriously water soluble and will leach following precipitation events if it is not being taken up by metabolic processes. Our heavy precipitation regime during the first phase of the growing season may have simulated spring melts, promoting leaching. These results fall in-line with a similar study where municipal biosolids were applied in deep trench rows at ~1000 Mg/ha and found nitrate did not reach the water table (10 m depth) where hybrid *Poplar* stands which noted to be especially productive (Felix et al., 2008)

The CCME threshold for elevated risk (or "trigger-range") of hyper eutrophication in surface waters from total phosphorus (TP) is 0.1 ppm. TP was observed to exceed this range throughout the entirety of the trial and in all treatments, controls (CON) included, and did not decrease with time. These results are somewhat surprising given pre-trial CON soils were analysed to contain 8 ppm of total phosphorus, while all other treatments were above 50 ppm. Excessive leaching could be a result of our irrigation regime as consistent precipitation may promote phosphate mobility. Given the sandy and organic poor nature of the gravel, leaching is promoted. This may have equalized our results as organic rich treatments with elevated TP would have improved nutrient retention.

Conclusions

This study assesses the effectiveness of industrial residuals, namely pulp mill sludge (PMS), biomass boiler fly ash (BBFA), and lime-stabilized municipal biosolids (LSMB), in improving the physical and nutritional properties of gravel soils to enhance plant growth. The research shows that PMS significantly enhances SOM, moisture retention, and plant growth in these challenging substrates. Given these positive outcomes, we recommend that PMS be considered for larger-scale field trials to confirm and potentially extend these initial findings. However, our study also found that both LSMB and BBFA increased soil pH to levels potentially detrimental to microbial activity and nutrient availability for plants. Specifically, LSMB did not improve moisture retention, which may be attributed to its granular nature and the low application rate used in this experiment. This could limit its effectiveness in enhancing soil water-holding ability, a critical factor in plant growth. BBFA, while contributing to increased soil pH due to its alkalinity, may also interfere with nitrogen cycling by creating conditions unfavorable for nitrification. This highlights the need for careful management of application rates and consideration of soil chemistry when using BBFA and LSMB as soil amendments. Furthermore, we determined the risk to water resources immediately following the incorporation to gravel soils to be low. Here, metal loads were increased but did not mobilize with percolation water highlighting the absorption capacity of soil organic matter. Nutrient losses, particularly of nitrate and ammonium, were lower than expected given the rich nature of these materials. Elevated phosphate losses continue to be of concern. However, eutrophication risk is reduced given these soils are to be reclaimed with a single application of industrial residuals. In conclusion, while PMS shows significant potential for improving soil quality in gravel substrates, the applications of LSMB and BBFA require careful optimization to avoid adverse effects on soil pH and microbial function.

Chapter 5

Title: Enhancing Passive Vegetation Colonization in Acid and Metal-Damaged Soils: Evaluating the Role of Industrial Residuals in Reclaiming the Upland and Sloped Zones of Greater Sudbury, Ontario

Authors: Jonathan Lavigne, Kelly Chan-Yam, Peter Beckett, Graeme Spiers, Marc Hebert, Nathan Basiliko

Abstract

The Sudbury region has experienced extensive ecological degradation due ~1.5 centuries of mining and metal processing, leading to soil acidification, metal contamination, and widespread vegetation loss. While the Sudbury Regreening Program has made progress in restoring some areas, upland and particularly sloped sites continue to struggle with poor recolonization outcomes. This study evaluates the use of industrial residuals, including alkali-treated municipal biosolids (ATB), pulp mill sludge (PMS), and biomass boiler fly ash (BBFA), as soil amendments to improve soil properties and promote plant growth. Using a randomized block design, treatments, including controls and the current Sudbury regreening protocol were applied to examine their effects on soils, planted tree seedling, and broader plant communities over 4 years. Results showed that ATB treatments significantly enhanced species diversity, ground cover, and soil moisture retention, particularly through the establishment of moss carpets. In contrast, other treatments exhibited mixed effects on recolonization, with some promoting invasive species or high soil temperatures. The findings suggest that novel approaches using industrial residuals can enhance the resilience

and ecological function of reclaimed upland environments, but attention is needed to optimize material selection and application strategies, and ongoing research and monitoring is needed to understand benefits and limitations for long-term afforestation goals in Sudbury and similar mining-denuded landscapes.

Introduction

The Sudbury region of Ontario, Canada, has been severely impacted by over a century of industrial smelting, resulting in significant acid deposition and metal contamination (Freedman and Hutchinson, 1980; Gunn 1995). These activities have led to extensive ecological damage, including the decimation of mature *Pinus resinosa* stands that historically supported and stabilized the hilly region's glacial soils (Hutchinson and Whitby, 1977; Adamo et al., 1996; Danneyrolles et al., 2016). Soil acidification, driven by sulfur dioxide emissions, reduces the availability of essential nutrients such as calcium, magnesium, and potassium, while increasing the solubility and mobility of toxic metals like nickel, copper, and aluminum. Acidic conditions disrupt root function by displacing cations from root cell membranes, impairing water and nutrient uptake, and causing direct physiological stress to plant tissues. Metal toxicity compounds these effects by interfering with enzymatic processes, disrupting photosynthesis, and causing oxidative damage to cellular structures (Whitby and Hutchinson, 1974; Barceló and Poschenrieder, 1990; Gervais and Nkongolo, 2011; Mchale and Winterhalder, 1996). The combined stressors result in chlorosis, inhibited root and shoot growth, and ultimately plant death, creating a feedback loop where the vegetation loss further destabilizes soils through erosion, stripping away organic matter, altering soil microbial communities, and perpetuating degradation (Hutchinson and Whitby, 1974; Anand et al., 2003; Freedman and Hutchinson, 1980; Nriagu et al., 1998). Approximately 89000 ha have been affected, with roughly a tenth denuded down to bedrock (10000 ha), leaving barren landscapes devoid of plant life and essential ecological processes (Winterhalder, 1996).

Passive reclamation is the process of restoring a disturbed site to a self-sustaining ecosystem, where natural succession unfolds, and native species establish over time. In the Sudbury region, passive reclamation is underway, especially since air emissions of SO_2 and metals—previously major limiting factors—were significantly reduced in the 1970s and 1980s. However, the rate of recolonization varies widely, influenced by an acid and erosion gradient across the landscape. For instance, the most barren, acid-damaged lands, particularly the exposed upland hills, are expected to take centuries, millennia, or even longer for their plant communities to resemble the surrounding ecosystems, as they support little to no vegetation (e.g., characterized as “lichen deserts” by Beckett (1986). In contrast, nutrient- and moisture-rich lowland enclaves have shown rapid recolonization within decades, with metal-resistant species beginning to invade and establish. (Amiro and Courtin, 1981; Koptsik et al., 2016; Deschene et al., 2024).

Although soil acidification and metal toxicity have decreased following the reduction in air emissions, the improvements have not been as significant as anticipated, falling short of enabling the environment to naturally return to a healthy, pre-disturbance state. Active rehabilitation was necessary to support and guide succession toward a more natural ecosystem. Without such efforts, the lingering effects of soil acidification would persist, potentially on geologic timescales, due to the soil's poor buffering capacity and cold climate (e.g., lower decomposition rates). Therefore, a more active approach was required to restore ecological function to the damaged lands and improve overall recolonization rates given these legacy effects. In response to this widespread environmental degradation and following a significant reduction in local sulphur dioxide emissions, the Sudbury Regreening Program was initiated in the 1970s as a large-scale effort to treat soil acidification and begin actively regreening the landscape. (Beckett et al. 1995; City of Greater Sudbury, 2024). The initial phase of the program focused on effectively treating soil acidification and metal availability primarily through the application of limestone (10 t/ha), as well as mineral fertilizers (6-24-24 NPK at 400 kg/ha) to supply essential nutrients. Without this step, attempts at revegetation were expected to be fruitless. Following soil treatment, early efforts concentrated on sowing grasses and legumes and planting hardy coniferous species, such as *Pinus banksiana* and *Pinus resinosa*, selected for their ability to survive harsh, drought-like conditions (Gunn 1996). The overall objective of the programme was 3-fold: i) raise soil pH to reduce metal toxicity; ii) sow native and agronomic grasses to further promote recolonization; and iii) plant trees to promote soil stability and ensure natural forest succession via eventual canopy closure. Despite the success of the Sudbury Regreening Program in stabilizing soils and re-establishing vegetation in many areas, upland and sloped zones continue to face significant challenges (Mccall et al., 1995). These areas often experience severe erosion due to steep slopes, hindering the accumulation of organic matter and limiting the capacity of the soil to retain moisture and nutrients (Kellaway et al. 2021). The lack of soil organic matter (SOM), as well as mineral soil as a whole in severely eroded zones, are critical barriers to establishing diverse plant communities and achieving long-term reclamation success (Preston et al. 2022; Rumney et al. 2021). The inherently harsh conditions typical of upland Boreal forests are amplified in landscapes impacted by industrial activities, making these zones particularly resistant to traditional reclamation methods.

Post-treatment, these newly vegetated upland zones appear to struggle to return to ecological function (SARA, 2008). Perhaps most critically is the perceived absence of natural successional processes in these zones which suggests that planted species are not transitioning into more complex forested states, leaving questions about the future viability of these forests when the planted pines eventually die (Cunningham et al., 2015). Furthermore, the predominant establishment of even-aged, often monocultural softwood stands raises concerns about the long-term ecological stability of these sites. These stands lack the diversity and structural complexity needed to support resilient ecosystems (Nguyen et al., 2014; Di Sacco et al. 2020). However, this has been recognized as the program evolved, shifting their planting regime in order to create more diverse and resilient ecosystems by incorporating a wider array of tree and shrub species and emphasizing targeted planting based on site-specific conditions such as their preferred moisture and temperature regimes. This shift aimed to enhance biodiversity, restore more natural community structures, and increase the overall resilience of re-established ecosystems (Dymond et al., 2014; Messier et al., 2022).

In the 1990s, consensus regarding the successional fate treated zones in this region speculated recolonization to be dominated by grasses (given metal tolerant strains were already colonizing some untreated semi-barren zones), which would then foster woody species (particularly *Populus tremuloides*) as well as planted species. However, as noted by Winterhalder (1996), successful cases appear to cluster towards nutrient and moisture rich enclaves and notes Amiro and Courtin (1981; 1994) who question whether upland semi-barrens and barrens will ever develop past its open coppiced birch community type given widespread seedling deaths, crown dieback, drought, and elevated rates of insect infestation (believed to be spurred by monocultural or low diversity stands). This has prompted the need for innovative approaches to address these limitations and promote ecological resilience in upland and sloped landscapes.

Upland sites are not responding sufficiently to the existing liming, fertilization, and planting protocols. We posit several underlying reasons for this inadequate response, along with potential solutions. A primary factor may be the present planting strategy's tendency to bypass the natural successional seres, rapidly achieving canopy closure with conifer species. This approach effectively circumvents the intermediate stages involving herbs, grasses, shrubs, and early successional tree species such as *Populus tremuloides*, which has been specifically noted as a potential pioneer tree community in a recolonized setting. By omitting these critical successional stages, there is a substantial loss in the development of ecological processes, including the accumulation of organic litter, enhancement of species diversity, and establishment of a resilient soil microhabitat.

Furthermore, as indicated in the SARA report (2008), many upland sites that have been treated continue to remain stagnant in a coppiced *Betula papyrifera* community type, exhibiting little to no successional advancement, even over decadal timescales. The current LF treatments do not incorporate organic matter, although their liming effect remains effective for several decades post-application. We hypothesize that these upland areas may benefit from direct amendments with organic carbon and nutrient inputs, which could yield long-term improvements in soil moisture retention and nutrient availability, ultimately facilitating a more resilient and diverse vegetative community. Therefore, addressing the limitations observed in these upland sites may necessitate the adoption of novel materials, revised management practices, and potentially a re-evaluation of the criteria used to define a "complete" or "revegetated" state. These considerations will be further explored in this study. In direct response to the limitations of traditional reclamation methods, the use of industrial residuals—pulp mill sludge (PMS), alkaline-treated biosolids (ATB), and biomass boiler fly ash (BBFA)—has emerged as a promising alternative for enhancing soil fertility, improving structural stability, and supporting vegetation growth.

PMS is a waste byproduct of the paper manufacturing process, composed primarily of organic matter, wood fibers, and residual chemicals, reclaimed during the wastewater treatment process. The sludge can vary in pH depending on the pulping process used: Kraft (alkaline due to its use of soda to loosen fibres) or Sulfite-Thermomechanical (neutral due to its use of ammonium sulfate to loosen fibres). PMS generally is rich in organic matter and has been found to improve soil structure, water retention, and microbial activity (Camberato et al. 2006; Alvarenga et al., 2019). The material also provides essential nutrients such as calcium, magnesium, and potassium, which benefit plant growth. The application of PMS significantly enhances the chemical properties of soil, including increased organic matter and nutrient content, leading to improved plant biomass production (Gallardo et al., 2012).

ATB is produced by treating municipal biosolids with lime (CaO), which quickly raises its pH (~12) and temperature (~70 °C following exothermic hydration) to neutralize pathogens, stabilizing organic matter. ATB have been shown to improve soil pH, enhance nutrient content – especially nitrogen, phosphorus, and potassium – and increase organic matter content, which collectively boost soil fertility and promote plant growth (Wong et al., 2001; Silva-Leal et al., 2021). The increase in organic matter from LSMB further contributes to improving soil structure and fertility, leading to better water retention and nutrient availability, which are vital for sustainable plant growth (Dad et al., 2018).

BBFA is a fine particulate byproduct generated from burning biomass in industrial boilers. BBFA offers benefits such as high calcium, magnesium, and potassium content, improving soil pH and fertility while acting as a liming agent to neutralize acidic soils and enhance nutrient availability (Park et al., 2012, Ondrašek et al., 2020, Cherian and Siddiqua, 2021).

The selection of these residuals is driven by their specific chemical and physical properties, which address the unique challenges of Sudbury's upland and sloped zones, as well as their manufacturing proximity. Applying these materials to land not only recycles industrial byproducts (where millions of tonnes would otherwise be landfilled or incinerated), reducing waste disposal impacts, but also contrasts with traditional inputs like limestone and fertilizers, which require external mining, largely linear manufacturing processes, and long-distance transportation. The potential benefits include improved soil structure, increased water retention, and enhanced soil microbial activity, creating a more favorable environment for plant growth.

While industrial residuals have shown potential in improving soil conditions, there remains limited understanding of their role in promoting recolonization and long-term ecological resilience, particularly in severely degraded environments like Sudbury's acid and metal-damaged soils. Passive recolonization, the process by which ecosystems recover through the spontaneous establishment and succession of native species, may offer a more sustainable approach to restoring ecosystem function in severely disturbed environments. In contrast, traditional active reclamation strategies like tree-planting can be inappropriate or ineffective in such conditions, as leveraging natural successional processes allows ecosystems to adapt and foster biodiversity and resilience without forcing the development of a premature forest canopy. This study aims to assess the growth and survival of planted and colonizing species in response to these different industrial residuals, focusing on species composition, diversity, and successional dynamics. By evaluating how these residuals influence plant community development and ecosystem stability, the study seeks to advance reclamation practices, particularly in upland and sloped zones where traditional methods have struggled. This study seeks to address the limitations of traditional reclamation methods in Sudbury's upland and sloped zones by contrasting them to industrial residuals. By comparing the growth and survival of planted species across treated and untreated sites, this research aims to evaluate whether these materials can facilitate the establishment of more diverse and functionally complex plant communities. It is hypothesized that the application of industrial residuals will lead to higher growth rates, increased survival, and greater species diversity, particularly in challenging upland and sloped environments when compared to experimental controls (unamended soils and lime and fertilizer amended soils). Through this investigation, the study aims to provide insights into how these byproducts can contribute to sustainable land reclamation and the long-term restoration of ecological functions in degraded landscapes.

Methods

<u>Site Description</u>

The study was conducted in the City of Greater Sudbury region of northeastern Ontario, Canada, an area known for its rugged Precambrian shield terrain and history of industrial disturbance from extensive mining and metal smelting (primarily for nickel and copper production). The region experiences a humid continental climate, with temperatures ranging from cold winters averaging -13.0 °C in January to warm summers (19.1 °C) in July. Precipitation is significant, with an average of 903.3 mm annually, predominantly occurring in the winter months as snow (Environment Canada, 2024). The landscape is part of the Great Lakes—St. Lawrence mixedwood forest region, featuring shallow, stony soils on rocky outcrops, glaciolacustrine sands in low-lying areas, and a mix of forest and wetland ecotypes.

Two sites were selected: Coniston (CON) and Falconbridge (FB); named after nearby local centres in the broader City. Each site was selected for its representation of the barren to semi-barren conditions typical of the Sudbury landscapes adjacent to metal smelters. The CON site, located approximately 2 km from a smelter complex shuttered in the early 1970s, is characterized by patchy glacial till soils (fine fraction is silt-loam textured) on rocky slopes, with only sparse patches of remnant vegetation. Pre-treatment soil analyses indicated a highly acidic environment, with a mean pH of 4.2 and elevated concentrations of copper and nickel, averaging 232 mg/kg and 146 mg/kg, respectively across the ca. 1ha study areas. Vegetation was minimal, with scattered occurrences of stress-tolerant species such as *Betula papyrifera*, *Pinus resinosa*, and *Vaccinium angustifolium* set against a backdrop of exposed bedrock, pioneering mosses and lichen, as well large areas of bare ground and soils disturbed by frost action. This mirrors conditions described by Winterhalder (1996) in descriptions of the Sudbury landscape ca. 3 decades prior, despite major ongoing atmospheric pollution controls by the regional industries. In contrast, the FB site is situated on a relatively flat outwash plain within an active smelter property complex (though with modern environmental controls), characterized by deep and continuous sand-textured soils (relative to CON) that exhibit similar acidic and metal-contaminated conditions, but with minimal bedrock exposure. Pre-treatment analyses showed a mean pH of 4 and copper and nickel concentrations of 211 mg/kg and 131 mg/kg, respectively. Vegetation at this site was also sparse, with similar species as the found in the CON site. Both sites reflect the broader environmental challenges of the Sudbury region, where massive soil acidification, metal toxicity, and erosion have severely limited natural vegetation recovery.

Experimental Design

The experimental design was similar at each study site. The study employed a randomized block design, organized into five blocks (A-E), with each block containing eight treatment plots, resulting in a total of 80 plots per site. Each plot measured 5×10 meters and was divided into two 5×5 metre subplots to accommodate different tree species – with hardwoods occupying 1 half and the softwood species the other. The randomized block design was chosen to account for spatial variability within each site and to provide sufficient replication for statistical comparisons across treatments. To mitigate cross-contamination, plots were separated by ~1 meter of untreated buffer soil. In sloped areas, plot arrangement was adjusted to position control plots and low-addition-rate treatments upslope of more higher addition rate amendments, minimizing the potential for material runoff to affect neighboring plots while maintaining equal slope angles. In the latter, small berms were built with locally excavated stones and boulders. Otherwise, treatments were randomly assigned within each block using a coordinate system generated in the Microsoft Excel platform (Seattle, USA), ensuring that each plot had an equal probability of receiving any given treatment. We also determined the total rockiness, slope (using clinometer and stadia rod), and aspect (handheld compass), and relative slope position of each plot. Leaf collection was conducted prior to amendment application. Here, we collected the leaves of three species: *Pinus resinosa*, *Vaccinium angustifolium*, and *Betula papyrifera*. These were selected due to their availability within each plot and site and were collected to determine their baseline nutrient and metal concentrations, which were collected again at the end of the experiment (Summer 2022).

Treatments and Application

Amendments were applied in a staggered schedule due to site accessibility constraints, with CON being treated from mid-May to early June 2019, followed by FB from early to mid-June 2019. The residuals were manually distributed using 5-gallon pails and spread evenly across each plot with garden rakes. The amendment mass per pail was measured using a high-capacity balance, and the required number of pails per plot was calculated based on the predetermined application rates and plot dimensions. Application rates were calculated to match the total nitrogen content of current Sudbury Regreening Program methods 120 g of N per 5X10m plot). All plots were manually cleared of existing trees and shrubs prior to the application of soil amendments to standardize conditions (specifically sunlight exposure) across treatments and ensure that initial vegetation cover did not influence outcomes. Safety protocols, including gloves and masks, were observed during the application to manage exposure to the materials. Environmental Compliance Authorization (ECA) permits were obtained through the Ontario Ministry of Environment Conservation and Parks for land application.

The study employed eight distinct treatments to evaluate the effects of various soil amendments on plant and soil responses in the degraded soils of Sudbury. The treatments included:

i) Control (C) with no amendments

ii) 10 dry t/ha of dolomitic limestone and 400 dry kg/ha of 6-24-24 NPK fertilizer

Baseline Lime + Fertilizer (LF) treatment to align with the standard practice of the Sudbury Regreening Program

iii) PMS-K at 73.6 t/ha

Pulp Mill Sludge (PMS) Treatments: The characteristics of pulp mill primary sludge, secondary biosolids, and blends of both from wastewater treatment systems) vary significantly based across mills but are high in organic matter and some contain elevated plant essential nutrients. This study utilized two types of PMS. The first, PMS-kraft (Ps-K), was derived from a primary sludge produced at a kraft mill. This sludge is operationally mixed with fine-textured biomass boiler ash from the same facility before being pumped into a lagoon. The combined material, with an average residence time of six months in the lagoon, is dredged annually. This kraft mill processes both hardwood and softwood biomass for pulping and burns bark and hog fuel from these feedstocks in its biomass boiler.

iv) Ps at 5t/ha t/ha

The second type, PMS-Sulfite (Ps), was sourced from a pulp mill using both a sulfite chemical pulping and thermomechanical puling processes. This mixed primary (settled organic matter) and secondary biosolids (high in bacterial biomass), comprising approximately two-thirds primary sludge and one-third biosludge, undergoes a wastewater treatment with a short residence time, less than 24 hours half-life, which includes both primary settling and an aerated activated basin. This mill, located in a similar forest region as the kraft mill, also processes a mix of hardwood and softwood biomass. The sludge blend has a very high total N content relative to most other pulp mill wastewater treatment residuals because ammonium sulfite is used in woodchip digestion.

v) AF at 20 t/ha

Ash + Fertilizer (AF) Treatment: the AF treatment included wood ash combined with nitrate urea fertilizer, serving as a substitute for conventional lime and fertilizer applications. Biomass boiler ash, recognized for its significant liming potential, contains P and K but lacks N, which is typically lost during combustion. This treatment aimed to utilize the ash's liming and nutrient-providing properties without relying on mined limestone products.

vi) Ps at 5 t/ha and A at 20 t/ha

PMS-Sulfite + Ash (Ps-SA) Treatment: Since PMS-Sulfite does not contain ash/liming agents, an additional treatment was created by co-applying PMS-Sulfite with biomass boiler ash.

vii) ATB-1 at 20 dry t/ha and;

viii) ATB-2 at 40 dry t/ha.

ATB Treatments: A municipal biosolids based compost product, N-Rich(™) (Walker Industries) was chosen. The wastewater biosolids, rich in nitrogen, were lime-stabilized with cement kiln dust, a process that raises pH and generates heat sufficient to disinfect the material. These biosolids were sourced from the Walker plant adjacent to the Kelly Lake Wastewater Treatment Plant in Sudbury, providing a locally available amendment with strong buffering capacity and elevated nutrient content.

Tree Planting and Vegetation Surveys

Tree planting was conducted to evaluate the growth response of *Pinus banksiana*, *Quercus rubra*, and *Betula alleghaniensis* across the different soil treatments. Seedlings were planted manually using standard forestry shovels, with spacing and arrangement designed to minimize competition and ensure consistent exposure to treatment effects. Pinus banksiana and Betula alleghaniensis were planted in Spring 2020 (the following growing season) to allow residual weathering and soil integration, and *Quercus rubra* was planted in Fall 2020 due to logistical constraints. This staggered approach intended to avoid planting this species during the driest summer months, thereby reducing transplant shock and while retaining three full growing seasons of monitoring. Surveys of the planted tree species were conducted biannually in the spring and fall of each growing season over three years. Key parameters measured included stem length (accounting for the largely horizontal growth of *Quercus rubra*), and overall survival (categorized as alive or dead). Additional observations were made for herbivory, recording evidence of damage from ungulates, rodents, and *Leporidae* sp. (specifically *Lepus americanus* Erx.). Health status assessments were conducted for each seedling, categorizing them as verdant, dry, broken, or expelled (or any other conditions of note). For hardwood species, chlorophyll content was measured using an atLEAF chlorophyll pen. However, this tool was incompatible with *Pinus banksiana* needles. Tool readings (x) were converted to g/m^2 of chlorophyll using the following equations which tailored to *Quercus rubra* ($r^2 = 0.88$) and silver birch ($r^2 = 0.89$) (nearest species to *Betula alleghaniensis*) respectively (Brown et al. 2022):

$$ROy = 0.117e^{0.0397x}$$

$$YBy = 0.0442e^{0.0513x}$$

Vegetation surveys of colonizing species within each plot were also conducted biannually, coinciding with the planted species assessments. Surveys utilized a modified Braun-Blanquet scale to estimate percent cover of each species, as well as cover types (e.g., rocky, barren, leaf litter), allowing for rapid and repeatable assessments of vegetation dynamics. Pre-application surveys were also conducted to establish baseline conditions against which post-treatment responses could be compared. The surveys recorded species composition, cover, and growth patterns, focusing on both herbaceous and woody species that naturally colonized the plots. In addition to percent cover, stem height and leaf width measurements were taken specifically for colonizing *Betula papyrifera* as an additional indicator of growth response to the treatments. The surveys aimed to capture the progression of succession without amendments and the extent to which the soil amendments influenced the establishment and diversity of native plant communities.

The relative occurrence of species within each treatment was calculated based on percent cover data. For each species, the percent cover values were summed across all plots within a treatment to obtain the total percent cover per species for that treatment. The total percent cover of all species within each treatment was then calculated by summing the percent cover values across all species and plots in the treatment. The relative occurrence of each species was determined by dividing the total percent cover of the species by the total percent cover of all species within the treatment. This approach allowed for the integration of species data across multiple plots within each treatment, providing a comprehensive measure of species dominance and community structure influenced by the soil amendments. The relative occurrence values were used to compare the effects of different treatments on plant community composition and to identify shifts in biodiversity and species distribution patterns.

<u>Soil Physicochemical Surveys</u>

Soil samples were collected at the beginning and end of the growing season (May-October) in 2018 (pre-amendment), 2020, and 2021 to evaluate the effects of treatments on soil properties over time. Sampling was conducted by collecting composite samples from each 5×5 m subplot within the larger 5×10 m plots. For each subplot, at least ten soil cores, each 10 cm deep, were taken along a W-shaped pattern using a 3-cm-diameter soil corer. These cores were pooled into a single composite sample per subplot to ensure a representative sample across each plot. The soil corer was cleaned with 70% ethanol between plots to prevent cross-contamination. On the day of sampling, soil volume and mass were recorded to calculate bulk density, and gravimetric moisture content was determined by drying triplicate subsamples at 105 °C for 48 hours (minimum 50 g each). After collection, the soil samples were air-dried and sieved through a 2 mm mesh to remove gravel and other large particles. The sieved soil from each subplot was pooled by weight for further analysis.

Soil pH was measured using a 1:5 ratio of soil to 0.01 M $CaCl_2$, with samples shaken for one hour and allowed to settle for 30 minutes before pH measurement using an Accumet AB15 pH meter (Fisher Scientific, Waltham, MA, USA). Soil ammonium levels were assessed using the salicylate method with a DR3900 Laboratory Spectrophotometer (Hach Company, Loveland, CO, USA), adjusting test ranges based on sample turbidity between the years sampled. Organic mater content was estimated through a loss on ignition method, which involved drying approximately 10 g of soil at 105 °C to remove moisture, followed by combustion at 550 °C for 5.5 hours. Additionally, in situ soil temperature and moisture were monitored using an Accumet TDR 150 probe during the peak of summer (July) in 2018, 2020, and 2021 to estimate maximum temperature conditions. To complement these measurements, probes with multiple sensers through soil depth were installed in 2 of 5 replications for each treatment to record temperature and moisture readings every 5 minutes throughout the 2021 growing season, providing high-resolution data on soil environmental conditions (Odyssey Data Recording, New Zealand). However, the effectiveness of these depth probes was compromised due to theft and damage from wildlife, which reduced the total amount of data collected and affected the continuity of environmental monitoring for some plots.

Soil samples from 2018 were analyzed at the Perdue Central Analytical Facility at Laurentian University, where total metals and phosphorus were quantified via ICP-MS following microwave digestion (EPA method 3051a), and total carbon, nitrogen, and sulfur were measured using a Costech elemental analyzer. The 2020 and 2021 samples were processed similarly at the

Natural Resources Analytical Laboratory at the University of Alberta. Extractable elements were analyzed using a 1:4 soil to 0.01 M $LiNO_3$ extraction, with metals, sulfur, and phosphorus quantified via ICP-OES, and total carbon and nitrogen measured through dry combustion techniques.

Data Analysis

All soil parameters, including soil carbon, nitrate levels, bulk density, moisture, and temperature, underwent normality testing using the Shapiro-Wilk test. Data that did not meet normality assumptions were log-transformed to achieve a normal distribution. Data were standardized using Z-scores to ensure consistency and facilitate comparison across variables. Plant data, which included metrics such as plant length, survival, health status, herbivory rates, and effective species number, were similarly standardized. The relative occurrence of each plant species was calculated within the plots, and a Hellinger transformation was applied to this data. This transformation, which down-weights the influence of absent or especially rare species, allowed for effective ordination of plant community structure, meeting the assumptions necessary for subsequent multivariate analyses.

To assess the effects of soil treatments on plant growth, survival, and community composition, a combination of univariate and multivariate statistical methods was employed. Analysis of Variance (ANOVA) was used to test for significant differences in plant growth metrics such as length and chlorophyll content along the different soil treatments. Where significant differences were identified, pairwise comparisons were conducted using Tukey's HSD post-hoc tests to determine specific treatment effects.

Ordination techniques, specifically Principal Component Analysis (PCA), were performed on the Hellinger-transformed plant community data to visualize differences in community structure across treatments. This approach facilitated the exploration of treatment effects on overall plant community composition, illustrating shifts in species abundance and diversity in response to soil amendments. To identify which soil conditions had the most significant impact on these community shifts, redundancy analysis (RDA) was applied, linking soil parameters—such as carbon content, nitrate levels, bulk density, moisture, and temperature—to plant community composition. This constrained ordination method allowed for the identification of key soil factors driving changes in species abundance and diversity, helping to clarify the influence of specific amendments on ecological outcomes. All data analyses and visualisation were performed in R version 3.6.2 and 4.2.3 (R Core Team, 2019, R Core Team, 2023).

Results

Soil Properties

Baseline Soil Conditions

The soil profile was clearly disturbed, exhibiting a history of erosional layering as well as charcoal inputs. Soil texture was very heterogeneous, with soil cores (10 cm) often containing multiple bands of varying texture, typical of remnant glacial tills found in the region, as well as charcoal fragments – evidence of historic forest fires. Baseline soil conditions were assessed prior to the application of treatments at both the Coniston and Falconbridge sites to establish initial soil characteristics. Key parameters measured included soil pH, soil organic matter content, ammonium levels, bulk density, moisture, and temperature, providing a reference point for evaluating the effects of soil amendments throughout the study. A summary of all data presented here can viewed in Table 1.

Table 2. Summary of soil physicochemical properties and vegetation response following industrial residual application - ± indicates standard deviation

Parameter	Site	PA 2018	LF	Ps-K	Ps-S	Ps-SA	AF	ATB1	ABT2	C
Soil pH	FB	3.99 ± 0.02	4.66 ± 0.20	6.78 ± 0.15	4.20 ± 0.21	6.35 ± 0.46	6.14 ± 0.27	6.41 ± 0.34	6.60 ± 0.64	4.08 ± 0.12
	CON	4.21 ± 0.02	5.40 ± 0.80	7.01 ± 0.13	4.39 ± 0.18	6.71 ± 0.29	6.75 ± 0.47	6.55 ± 0.45	7.07 ± 0.39	4.29 ± 0.31
Soil Organic Matter (%)	FB	2.05 ± 0.04	1.66 ± 0.21	1.55 ± 0.19	1.55 ± 0.30	1.66 ± 0.21	1.59 ± 0.22	1.54 ± 0.43	1.61 ± 0.46	1.59 ± 0.40
	CON	1.89 ± 0.06	1.39 ± 0.45	1.76 ± 0.38	1.34 ± 0.36	1.83 ± 0.32	0.17 ± 0.35	1.28 ± 0.32	1.48 ± 0.51	1.45 ± 0.31
Ammonium (mg/L)	FB	0.49 ± 0.01	0.61 ± 0.05	0.97 ± 0.06	0.57 ± 0.10	0.83 ± 0.08	0.83 ± 0.03	1.05 ± 0.09	1.02 ± 0.05	0.72 ± 0.20
	CON	0.57 ± 0.01	0.18 ± 0.05	0.22 ± 0.05	0.35 ± 0.13	0.20 ± 0.03	0.19 ± 0.03	0.22 ± 0.03	0.24 ± 0.04	0.24 ± 0.06
Bulk Density (g/cm3)	FB	0.88 ± 0.01	0.87 ± 0.01	0.91 ± 0.01	0.90 ± 0.03	0.9 ± 0.02	0.87 ± 0.01	0.93 ± 0.01	0.91 ± 0.01	0.90 ± 0.01
	CON	0.90 ± 0.01	0.88 ± 0.06	0.88 ± 0.05	0.89 ± 0.01	0.92 ± 0.01	0.87 ± 0.03	0.93 ± 0.01	0.91 ± 0.09	0.87 ± 0.02
In-Situ Soil Moisture (%)	FB	5.14 ± 0.71	3.89 ± 0.26	2.87 ± 0.47	0 (<MDL)	0 (<MDL)	0 (<MDL)	9.33 ± 0.89	9.64 ± 1.12	4.13 ± 1.41
	CON	7.40 ± 0.13	4.11 ± 0.46	2.11 ± 0.39	0 (<MDL)	0 (<MDL)	0 (<MDL)	9.21 ± 1.17	9.03 ± 1.54	4.51 ± 1.31
Gravimetric Soil Moisture (%)	FB	23.3 ± 4.91	17.4 ± 2.14	29.2 ± 3.64	22.9 ± 3.45	19.9 ± 2.87	20.0 ± 4.71	25.1 ± 4.12	26.2 ± 5.89	24.2 ± 5.12
	CON	29.3 ± 10.0	15.7 ± 1.23	31.1 ± 5.71	17.2 ± 4.23	22.2 ± 8.15	19.0 ± 6.33	17.0 ± 3.81	17.3 ± 5.10	24.5 ± 3.66
Surface Soil Temperature (°C)	FB	39.7 ± 4.21	37.6 ± 6.54	55.3 ± 4.67	59.8 ± 10.80	55.2 ± 9.21	41.3 ± 2.61	24.7 ± 2.14	23.8 ± 2.64	40.5 ± 6.77
	CON	41.3 ± 8.41	42.3 ± 6.74	54.9 ± 7.11	54.2 ± 6.89	56.4 ± 7.21	42.8 ± 6.51	25.9 ± 2.01	22.3 ± 2.87	42.6 ± 6.12
Depth Soil Temperature (°C)	FB	19.4 ± 3.70	20.5 ± 2.31	19.7 ± 2.36	20.0 ± 2.46	20.1 ± 3.03	24.0 ± 2.37	20.5 ± 2.65	20.7 ± 2.45	18.4 ± 2.31
	CON	22.2 ± 2.90	21.8 ± 2.55	21.0 ± 1.47	20.2 ± 2.81	20.8 ± 1.64	22.6 ± 1.74	21.1 ± 3.01	18.4 ± 2.14	19.4 ± 1.78
Vegetative Cover (%)	FB	49.3 ± 11.3	51.3 ± 8.41	62.7 ± 10.2	11.3 ± 2.45	5.9 ± 1.23	6.4 ± 1.31	210 ± 21.3	251 ± 21.0	45.9 ± 12.4
	CON	41.3 ± 9.51	43.9 ± 7.46	51.3 ± 7.65	9.84 ± 2.11	5.7 ± 0.87	4.1 ± 1.31	173 ± 13.3	218 ± 16.3	44.2 ± 23.1
Effective Species Number	FB	4.12 ± 0.33	5.74 ± 0.91	6.21 ± 1.89	1.84 ± 0.32	2.51 ± 0.21	2.13 ± 0.29	10.9 ± 0.98	12.1 ± 2.1	4.51 ± 0.36
	CON	4.64 ± 0.50	5.91 ± 0.61	6.97 ± 1.27	1.81 ± 0.51	2.34 ± 0.41	2.08 ± 0.54	9.71 ± 0.87	11.1 ± 1.8	4.41 ± 0.32

Baseline soil conditions were assessed at Coniston and Falconbridge to establish reference values before treatment applications. Soil pH averaged 4.21 ± 0.02 at Coniston and 3.99 ± 0.02 at Falconbridge. Organic matter content was slightly higher in Falconbridge (2.05 ± 0.04%) than Coniston (1.89 ± 0.06%). Bulk density remained consistent between sites (0.90 ± 0.01 g/cm^3 in Coniston, 0.88 ± 0.01 g/cm^3 in Falconbridge). Soil moisture varied, with Coniston showing higher gravimetric water content (29.3 ± 10.0%) than Falconbridge (23.3 ± 4.91%), whereas Falconbridge had greater volumetric moisture content in summer (7.40 ± 0.13% vs. 5.14 ± 0.71% in Coniston). Surface soil temperature peaked at 41.3 ± 1.2°C (Coniston) and 39.7 ± 0.61°C (Falconbridge), cooling significantly at 10 cm depth (22.2 ± 2.90°C and 19.4 ± 3.70°C, respectively). No significant differences were observed between sites in most parameters ($p > 0.05$).

Comparative analysis of baseline conditions between Coniston and Falconbridge revealed no significant differences in most parameters, with p-values of 0.31 for pH, 0.74 for organic matter, 0.21 for ammonium 0.84 for bulk density, 0.64 for moisture, and 0.54 for temperature (at surface) and 0.33 (at 2.5 cm depth).

Treatment Effects on Soil Properties

Soil pH increased significantly in ATB-high (7.07 ± 0.39 in 2021) and PMS-Kraft (7.01 ± 0.13 in 2021), whereas Control (C) and PMS-Sulfite (Ps) showed minimal change (~4.2–4.4). Ammonium levels diverged by site: Coniston soils exhibited significant declines across all treatments, while Falconbridge soils showed increases, peaking in ATB-low (1.05 ± 0.09 mg/L).

Soil moisture content measured via TDR probes revealed significant differences, particularly in ATB-treated soils, which maintained higher moisture and exhibited slower drying after precipitation. The ATB treatments retained up to 9.31 ± 2.41% moisture, while Control soils averaged only 4.51 ± 1.04%. PMS and BBFA treatments resulted in extreme drying, often <1% moisture in surface layers.

Soil temperature also varied by treatment. ATB-treated soils remained significantly cooler than other treatments, averaging -25.9 ± 5.5°C lower than all others during summer sampling. PMS and BBFA treatments exhibited the highest temperatures, significantly exceeding those in Control plots ($p < 0.05$). ANOVA results indicated significant differences between treatments ($F = 16.91$,

$p < 0.05$), with post-hoc tests highlighting 2 distinct groups when compared to C soils: i) ATB (high and low); ii) PMS and BBFA treatments.

Passive Recolonization

Vegetative Cover

Vegetation cover was significantly impacted by treatment. Ps-S (with or without ash), Ps-K, and AF treatments immediately reduced cover to <10%, with residual effects persisting throughout the experiment. In contrast, ATB-1 and ATB-2 greatly increased vegetative cover, reaching 194.5 ± 25.1% and 233.4 ± 46.7%, respectively, by the end of the study. These increases reflect multi-layered plant growth, and a negative relationship between slope and cover was observed ($p < 0.001$).

Treatment Effects on Effective Species Number

The effective species number (ESN) was evaluated to assess the impact of soil amendments on plant community composition and biodiversity. ESN provides a measure of diversity that accounts for both species richness and evenness, reflecting the ecological success of the treatments in promoting balanced plant communities. Plant community diversity (ESN) varied significantly by treatment. ATB-high (11.8 ± 2.1) and ATB-low (10.3 ± 2.1) treatments supported the highest species diversity. The Ps-K treatment (6.54 ± 1.61) also promoted diversity but to a lesser extent. Conversely, Ps-S and AF treatments significantly reduced ESN (1.8–2.4, $p < 0.05$), indicating a failure to enhance plant communities. The Sudbury treatment had no measurable impact compared to the Control (4.1 ± 1.5). ANOVA confirmed significant treatment effects on effective species number ($F = 36.4$, $p < 0.0001$), with post-hoc comparisons highlighting that ATB-high, ATB-low, and PMS-Kraft treatments were associated with higher ESN compared to the C and other treatments.

Changes in Community Structure

PCA of the relative occurrence data revealed distinct patterns in community structure based on treatment type (Fig. 15). ATB-high and ATB-low treated plots (and sites) were largely indistinguishable from each other, clustering closely, which suggests similar effects on community composition. Ps-K treatment formed a unique cluster, though similar to ATB, reflecting its distinct impact on plant communities. Ps-S (with or without ash) and AF treatments showed overlapping clusters, indicating similar influences on the plant communities. Specifically, these treatments were most influenced by "bare ground" and "leaf litter" "communities", highlighting their distinct negative impacts. Without the inclusion of these abiotic cover types, we had difficulty plotting these treatments. The SUD and CON treatments also clustered together, suggesting minimal divergence from baseline community conditions, with little impact on species composition or diversity (Fig. 15).

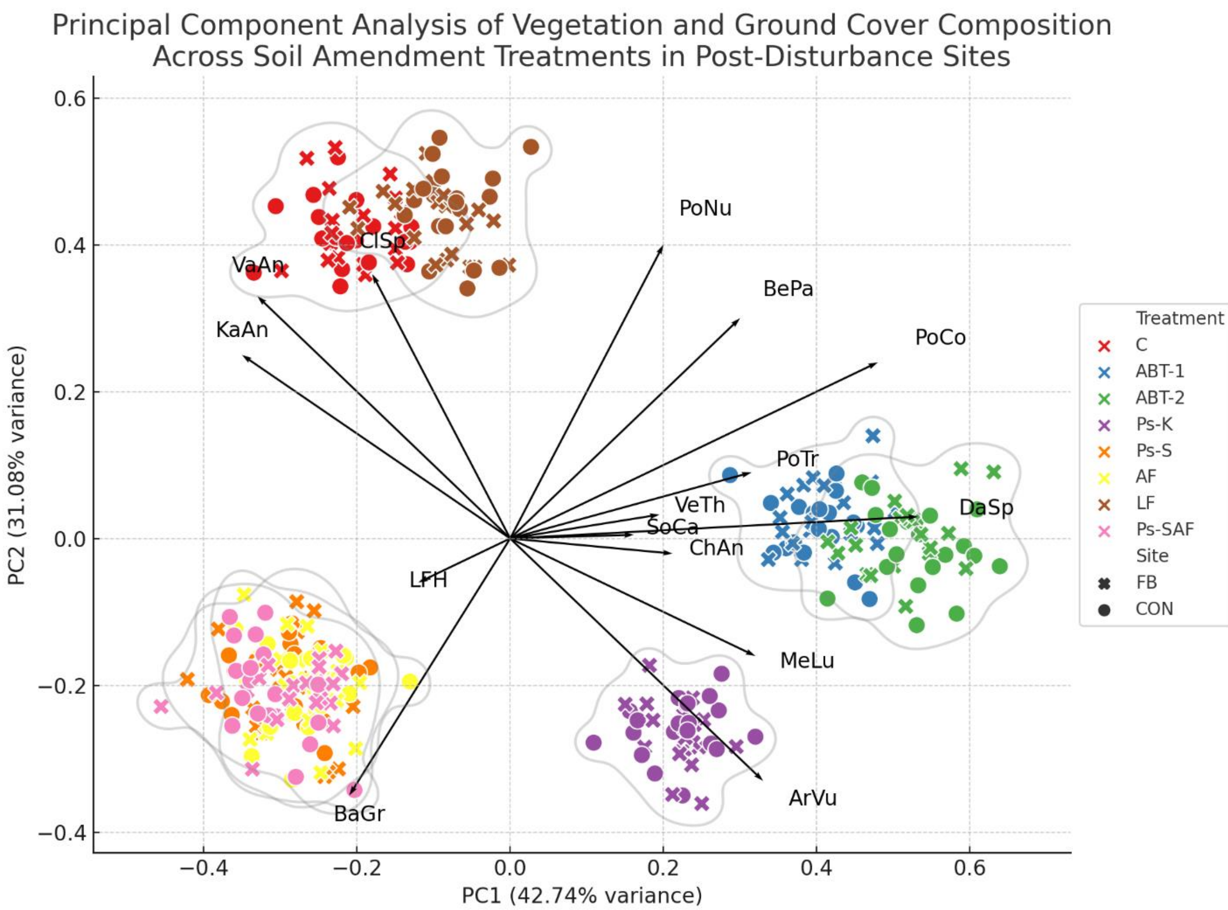

Figure 15 - Principal Component Analysis (PCA) of plant community composition across soil amendment treatments in Sudbury's degraded upland and sloped sites. Clustering patterns indicate distinct community structures associated with treatments, with ATB-treated plots showing higher species diversity and cover, while Ps-S and AF treatments cluster closer to bare ground and low diversity conditions. Arrows represent key soil variables influencing community composition, including moisture, temperature, and pH.

Pre-amendment plots, where vegetated, were largely dominated by 2 pioneering and acid tolerant moss species: *Pohlia nutans* and *Polytrichum communes*. Very large patches of acid tolerant *Cladonia* species were repeatedly observed as well (roughly equally represented *C.*

multiformis, *C. borealis*, *C. pleurota*, *C. cristatella*, *C. rangiferina*, and *C. arbuscula*). Interestingly, colonies of *Dibaeis baeomyces* become more noticeable throughout the trial, often invading experimental C plots. Truly vascular species were indeed rare but were composed by patches of heaths *Kalmia angustifolium* and *Vaccinium angustifolium*, and more rarely, *Rhododendron groenlandicum.* Even rarer were trees and shrubs, these were represented by *Betula papyrifera*, *Acer rubrum*, and *Pinus resinosa*.

The application of Ps-K, Ps-S, and AF resulted in the extirpation of these species from their plots. In the case of Ps-S and AF, only the tree and heath species remained. Passive recolonization was not observed in plots treated with Ps-S or AF for the duration of the experiment. In Ps-K, the lichen species remained extirpated, but a significant return of the pioneer moss species were observed. Passive recolonization did occur in Ps-K, which was dominated by ruderal and often noxious herbs, particularly *Erigeron canadensis*, *Artemisia vulgaris*, *Bidens frondose, Pilosella aurantiaca, Medicago lupulina*, and *Convolvulus* sp. Native species did invade as well, particularly*, Chamaenerion angustifolium* and *Solidago canadensis*. We observed no site effects, and little variation between plots.

Again, any presence of lichens was removed in ATB-1 and ATB-2 amended soils but were largely being colonized by pioneer and traditionally "roadside" herb species. Any presence of exotic species appeared to spread from Ps-K plots, as more isolated ATB plots had significantly lower occurrences these species Soils amended with these materials repeatedly followed this recolonization pattern: i) complete (100%) and rapid (within months) coverage of *Pohlia nutans* and *Polytrichum communes*, as well smaller patches of *Polytrichum juniperius*; ii) significant establishment of graminoids (particularly *Danthonia spicata*, *Agrostis gigantea*, *Deschampsia cespitosa*, *Calamagrostis canadensis*, *Carex* scoparia, and *Agrostis scabra*) and forbs (particularly *Chamaenerion angustifolium*, *Symphyotrichum ericoides*, *Verbascum thapsus*); iii) the reintroduction of *Populus tremuloides* and *Populus grandidentata*, as well as the resurgence of *Betula papyrifera.* In the latter, growth was especially vigorous, reaching heights approximating 2.5 metres in flat plots by the end of the experimental trial (the plants were originally mowed down in the beginning of the trial). Of note was the verdant colouring and width of these new sapling leaves, which were approximately 126.9 ± 15.3 % greater in chlorophyll content and 157.0 ± 51.1 % greater in leaf width than their unamended counterparts in C plots. Indeed, this species created nearly closed canopies in especially flat plots. Such growth was not observed in any other treatments and was observed at both experimental sites.

PERMANOVA confirmed significant differences in plant community composition among treatments ($F = 19.5$, $p < 0.001$), with pairwise comparisons indicating highlight the following clusters: i) ATB; ii) Ps-K; iii) C and LF; iv) Ps-S, Ps-SA, AF.

<u>Outcomes of Planted Species Across Treatments</u>

Survival, health, and growth metrics were assessed to evaluate the response of the planted tree species — red pine, red oak, and yellow birch — to different soil treatments. Key growth parameters measured included stem length and chlorophyll content recorded biannually in the spring and fall of each growing season from 2020 to 2022. However, due to elevated mortality rates (especially in the CON site), lowered sample counts diluted the statistical significance of response of variables, and the following results should be interpreted with caution. Nonetheless, treatment effects were observed in all species. A summary of outcomes can be viewed in Table 3.

Pinus banksiana:

Survival rates were largely driven by site factors and browsing rates. Treatment effects were largely not observed across both sites (averaging 42% in CON sites and but 87% in FB sites), with the noted exception of LF in CON plots, which improved survival by 29% compared to controls. In CON plots, survival rates were 45% lower than those observed in FB plots. Here, topography was a significant contributor. Unlike FB, 2 of 5 CON blocks were installed along steep slopes (averaging 29.5 degrees) where non-browsing seedling deaths were observed at significantly higher rates than their flat counterparts (12.5% survival vs. 63.1%). There appears to be a soil depth effect as well, as the planting soil medium in CON plots often represented the entirety of the soil profile. Here, cases of seedling expulsion due to frost heave were more commonly observed in CON plots than FB plots where such events ultimately led to the expiration of the individual (25.7% vs. 13.5%). However, in both sites we observed a significantly lower rate of such events in ATB-1 and ATB-2 amended plots (only 2.4% of planted jack pines were expelled). Overall, non-expelled or browsed individuals who had expired were nearly universally described as being “dry” or having experienced “loss of turgor”, with rare mention of leaf discolouration or other form of stress or disease. Overall, health status, a ranked assessment of the individual, with 5 being verdant and showing no signs of stress, decreasing with increasing discolouration, loss of turgor, premature leaf loss, or other forms of non-browsing stress, was greatest in ATB and Ps-K plots (4.3 and 4.0 respectively), with only Ps-SA being significantly lower than controls (ANOVA, $p<0.001$).

Browsing rates were significant in both sites, but slightly greater in CON plots. Here, browsing occurred in 2 ways: i) decapitation via snowshoe hare (65.3% of cases); ii) total removal or significant jagged damage from ungulates (34.7% of cases). Co-occurrence was observed, but relatively rare (only 5.4% of cases) as browsing events nearly always led to the individual expiring (78.3%). In total, 26.4% of individuals were browsed, resulting in the expiration of 20.7% of planted Jack pines. Remaining cases of expiration were largely drought driven, with no other signs of damage (browsing), it appeared the conductive tissues had cavitated.

Of the 3 experimental species, *Pinus banksiana* was expectedly the most productive but still exhibited strong treatment ($p<0.001$) and site responses ($p<0.001$) following ANOVA testing ($F = 9.12$ and 13.87). In FB plots, with post-hoc tests confirming several treatments showed significant differences compared to the control (C). The ATB-1 and ATB-2 treatments had significantly higher relative growth rates (RGR) than the control, with mean RGRs of 3.84% and 4.04%, respectively, and p-values of less than 0.0001. Both AF and LF also significantly outperformed the control, with mean RGRs of 2.81% and 2.94%, respectively ($p < 0.0001$ for both). The Ps-K treatment, although showing a moderately higher mean RGR (2.48%) compared to the control, was also significantly different with a p-value of 0.0004. Overall, ATB-1, ATB-2, AF, LF, and Ps-K all had significantly better growth than the control, with ATB-1 and ATB-2 having the most substantial positive impact.

In the CON site, the post-hoc test revealed that two treatments had significantly different relative growth rates (RGR) compared to the control (C) for this species at the CON site. The ATB-2 treatment, with a mean RGR of 2.03%, significantly outperformed the control, which had a mean RGR of 1.0% ($p < 0.001$). Similarly, the Ps-S treatment, which had a lower mean RGR of 0.50%, was significantly different from the control ($p = 0.0076$). Other treatments, such as AF, Ps-K, LF, ATB-1, and Ps-SA, had similar RGRs to the control and were not significantly different, indicating comparable effects on growth.

Quercus rubra:

Similar patterns were observed in planted *Quercus rubra* seedlings but were generally much milder. Again, the CON site exhibited generally lower survival rates across all treatments compared to the FB site (76.9% vs 93.0%) – with moderate treatment effects. Survival again correlated with elevated frost heave expulsions and slope which was significantly lowered in ATB amended plots. Interestingly, this species was able to survive browsing events at remarkable rates. Nearly all (93.1%) of individuals planted across both sites observed some form of browsing, however, nearly all survived the event (96.3%). Only complete removal from the soil profile following ungulate browsing resulted in expiration. This species would consistently exhibit regenerative growth – often requiring their survival status to be amended in future surveys as new buds activated. Treatment effects were again mild to non-existent: only ATB-1 and ATB-2 were significantly higher ($p<0.05$), while remaining treatments were indistinguishable from controls. However, again, healthy individuals were associated with ATB and Ps-K plots at elevated rates (Tukey's HSD, $p<0.001$), with all other treatments being indistinguishable from controls ($p>0.05$).

Similar patterns were observed in *Quercus rubra* seedlings planted in the FB site: post-hoc tests revealed significant differences between several treatments and the control (C). The ATB-1 and 2 treatments had the highest relative growth rates (RGR) for this species at the FB site, with mean RGRs of 1.68% and 2.18%, respectively, and both significantly outperformed the control (mean RGR of -0.07%) with p-values less than 0.001. The AF treatment also showed a significant improvement compared to the control (mean RGR of 0.53%, $p = 0.0031$). In contrast, the Ps-K and LF treatments, with mean RGRs of 0.37% and 0.11%, respectively, did not significantly differ from the control, suggesting a more moderate effect on growth.

In CON plots, a post-hoc test revealed that all treatments for this species showed significant differences compared to the control (C). The control had a mean relative growth rate (RGR) of -0.89%. The AF treatment, with a mean RGR of -0.13%, significantly outperformed the control ($p < 0.001$), as did the Ps-K (mean RGR = 1.25%), LF (mean RGR = 0.04%), ATB-1 (-0.18%), ATB-2 (0.53%), and Ps-SA (1.00%) treatments. Ps-K, ATB-2, and Ps-SA treatments had the most positive impacts on growth, with mean RGRs of 1.25%, 0.53%, and 1.00%, respectively. Even though AF and ATB-1 had negative mean RGRs, they still significantly outperformed the control, albeit with smaller differences. In both sites, chlorophyll content was quite positively correlated with RGR (r^2=0.86). Again, these values are to be particularly interpreted with caution given the widespread browsing which occurred, followed by the regenerative growth of this species. Negative RGR values may better indicate a poor response to browsing (as seen in C plots) rather than a direct loss in stem length of time.

Betula alleghaniensis:

In CON and FB plots, only 11.2% and 28.2% of individuals survived the experimental trial. Like Quercus rubra, browsing occurred at elevated rates in both sites (63.9% and 55.3%), typically stemming from snowshoe hares. Unlike *Quercus rubra*, this species was largely unable to recover from these events. Frost heave expulsion occurred as well, at similar rates to the other species, sites, and treatments. Treatments were generally unable to improve survival rates of this species in either site, the exception being ATB-1 in the FB site, which improved survival by 32% (to 65%) compared to controls. Here, only ATB plots were associated with healthy individuals, with Ps-S, Ps-SAF, and AF being largely unhealthy, while Ps-K and LF were indistinguishable from controls.

In FB plots, this species benefited most from the application of ATB-2, Ps-K, and Ps-SA when compared to C, which showed essentially no growth for the entirety of the trial. Post-hoc tests revealed that several treatments had significantly higher relative growth rates (RGR) compared to the control (*C*) for this species. The control had a negative mean RGR of -0.89%, while all other treatments, including AF (0.85%), Ps-K (1.15%), LF (0.98%), ATB-1 (0.90%), ATB-2 (1.06%), and Ps-SA (1.21%), demonstrated positive mean RGRs. Each of these treatments significantly outperformed the control, with p-values of less than 0.001. This indicates that all treatments substantially improved growth compared to the untreated control, with Ps-SA, Ps-K, and ATB-2 showing the largest improvements.

In CON plots, the post-hoc test revealed that several treatments showed significant differences compared to the control (C). The control had a mean relative growth rate (RGR) of 0.56%. The AF treatment, with a mean RGR of -0.03%, was significantly lower than the control ($p < 0.001$), while Ps-K (mean RGR = 2.54%), ATB-1 (mean RGR = 0.99%), and ATB-2 (mean RGR = 1.76%) all significantly outperformed the control ($p < 0.05$ for each). The P and Ps-SA treatments, with negative RGR values of -0.50% and -1.35%, respectively, also showed significantly lower growth than the control ($p < 0.001$).

Table 3. Overview of planted tree outcomes (CON) (t=4 years) - ± indicates standard deviation.

Parameter	Species	LF	Ps-K	Ps-S	Ps-SA	AF	ATB1	ABT2	C
Survival (%)	J. Pine	70	52	35	44	33	48	41	41
	R. Oak	76	81	83	58	75	88	75	79
	Y. Birch	19	10	22	1	5	11	12	11
Health Status	J. Pine	3.87 ± 0.23	4.02 ± 0.14	2.23 ± 0.11	1.87 ± 0.51	1.68 ± 0.16	4.46 ± 0.26	4.74 ± 0.14	2.03 ± 1.23
	R. Oak	3.51 ± 0.65	3.69 ± 0.97	2.14 ± 0.14	1.47 ± 0.05	1.32 ± 0.28	4.32 ± 0.47	4.56 ± 0.08	2.66 ± 0.41
	Y. Birch	1.41 ± 1.11	1.84 ± 0.84	0.31 ± 0.04	0.32 ± 0.02	0.12 ± 0.04	2.47 ± 1.47	3.21 ± 1.23	0.89 ± 1.21
RGR (%/mt)	J. Pine	1.38 ± 2.23	1.34 ± 2.48	0.50 ± 2.13	1.09 ± 2.25	1.03 ± 2.10	1.28 ± 2.42	2.03 ± 2.01	1.00 ± 1.94
	R. Oak	0.03 ± 2.01	1.24 ± 2.45	-0.38 ± 2.22	0.99 ± 2.25	-0.13 ± 1.90	-0.19 ± 2.15	0.52 ± 1.68	-0.90 ± 2.00
	Y. Birch	0.53 ± 1.98	2.53 ± 1.94	-0.51 ± 2.21	-1.36 ± 1.37	-0.04 ± 1.58	0.99 ± 1.81	1.75 ± 1.84	0.55 ± 1.66
LCC (g/m^2)	J. Pine	NA	NA	NA	NA	NA	NA	NA	NA
	R. Oak	0.18 ± 0.06	0.21 ± 0.14	0.08 ± 0.12	0.09 ± 0.14	0.07 ± 0.03	0.34 ± 0.16	0.39 ± 0.13	0.12 ± 0.08
	Y. Birch	0.21 ± 0.13	0.18 ± 0.13	0.07 ± 0.11	0.05 ± 0.08	0.13 ± 0.06	0.31 ± 0.18	0.33 ± 0.21	0.11 ± 0.08
Browsing Rate (%) (% of which survived)	J. Pine	21 (31)	18 (61)	26 (35)	41 (12)	11 (11)	30 (74)	31 (81)	26 (36)
	R. Oak	91 (94)	93 (92)	81 (91)	83 (99)	84 (94)	99 (0.91)	99 (96)	86 (94)
	Y. Birch	66 (11)	71 (13)	81 (9)	51 (8)	62 (11)	81 (21)	82 (20)	51 (10)

Relationship Between Seedling Outcome and Soil Properties

The redundancy analysis (RDA) conducted in this study evaluated the relationships between soil properties, treatments, and the growth and health of jack pine, red oak, and yellow birch. The analysis revealed significant insights into how various soil conditions are linked to plant outcomes under different treatments. Key soil variables examined included soil temperature, moisture, NH_4 content, ground cover, and pH.

The RDA results demonstrated clear clustering patterns, with ATB-1 and ATB-2 treatments associated with positive plant outcomes, including higher growth rates and better health status for Jack Pine and Red Oak. These treatments exhibited favorable conditions, such as cooler soil temperatures and higher surface moisture, which correlated strongly with improved plant responses. Ground cover was also significantly higher in the ATB treatments, buffering seedlings from environmental extremes and promoting favorable microclimatic conditions. Ps-K showed moderate success, with plant outcomes clustering near ATB treatments but at slightly higher soil temperatures, reflecting its intermediate performance in terms of growth and health.

Soil properties, which formed the first two axes of the RDA, captured 83.4% of the total variance, with PC1 explaining 82.56% and PC2 explaining 7.41% of the variation in plant responses. The eigenvalues for these axes indicated that the separation of treatments was largely driven by differences in soil temperature, moisture, and ground cover, with these variables showing the strongest associations in the biplot. The loadings for these soil properties were higher along the PC1 axis, reflecting their strong correlation with positive plant outcomes in the ATB treatments. In contrast, pH had a weak association, positioned almost perpendicular to the overall spread of treatments, indicating it did not contribute substantially to the observed separation. A permutation test (999 permutations) confirmed the statistical significance of the RDA model, with a $p\text{-value} < 0.05$, indicating that the observed relationships between soil properties and plant responses were unlikely due to random chance.

In contrast, treatments such as Ps-S, Ps-SA, and AF clustered separately, indicating poorer growth and health outcomes. Despite higher NH_4 levels across these treatments, positive plant responses were limited, suggesting that the extreme soil conditions (e.g., high temperatures and low moisture) in these plots negated the potential benefits of increased nutrients. The C and LF treatments clustered closer together, displaying similar, intermediate outcomes, characterized by dry soil conditions and minimal cover, which constrained growth and overall health.

The RDA plot also highlighted the influence of slope, which negatively impacted plant outcomes, particularly in vegetative cover. The erosion on sloped plots exacerbated moisture deficits, reducing plant performance even in nutrient-rich treatments like ATB. Jack pine showed relatively high survival but variable growth across treatments, while red oak displayed lower growth rates but higher survival. Yellow Birch did not contribute meaningfully to the RDA due to poor outcomes across all treatments (Fig. 16).

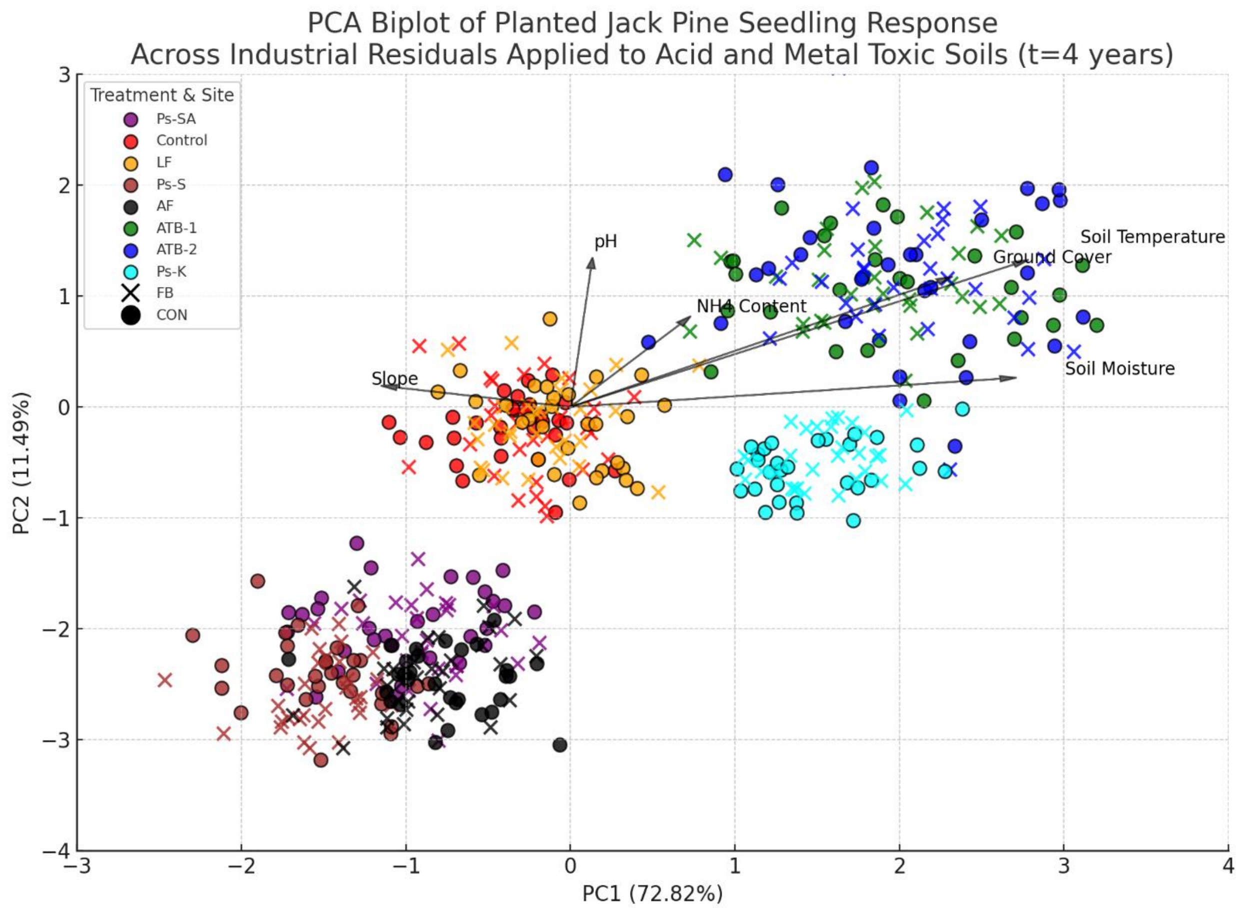

Figure 16 - *Redundancy Analysis (RDA) biplot showing the relationship between soil properties, treatment types, and plant growth metrics for Jack Pine across experimental plots. Soil temperature, moisture, and ground cover are the primary factors driving plant outcomes, with ATB treatments correlating with improved growth rates and health. Treatments such as Ps-S and AF show poorer performance, characterized by higher temperatures and lower moisture availability.*

In conclusion, the RDA and subsequent analyses underscore the likely critical roles of properties like soil temperature, moisture, and ground cover in driving plant outcomes under the treatments. The findings suggest that while nutrient availability (NH_4 and pH) contributes to soil fertility, optimal plant growth was primarily associated with favorable microclimatic conditions and high ground cover in ATB-treated plots, highlighting the potential of these treatments in enhancing forest succession in disturbed environments.

Discussion

Passive Recolonization

One of the most striking findings of this study was the success of ATB in its ability to promote plant diversity through passive establishment. ATB-treated plots showed a remarkable increase in species richness and evenness, fostering the establishment of a diverse plant community dominated by native grass and herb species, with *Pohlia nutans* and *Polytrichum commune* forming a key part of the initial ground cover. The high rates of recolonization in these plots suggest that ATB not only enhances soil fertility but also supports successional processes, enabling the recruitment of a wider range of species. This result highlights the potential for ATB to play a crucial role in long-term reclamation strategies aimed at restoring ecological function to acid and metal-damaged soils. In contrast, while Ps-K also increased species diversity, it often did so through the recruitment of exotic or ruderal, heat resistant species, such as *Bidens frondosa* and *Artemisia vulgaris*, which are not welcome in the context of ecological restoration. However, it is suspected that many of these species were "stowaways" from when the sludge was dredged from the sewage lagoon, as these lagoons are known to house such species (Wolverton, 1986; Vandevenne, 1995). Recent studies have highlighted the elevated risk of non-target species introduction following the application of dried paper mill lagoon sludge, particularly to agricultural lands (Paiva et al., 2009; Bull et al., 2021). While Ps-K increased pH and improved conditions for plant establishment, the unintended introduction of these exotic species complicates its use in restoration, as these species are not desirable in the context of promoting long-term ecosystem resilience and native biodiversity (D'Antonia and Meyerson 2002; Cordero et al., 2023). This underscores the need for careful consideration of the source and composition of the materials used in soil amendments, particularly in cases like Ps-K, where the potential for introducing non-native species is higher due to the origins of the sludge. The recruitment of exotic species can disrupt the recolonization process, outcompeting native species and reducing the overall ecological value of the restoration efforts (Meinhardt and Gehring, 2012; Chen et al., 2013; Wang et al., 2013). This highlights a key distinction between treatments: while both ATB and Ps-K improved diversity metrics, only ATB effectively promoted the reestablishment of native plant communities crucial for long-term ecosystem resilience. Other treatments, such as Ps-S and Ash + Fertilizer (AF), had fewer positive outcomes. These treatments often reduced species diversity, which was driven by the extirpation of native lichen species without having promoted significant recolonization of other plant types.

One of the most striking findings was the ability of ATB treatments to significantly improve soil moisture retention and regulate temperature extremes, which may be linked to the widespread establishment of moss carpets, primarily *Pohlia nutans* and *Polytrichum commune*. These mosses quickly colonized the treated plots and contributed to a more stable and moist soil surface, even during the driest months. Moss carpets have been shown in other studies to enhance moisture retention by forming a protective layer over the soil, reducing evaporation, and improving water infiltration (Thomas et al., 1994; Yang et al., 2015; Thielen et al., 2021). This is crucial in the context of Sudbury's sloped and upland zones, where erosion and poor soil structure typically result in low moisture availability (Gundermann and Hutchinson 1995). The reduced soil temperatures observed in ATB-treated plots further underscore the role of these mosses in moderating soil microclimate, providing a more hospitable environment for plant establishment and growth (Parker et al., 1997; Groeneveld et al., 2007). The role of moss cover, especially *Pohlia nutans* and *Polytrichum commune*, in improving moisture retention and stabilizing the soil surface has been less explored in reclamation literature, though studies have noted the importance of early successional species in facilitating ecosystem recovery (Parker et al., 1994; Corradini and Clément, 1999). In this study, mosses played a pivotal role in creating microenvironments conducive to recolonization, an effect that was particularly evident in the ATB-treated plots. Carpet-forming mosses, particularly *Pohlia nutans* and *Polytrichum commune*, play an essential role during early successional stages, especially in disturbed environments where soil degradation and erosion are prevalent (Thomas et al., 1994). These species possess several traits that make them ideal pioneers in fostering recolonization and promoting plant diversity. *Pohlia nutans*, known for its high tolerance to metal toxicity and poor soil conditions (Samecka-Cymerman and Kempers, 2007), colonizes exposed substrates quickly (Jonsson, 1993), while *Polytrichum commune* is renowned for its dense, deep-rooted mats that stabilize soil and prevent erosion (Sarafis 1971; Thomas et al., 1990; Thomas et al., 1994). Their ability to thrive in nutrient-poor environments, combined with their capacity to improve soil structure, allows these mosses to create microhabitats that favor the establishment of vascular plants by increasing soil moisture retention and moderating temperature extremes. Both moss species exhibit significant beneficial effects on soil, particularly in regulating temperature and moisture. The dense mats formed by these species insulate the soil, buffering it against diurnal temperature fluctuations. This temperature moderation creates a more stable environment for seed germination and root development (Bayfield 1973; Thomas et al., 1994). Moreover, Bayfield explicitly describes these thick moss layers as sponges, absorbing and retaining water, which is critical in environments prone to desiccation or irregular precipitation. This increased soil moisture not only benefits the mosses themselves but also facilitates the growth of moisture-dependent vascular plants. The presence of *Pohlia nutans* and *Polytrichum commune* can therefore accelerate soil development processes, increase organic matter input, and promote microbial activity, ultimately creating conditions conducive to greater plant diversity (Corradini and Clément, 1999; van der Heijden et al., 2008). Beckett (1986) also observed *Pohlia nutans* providing a suitable bed for the germination of tickle grass (*Agrostis scabra*). By stabilizing the soil and regulating critical environmental factors, these mosses play a foundational role in facilitating ecosystem recovery and promoting natural successional trajectories. These findings suggest that mosses may be underutilized but valuable contributors to recolonization efforts, particularly in environments where soil instability and moisture fluctuations present major challenges.

The beneficial influence of ATB, and by extension these carpet forming mosses, on recolonization rates are clear. However, before investing in this treatment, and by extension these species as reclamation vectors, or in order to replicate these results on a larger scale, we must understand why their re-emergence was solely observed in ATB plots. The application of industrial residuals, particularly ATB, had further notable effects on key soil properties, including pH, moisture retention, and temperature regulation, which are believed to be critical for the reestablishment of plant communities in such degraded landscapes (Sloan and Basta, 1995; Cele and Maboeta, 2016; Luo and Christie, 2001). These changes are especially significant given the acidic and metal-contaminated conditions of the Sudbury region, where soil acidity and metal toxicity have severely hindered natural vegetation recovery (Freedman and Hutchinson, 1980; Gunn, 1995). By increasing soil pH, ATB not only created a more favorable environment for nutrient availability, particularly nitrogen and phosphorus, but also helped mitigate the toxic effects of metals such as nickel, aluminum, and copper, which are more soluble and harmful under acidic conditions (Barceló and Poschenrieder, 1990).

Despite these positive changes in pH and moisture, we observed no significant differences in bulk density of soil organic matter content across treatments. This is likely due to the 10 cm sampling depth, which may have diluted any detectable changes in these properties. The soils in this study, which are composed of eroded glacial till, exhibited relatively low bulk density values (~0.91 g/cm^3), consistent with their sandy, silty, and clay-rich composition, as noted during field assessments. Low bulk density in these soils is unlikely to impede plant growth directly, as it generally allows for adequate root penetration and air exchange (Périé and Ouimet, 2008). However, given the harsh conditions and lack of significant organic inputs, the absence of increases in SOM suggests that additional organic amendments may be needed to support long-term soil fertility and structural stability. The overall success of ATB in promoting plant growth and diversity indicates its potential as a valuable reclamation tool, but long-term sustainability may depend on addressing these deeper soil challenges.

Treatments such as AF, Ps-SA, Ps-K were effective in improving soil pH, reaching levels comparable to those achieved by ATB. This pH increase is known to reduce metal bioavailability in these exact soils, as documented by Chan-Yam et al. (2024). In addition to the pH improvements, the Ps-SA and Ps-K treatments share many similarities with ATB in other respects. These treatments also introduced elevated nutrient concentrations while being rich in organic matter, both of which are crucial for supporting plant growth and facilitating ecosystem recovery (Ribeiro et al., 2010; Camberato et al., 2006; Asemaninejad et al., 2018). Despite these favorable conditions, recolonization, specifically the proliferation of these pioneering carpet mosses, was significantly impeded in the Ps-SA, AF, and to a lesser extent, Ps-K treated soils. This raises further questions as to why these treatments, which are comparable to ATB in terms of nutrient content and organic matter enrichment, did not support a more robust recolonization process. It suggests that factors beyond pH and nutrient availability—such as microbial activity, moisture retention, microclimate, or soil structure—may play a critical role in driving the successful recolonization observed in ATB-treated soils but are absent or less effective in the Ps-SA and Ps-K treatments.

One key difference may be the significantly decreased albedo in these PMS and BBFA treatments (naturally black, or dark grey soil like material), which blanketed the plots and potentially contributed to increased soil temperatures. Verheijen et al. (2013) observed significant decreases in albedo (and increases in soil temperature) following the application of biochar (a similar material to those used in this study) at a rate of 120 t/ha to cropland. In contrast, our experimental ATB material is beige and sandy which readily dissolved and incorporated into soil following precipitation events. By the end of the trial, we could not observe any ATB material remaining on the plot whereas remaining treatments were still visible. Soil surface temperatures in AF and both types of Ps treatments frequently reached extreme levels, often exceeding 70°C. Such conditions are only conducive to the germination of a few species native to the region, and these typically require short-lived, elevated temperatures (for example, *Pinus banksiana* cones require heat to open, and their seeds to germinate). However, a consistently hot soil surface is not the same as these temporary temperature spikes, which are crucial for some species' reproductive cycles. Prolonged exposure to such high temperatures can inhibit plant growth and soil recovery (Marty et al., 2020; Allison and Treseder, 2008; Verburg et al., 2004). Though species found earlier during the succession of such disturbed environments (perhaps as found in ATB plots) may possess some ability to withstand elevated soil temperatures, those measured in PMS and BBFA plots may be too elevated – especially given these soils were often considered bone-dry by our in-situ analysis. Specifically, these mosses are known to prefer more moderate environments, often failing to thrive in temperatures observed in this study (Potter et al. 2015). The RDA results, along with supporting literature, leave no doubt that low-albedo surfaces, when combined with thin, disturbed mineral soils of poor moisture retention, can actively hinder the proliferation of native species, even when their acidity and poor nutrient content are effectively treated.

Temperature extremes may have shifted microbial community composition as well. ATB nitrogen is primarily in organic forms, necessitating mineralization by soil bacteria or fungi to become available to plants. This process seems to have occurred effectively, as evidenced by the verdant growth observed across a variety of species in ATB-treated soils as well as elevated leaf chlorophyll levels. Price et al. (2015) applied ATB to similar acid damaged sandy loams where they observed a significant rise in seasonal soil mineral nitrogen, enhancing nitrogen availability for plants (42 Mg ha-1). In a previous study (Chan-Yam et al. 2025), we found that ATB-treated soils were particularly rich in enzymes produced by nitrifying bacterial species, though it was not identified. Asemaninejad et al. (2018) found that following the incorporation of highly alkaline blended pulp mill sludge (elevated in biosludge) to acid tailings, the proportion of members belonging to the nitrogen cycling phyla *Proteobacteria, Actinobacteria,* and *Acidobacteria* increased significantly. This raises the possibility that the efficiency and proliferation of these bacteria are pH-dependent, or perhaps temperature dependent following the proliferation carpet mosses. Many nitrifying bacteria are known to perform optimally in near-neutral pH conditions (Rousk et al., 2010; Xu et al. 2020). In a recent sister study investigating the fungal and bacteria community composition shift following the application of these materials to these soils, we observed a strong pH dependent shift towards *Proteobacteria*, a phylum commonly associated with nutrient rich conditions, as well as nitrification as well as nitrogen-fixing (Hovanec and Delong, 1996; Rudnick et al., 1997; Dai et al., 2017). Furthermore, *Polytrichum commune* and similar mosses foster bacterial communities through their rhizoid systems and surrounding microhabitats, potentially enhancing nutrient cycling (Juottonen et al. 2019). The moss's structure can create microenvironments that support diverse microbial taxa, including nitrogen-fixing and organic matter-decomposing bacteria (Thomas et al., 1990; 1994). This could explain why ATB-treated plots, with their more favourable pH and temperature conditions, supported both enhanced bacterial activity and improved plant growth.

The suspected shift in microbial dynamics, particularly under extreme temperature conditions, may also explain the reduced nitrogen mineralization observed in these plots. Multiple studies have shown phyla related to nitrogen mineralization to be severely inhibited when exposed to soil temperature ranges observed in this study (Wong-Chong and Loehr, 1978; Zhu et al., 1986). Such extreme temperature fluxes can create unfavorable conditions for nitrogen-transforming bacteria, disrupt nitrogen cycling, and ultimately hinder ecosystem recovery and plant establishment (Li et al. 2018). We noted lower chlorophyll content in the leaves of species growing in Ps-K and Ps-S, and Ps-SA-treated soils, indicating lower overall nitrogen availability or plant uptake, but also other moisture related stressors. This may suggest lower nitrogen mineralization rates, as nitrogen in these PMS treatments are again primarily organic in form (Henry, 1991; Cordovil et al. 2013). Soil ammonium was indeed greatest in ATB soils, whereas remaining treatments (save Ps-K) were indistinguishable from, or lower than, controls though total N rates were consistent.

This negative relationship between albedo and productivity may initially seem counterintuitive, as healthy organic soils are often darkly coloured, and exposed following natural forms of disturbance (e.g., forest fires where the soils are covered with charred materials, or ash, with similar properties to the residuals used in this study). However, post-fire soils nearly always retain a healthy rhizome layer saturated with biological legacy, which rushes up to vegetate the soil and leverage newly available solar energy and nutrient sources (Brown et al., 2015; Sun et al., 2015). Furthermore, the disturbance may also increase the heterogeneity of the microtopography (e.g., fall or overturned trees, stumps providing shade) which can further promote the natural ability of soil organic matter to retain elevated volumes of moisture and help moderate soil temperatures (Keeton and Franklin, 2004). This all combines to foster an environment suited for rapid recolonization following a disturbance. In contrast, the soils of experimental sites are believed to house little, or a vastly disturbed pool of biological legacy, while containing little to no organic matter, and little microtopographic variation (Feisthouser et al., 2016; Goupil and Nkongolo, 2014; Goupil et al., 2015)

In AF-treated plots, where nitrogen was applied in a top-dressed manner as a combination of ammonium nitrate and urea, the lack of sustained plant growth could also be explained by nitrogen loss through leaching or volatilization. Ammonium nitrate may have leached through the soil profile, particularly due to the low vegetation cover. Urea, on the other hand, may have volatilized, especially when unincorporated into the soil profile, and exposed to high temperatures and low moisture conditions. Urea volatilization is a significant concern when applied to dry, acidic, and metal-contaminated soils, as nitrogen (N) losses can be substantial under such conditions. Studies have shown that volatilization is highly dependent on soil moisture, temperature, and buffering capacity. In drought-prone acidic soils, surface-applied urea may hydrolyze more slowly, delaying volatilization. However, once moisture is introduced—whether through rainfall or irrigation—volatilization rates can surge, leading to N losses of up to 26% of applied fertilizer (Stevens et al., 1989). This pattern is particularly problematic in metal-damaged till soils, where low organic matter and buffering capacity further exacerbate nitrogen loss. Additionally, research has demonstrated that temperature and initial soil moisture play a critical role—with dry soils delaying volatilization, only for losses to intensify when moisture conditions change (Burch and Fox, 1989). These losses would leave the plants with insufficient available nitrogen, further exacerbating the poor mineralization rates and leading to the observed lower chlorophyll content and reduced growth.

The lack of moss establishment in the LF-treated plots raises additional questions, especially since this treatment did not alter albedo significantly. Sulfuric-acid darkened bedrock and dry mineral soils did indeed generate warm conditions, though milder to what we observed in Ps-S and AF treatments. However, the pH improvements in LF-treated plots were only moderate, never reaching greater than 4.6 and 5.4 in experimental sites FB and CON respectively. This may not have been sufficient to trigger the rapid moss colonization seen in the ATB-treated soils. It is possible these species of moss, though typically considered acid tolerant, thrive under more elevated pH conditions, which could enhance nutrient availability and create a more suitable environment for their growth observed in ATB plots. Thomas et al. (1994) explicitly shows this, as the growth of *Polytrichum commune* was positively correlated with higher pH levels (3.5 to 6.4). Germination rates tended to improve as pH increased within this range, indicating that *Polytrichum commune* may perform better in less acidic conditions. However, their results indicate that *Pohlia nutans* may be more tolerant of a broader pH range, showing good germination across various acidic to neutral environments. Another consideration is the form and availability of nitrogen in the LF plots. Given the fertilizer is ammoniacal in nature, its mobility should be limited, and therefore readily available for plant uptake immediately following application. However, volatilization is promoted when co-applied with dolomitic limestone (in contrast, the Sudbury Regreening Program adopts a staggered approach, applying the fertilizer months after the lime as been applied and dissolved to the soil). When NH_4 reacts with greater fractions of hydroxides, which are especially concentrated immediately following application, it volatilizes as $NH_3(g)$ and water. Volatilization of ammonium when co-applied with lime products is well understand in the literature – where >55% of N could be lost (Hargrove et al., 1977; Whitehead and Riastrick, 1990). Due to this experimental oversight, much of the nitrogen could have already been lost, undermining the potential for moss growth (a primary reason why local regreening programs traditionally employ a staggered application schedule, allowing vegetation to establish before further nutrients are applied). Additionally, soil temperature may have played a role. The elevated temperatures in these plots are believed to increase evapotranspiration rates, which would further inhibit moss growth - Thomas et al. (1994) observed significant reductions in *P. communes* growth when temperatures rose above 30 Celsius. Without the establishment of moss carpets to stabilize the soil and conserve moisture, the conditions in the LF-treated plots may simply have been too harsh for recolonization to proceed effectively – explaining the apparent lack of development in plant community structure observed in the study. This interplay between pH, nutrient availability, and temperature could be key in understanding why mosses, and subsequently other species, failed to thrive in these plots.

Slope had a strong negative correlation with plant diversity, as steeper plots experienced greater erosion and poorer soil retention – especially that they were south facing (Geroy et al., 2011; Pachepsky et al., 2001). However, this was only observed statistically in ATB treated soils, given these were the only largely vegetated plots. These challenges limited the establishment of new species, even in treatments that otherwise promoted diversity on flatter terrain. Levasseur et al. (2022) observed very similar results in the same region, where ground cover and species diversity correlated negatively correlated with sloped – being the strongest predictor variable according to their models. The negative correlation between slope and diversity highlights the difficulty of revegetating sloped areas, where both water retention and soil stability are difficult to maintain. However, it is worth noting sloped ATB plots still retained significant moss cover (effectively 100%), though total vegetative cover was reduced.

The recolonization observed in ATB-treated plots is especially important in the context of long-term ecological recovery. Passive recolonization, defined as the establishment of self-sustaining native plant communities following perturbation, is a critical step in the restoration of ecosystem functions (Hobbs and Harris, 2001). In this study, the promotion of native species over exotic or ruderal species, as seen in Ps-K-treated plots, underscores the importance of soil amendments that not only improve soil conditions but also create environments conducive to the return of native biodiversity. The broader benefits of recolonization are significant: by promoting a diverse, native plant community, ATB-treated plots are more likely to support the re-establishment of ecosystem functions such as nutrient cycling, soil stabilization, and habitat provision for fauna (Zak et al., 2003; Quijas et al., 2010; Holland et al., 2017). This contrasts with plots where exotic species dominate, as these species can disrupt local ecosystems and reduce biodiversity in the long term (Mack et al., 2000). Furthermore, recolonization reduces the need for ongoing management interventions, as native plant communities are more resilient to environmental changes and capable of self-regeneration (Chazdon and Guariguata, 2016).

Overall, the results of this study contribute to the growing body of literature that emphasizes the importance of soil properties in driving successful recolonization. By improving key soil parameters such as pH and moisture retention, particularly through the application of ATB, this study demonstrates the potential for industrial residuals to play a critical role in reclamation strategies aimed at restoring degraded landscapes. The promotion of native species in ATB-treated plots is especially relevant in regions like the Sudbury area, where past industrial activity has led to widespread soil degradation and the loss of native biodiversity. These findings reinforce the need to prioritize soil amendments that not only improve soil fertility but also support long-term ecological recovery through recolonization.

Planted Tree Seedling Outcomes

Plants rely on their soil medium for four essential elements to survive and thrive, with soil organic matter and soil temperature playing crucial roles in supporting these needs. First, soil provides vital nutrients, including macronutrients like nitrogen, phosphorus, and potassium, and micronutrients such as calcium and iron, which are released and made more available through the decomposition of soil organic matter (Prescott 2005; Maathuis and Diatloff, 2013). This organic matter also enhances nutrient retention and supports beneficial soil microorganisms that help convert nutrients into forms that plants can readily absorb (Arcand et al., 2016; García-Orenes et al., 2016). Second, soil acts as a reservoir for water, with soil organic matter improving the soil's capacity to retain moisture while allowing excess water to drain, preventing root rot. Soil temperature directly influences water uptake, particularly in areas like the rhizome layer, where the interaction between temperature and moisture is strongest—warmer temperatures can facilitate better water absorption and nutrient transport, while excessively cold temperatures can limit root activity (Rawls et al., 2003; Pregitzer and King, 2005). Third, well-aerated soil ensures that roots receive the oxygen necessary for respiration, with soil organic matter contributing to improved soil structure and aeration (Bartholomeus et al., 2008; Scott and Renaud, 2007). Finally, soil provides physical support, anchoring plants and allowing roots to penetrate deeply, especially in soils with higher organic matter content that enhances soil aggregation (Bronick and Lal, 2005; Celik et al., 2010). Together, these factors, supported by soil organic matter and optimal soil temperature, create the conditions for plants to grow strong and resilient.

The various industrial residual treatments applied in this study had notable effects on these factors, which in turn either positively or negatively affected the growth and survival of experimental species: *Pinus banksiana*, *Betula alleghaniensis*, and *Quercus rubra*. Similarly to plant diversity, the outcomes were influenced by each treatment's impact on soil physical and chemical properties such as pH, moisture retention, and surface temperature, as well as by species-specific traits, including drought tolerance, water-use strategies, and resilience to environmental stresses like frost heave and herbivory.

Treatments generally influenced the causes of seedling mortality, though it did not significantly affect overall survival rates. For instance, deaths caused by frost heave were significantly reduced in ATB plots, where such events were rarely observed. We attribute this reduction to the protective weave formed by carpet-forming mosses, which likely contributed to stabilizing the soil (Groeneveld et al., 2007). In all treatments except ATB, needle ice was frequently observed during sampling sessions, along with instances of seedling expulsions. The ability of mosses to bind the soil appears to prevent both needle ice formation and frost heave from disrupting the soil and uprooting planted seedlings. Recent studies examining this phenomenon have arrived at similar conclusions, highlighting the critical role of mosses in mitigating these soil disturbances (Groeneveld and Rochefort, 2005). In other plots, seedlings most commonly perished due to apparent drought-induced cavitation. Drought conditions can cause cavitation in tree xylem, where air bubbles form within water columns, blocking water transport and significantly reducing hydraulic conductivity. This process occurs when water stress lowers the water potential enough to induce embolism, disrupting the tree's hydraulic function and impairing its ability to transport water effectively throughout its tissues (Nardini et al., 2017). If drought is severe enough, the extensive cavitation and embolism can result in hydraulic failure, which is a significant factor contributing to tree mortality, particularly in newly planted or young trees that may lack fully developed adaptations to cope with such stress (Barigah et al., 2013).In terms of growth, long-term drought effects can lead to reduced growth due to sustained damage in the xylem, limiting water transport even after the drought ends. Though trees may recover under improved conditions, significant loss of hydraulic function can have lasting impacts on growth and overall plant vigor (Borghetti et al., 1998).

From the Spring to Fall sampling sessions, seedlings that initially appeared verdant were often found completely desiccated within months of planting. Consequently, death rates were predominantly front-loaded, with the majority of mortality occurring during the first growing season. Once seedlings survived this initial period, subsequent causes of death were less likely to be linked to drought. This pattern was particularly evident in *Betula alleghaniensis* seedlings, where mortality rates were extremely elevated (~80%) in nearly all treatments. The only consistently positive factor was the presence of some form of canopy. When *Betula alleghaniensis* seedlings were planted in open areas, they almost universally died. In contrast, those planted within a thicket of low sweet blueberry (*Vaccinium* angustifolium) or under the shade of a *Betula papyrifera* sapling frequently survived. Binomial testing comparing survival in shaded versus unshaded environments revealed significantly higher survival rates in shaded conditions, although sample sizes were small. This result aligns with the well-documented relationship between sunlight exposure (or temperature) and moisture loss, which can eventually lead to cavitation and death (Beaudet and Messier, 1998; Gasser et al., 2010; Brown et al., 2014). Our RDA results highlight this strong inverse relationship as well, which was characteristic of PMS and BBFA amended soils. In these treatments, survival rates also correlated with cooler temperature and higher moisture. Furthermore, improvements in soil pH contributed to a more favourable environment for seedling development, especially in the context of disturbed soils where these parameters are typically limiting (e.g., compared to C or Ps-S). Indeed, the individuals planted in these treatments were consistently expressing symptoms related to soil acidity. Specifically, we had already observed nutrient imbalances, particularly in *Pinus banksiana* and *Quercus rubra* in the form of severe needle and leaf discolouration. Here, these species were consistently yellowing (N deficiency), beginning to purple (likely P deficiency), or scorching (likely K deficiency, especially seen in *Quercus rubra* seedlings) (Hermans et al., 2006). These stressors undoubtedly would impede reforestation efforts if any treatments without adequate buffering capacity were applied to these soils.

Another significant cause of death was animal browsing, primarily driven by snowshoe hare decapitation and jagged tearing of stem and leaf tissue likely caused by ungulates, with moose being the probable culprit given nearby scat (Wirsing and Murray 2002). Browsing pressure was most severe in ATB and Ps-K plots, which likely explains why the survival rates in ATB plots were similar to those in other treatments. The most verdant individuals, often found in ATB plots, appeared to be targeted more frequently. This raises the question of whether browsing animals, such as hares and moose, are capable of showing a preference for healthier-looking seedlings. Previous studies suggest that these animals may browse vigorously on newly planted seedlings in such environments, where other forms of vegetation on the slopes may be less palatable or desirable. This very phenomenon was observed by Bergeron and Tardif in 1988, where snowshoe hares were repeatedly observed to target newly planted seedlings during reforestation campaigns. In these disturbed settings, "fresh" seedlings may offer greater nutritional value compared to surrounding vegetation, which could contain elevated metal levels or consist of undesirable heaths (Turner and Dickinson, 1993). Browsing animals appear to be able to detect chemical composition, including elevated metal content, which influences browsing behaviour (Hartley et al., 1995; Mateos-Naranjo et al., 2013).

ATB treatment itself likely did not directly spur increased browsing; rather, the proportion of live individuals remained elevated for a longer period, making them more accessible to browsers. However, there may be a slight preference at play, as browsing rates were significantly higher in ATB-treated seedlings compared to other treatments ($p<0.0001$). Survival rates following browsing also varied significantly by species. *Betula alleghaniensis* and *Pinus banksiana* rarely survived browsing events, while *Quercus rubra* demonstrated a much higher survival rate. This species-specific browsing tolerance further highlights the differential impact of animal browsing on seedling survival across treatments.

The influence of species traits, in many cases, may be more impactful than treatment effects. We selected these species—representing both softwoods and hardwoods—precisely because of their differing traits related to stress tolerance, drought resistance, and successional status (ranging from early to late), to capture a gradient of responses to treatment. For instance, we anticipated that *Pinus banksiana*, a hardy, stress-tolerant conifer, would thrive under limed conditions. *Pinus banksiana* exhibits remarkable metabolic control, regulating its sunken stomata to maintain osmotic balance and optimize water use (Rajasekaran and Blake, 1999). Additionally, its structural adaptations, such as narrow tracheids in the xylem, enable this species to resist cavitation during drought, which allows it to persist even in open, exposed conditions regardless of treatment (Blake and Li, 2003). *Pinus banksiana*'s efficient nutrient uptake system, bolstered by fine roots and symbiotic mycorrhizal fungi, further allows it to access nutrients in infertile soils (Boyle and Hellenbrand, 1991). These physiological advantages, combined with its preference for low-competition environments, suggest the inherent resilience of this species may dilute treatment effects.

We expected *Quercus rubra* to perform similarly well, albeit for different reasons. *Quercus rubra* is both resistant to cavitation, with its thick, woody tissues and sparse stomata, and is a risk-taking species, continuing to metabolize even at the risk of drought-induced mortality (Wang et al., 2023). This strategy allows *Quercus rubra* to expand its root system, potentially tapping into deeper moisture reserves. Moreover, this species' capacity to retain nutrients through its thick, durable leaves and its extensive, plastic root system allows it to rapidly respond to changing environmental conditions (Ashton and Berlyn, 1994). This root plasticity enables the species to adjust its growth strategy in response to drought or nutrient availability, making it adaptable to varying soil conditions (Suseela et al., 2020).

In contrast, *Betula alleghaniensis* is less well-adapted to drought or cavitation resistance. Preferring moist, well-drained environments, this species is more vulnerable to drought stress compared to *Pinus banksiana* and *Quercus rubra*. Its larger xylem vessels make it more prone to cavitation under water stress, and its shallow root system, particularly in younger trees, increases its dependency on consistent moisture availability (Zhu et al., 2000). These traits make *Betula alleghaniensis* less suited to open environments and explain its preference for semi-shaded conditions, which has implications for future planting strategies – this species should not be planted in open areas (Lodding et al., 2000). As a species with moderate nutrient requirements and relatively thin bark and leaves, *Betula alleghaniensis* relies heavily on mycorrhizal associations for nutrient acquisition, which may be less effective in disturbed soils where fungal communities are degraded (Massicotte et al., 1990). Consequently, we expected this species to exhibit the most pronounced treatment responses, especially given its vulnerability to adverse soil conditions. Such traits and strategies may elucidate why while desiccation was less common in ATB-treated plots, it remained prevalent among *Betula alleghaniensis* seedlings. We can attribute this reduction in desiccation to both the beneficial effects of carpet-forming mosses and the rapid establishment of *Betula papyrifera* canopies in these plots, while the species itself is generally unsuited to thrive in such conditions regardless of these benefits (Busby et al., 1978; Parker et al., 1997).

The response to browsing further underscores the importance of species traits. Both *Betula alleghaniensis* and *Pinus banksiana* are particularly vulnerable to browsing, with the latter relying heavily on its apical shoot for growth, making it less resilient to damage (Holopainen, 1990; Cecich, 1979). While *Betula alleghaniensis* is known to resprout following browsing, this was not commonly observed in our trial, likely due to insufficient moisture or nutrients needed for recovery – which was observed by Suffice et al. (2015), as well. *Quercus rubra*, on the other hand, demonstrated a remarkable ability to survive browsing. Nearly all Quercus rubra seedlings coppiced after browsing events, redirecting resources to basal buds or dormant buds along the stem to produce vigorous new shoots – though repeated damaged may hinder long-term outcomes (Stange and Shea, 1998; Miller et al., 2017). This species' thick, resource-rich leaves and stems provide a buffer against damage, allowing it to recover rapidly and continue growing even after significant physical trauma (Woolery and Jacobs, 2011). This capacity for resource redistribution makes Quercus rubra highly resilient to both environmental stress and browsing, further supporting its suitability in challenging environments.

Site effects were also evident, primarily due to topographical challenges, as well as the physical structure and limited availability of soil. The CON site was especially rugged and hilly, with exposed bedrock outcrops as common as the thin mineral soil remnants. This type of landscape is typical of the larger "upland" region, which presents significant challenges for reforestation efforts. In the CON plots, soils were often so shallow that the depth of the Jiffy pot used during planting was equal to the actual soil depth. It was frequently difficult to find 15 samples with soil depths of 10 cm or more, which could significantly impede root expansion and limit the potential future growth of trees. Properly planting seedlings at the CON site was therefore particularly difficult; when not contending with soils only centimeters thick, we were often forced to plant between boulders or even sideways into the limited soil, further complicating the process and potentially artificially lowering survival rates from the onset of the experiment. This raises concerns about the long-term viability of planting trees in such shallow soils. A more prudent approach might be to allow these soils to undergo earlier stages of succession—such as moss- and herb-dominated communities, as observed in ATB plots—for several decades to allow soil buildup before introducing trees and shrubs. The natural litter production from these communities could contribute to building up the soil profile over time. However, it is also important to note that certain tree and shrub species can thrive in shallow soils, particularly in cliffside environments or similar landscapes. Species such as *Thuja occidentalis*, *Pinus banksiana*, and pioneering hardwoods like *Betula papyrifera*, which are abundant in this region, have traits specifically adapted for growth in such conditions and offer critical carbon inputs to soil (Booth and Larson, 2000). Furthermore, these trees develop extensive shallow and fibrous root systems that can slowly break apart bedrock, potentially accessing new reserves of moisture and nutrients (Matthes-Sears and Larson, 1995). Yet, this process is energy intensive, and the individuals in this study may not possess sufficient energy reserves to fully capitalize on these adaptations given the difficult conditions. In contrast to the CON site, the FB site exhibited far greater soil depth, to the extent that total soil depth could not be determined even using a 2-metre sampling probe. Erosion was not consistently observed at FB, further highlighting the stability of the site's soil profile. While moisture levels at a depth of 10 cm were similar to those recorded at CON, surface moisture rates were somewhat higher, particularly during the summer months. This increased surface moisture, along with the deeper soil profile, suggests that the FB site may support much greater future tree growth, particularly for species that access different depths of the soil profile for water and nutrients. The topography at FB was also much milder, consistent with its description as an outwash plain, making it a more favorable environment for planting. Unlike the challenging conditions at CON, planting at FB was notably easier, as the tilly soil was far from any bedrock, offering an ideal substrate for tree and shrub establishment.

Planted tree seedling growth followed similar patterns to those seen in recolonization and survival rates. Here, ATB best improved growth rates across all species. Other treatments, such as Ps-K, provided more mild benefits, though these were variable. However, we must contextualize these results with both beneficial effects of these treatments on the physical and chemical properties of the soils, and the specific traits of each species. Our RDA results again highlight the benefits of cool, moist, and nutrient-rich soils, toward growth and chlorophyll content, as expected. In the context of soil remediation in Sudbury, the prevailing approach historically emphasized pH adjustment as the most critical requirement for plant establishment in disturbed soils. Winterhalder (1996) highlights the application of ground dolomitic limestone as the "trigger factors". Here, pH adjustments are believed to create positive feedback loops, where grasses, specifically *Agrostis scabra* and *Deschampsia caespitosa* rapidly colonize the plot, which further promotes recolonization. While the importance of other factors, such as nutrient availability, moisture retention, and soil structure, was recognized, the review appears to surmise that these elements did not necessarily demand active intervention in the event of ongoing regreening and recolonization. The prevailing thought was that pH correction, followed by NPK application (given severe phosphorus limitations) would suffice to facilitate plant growth. Indeed, the critical role of pH is underscored by the findings from the LF treatments, where pH was adjusted, but other soil attributes remained largely unaltered. Under these conditions, improvements in growth were minimal, often only marginally better than in untreated controls. However, there are plethora of studies conducted in environments similar and nearby to those at the CON and FB sites indicate that LF treatments do indeed promote improved growth of planted trees, particularly of the genus Pinus, as well as highlight limited evidence of grass dominated colonization – albeit over decadal timescales. This short-term trial does not directly discount the effectiveness of dolomitic limestone and fertilizer as tools to treat soil acidification and low nutrient content, but perhaps highlights the critical synergistic effects of nurse While there have no direct investigations of recolonization rates in these upland environments, indirect studies focusing on carbon storage have survey these zones and found that despite gains in tree growth, recolonization rates remain low, and the soil typically shows little change in terms of carbon content. Instead, what emerges are dense accumulations of seemingly recalcitrant litter, a closed canopy, and limited understory vegetation (Levasseur et al. 2023; Preston et al. 2022; Rumney et al. 2021). While this may be more a reflection of planting strategies than a limitation of the LF treatments themselves, the combination of LF and conventional planting practices does not appear to facilitate the expected sequence of ecological succession in the regions most disturbed zones.

If ATB-treated plots, which exhibit elevated diversity metrics, were to follow the current planting approach, a similar outcome could be anticipated: the canopy would eventually close, and it is uncertain whether the existing understory species would transition to more shade-tolerant communities. Given that several thousand hectares surrounding these sites are similarly disturbed and host comparable species assemblages, a shift in understory composition seems unlikely. Winterhalder (1996) speculated that seed availability to be a potentially limiting factor to recolonization as a whole and cites Archibold (1978) who found a lack of seed rain to be a limiting factor in a similarly acid damaged region in British Columbia, Canada. This raises a broader question: should we continue planting trees in these settings? Perhaps a more effective strategy would involve planting at lower densities or adopting an "island" distribution model to ensure the availability of seed sources once the stands mature, while surrounding colonizing zones are amended with ATB to encourage diverse open habitats. Again, Winterhalder (1996) describes this mosaic approach as well, describing vegetation patterning potentially being influenced by a gradient of pH (in order to retain these novel and genetically diverse grassy communities), microtopography, and canopy cover. However, we are unaware of any recent experiments explicitly studying this (though historically by Amiro and Courtin in 1981, though this concept has been studied globally (e.g., Wimberly, 2005; Corry et al., 2008). Regardless of the approach, the study underscores the significant benefits of ATB treatments, not only in enhancing planted tree growth and survival but also in fostering native species recruitment and overall plant diversity.

This study also reveals that other soil factors may have been historically, and even within our experimental design, undervalued in the remediation process. For instance, in treatments where pH was adjusted and nutrients were applied in organic forms, which allow for slow nutrient release and reduced risk of nutrient loss, but the physical soil conditions were compromised—as evidenced by increased soil temperatures in the PMS and BBFA treatments—plants continued to struggle despite the pH correction. Conversely, when both the chemical conditions (pH and slow-release nutrient availability) were optimized, and the physical properties of the soil (such as temperature and moisture retention) were not negatively affected, as seen in the application of ATB, the barriers to ecological succession were significantly reduced. Under such balanced conditions, there were remarkable increases in species richness and diversity, along with notable improvements in relative growth rates, even within the short duration of the study. This underscores the necessity of a holistic approach to soil remediation that goes beyond pH adjustment, addressing chemical, biological, and physical soil properties to fully support plant establishment and growth.

The findings of this study provide valuable insights into the potential of ATB in supporting recolonization and reforestation efforts. However, several areas require further exploration to optimize its use in large-scale reclamation projects. Manual application of large volumes of these materials presents significant logistical challenges, particularly in remote or difficult-to-access areas. Treatments such as ATB-1 and ATB-2, which require 1.92 and 3.85 times the tonnage of traditional LF, and Ps-K, which requires 7.08 times the volume of LF, would be labor-intensive (as experienced in this study) and costly to apply manually. Aerial application offers a scalable solution to these challenges, enabling the efficient distribution of high-volume treatments across large tracts of degraded land. Although the higher tonnage of these experimental treatments compared to LF presents some logistical hurdles, aerial delivery can significantly reduce labor demands, making it a practical alternative for large-scale reforestation. Additionally, such treatments allow for a one-time application that combines both pH amendment and nutrient delivery, whereas LF requires separate applications months apart, increasing site visits and labor costs.

Future research should focus on large-scale trials to explore the feasibility and effectiveness of aerial application for ATB treatments. These studies should evaluate the capacity of aerial systems to distribute higher volumes of material evenly and assess the potential environmental risks, such as leaching or contamination. In fact, aerial delivery is already the dominant application method of LF in the Sudbury Regreening Program – lending credence to its feasibility (City of Greater Sudbury, 2024). The long-term effects of aerially applied IR on soil health, plant survival, and ecosystem recovery should also be a key focus of future studies. While this study demonstrated short-term improvements in soil properties and seedling survival, long-term monitoring is essential to assess the sustainability of these benefits. Future research should investigate how ATB treatments affect soil nutrient cycling over extended periods, particularly in relation to the persistence of pH improvements, organic matter accumulation, and plant community dynamics. Understanding how these factors change over time will be crucial for evaluating the long-term success of ATB in promoting ecological restoration. Given the industrial origin of residuals like ATB and Ps-K, potential contamination risks, particularly with heavy metals, need to be closely monitored. Future studies should focus on assessing the leaching potential of these treatments under varying environmental conditions, especially in areas with sensitive groundwater resources. Combining IR with other soil amendments, such as biochar or organic compost, may enhance soil structure, moisture retention, and nutrient availability. Future research could investigate the potential synergistic effects of such combinations, optimizing soil fertility and plant growth in more diverse reforestation contexts.

Conclusion

The findings of this study emphasize the critical role of holistic soil remediation strategies in fostering ecological recovery in the acid- and metal-impacted soils of Sudbury's upland and sloped regions. While historical reclamation efforts focused primarily on adjusting soil pH and introducing hardy conifer species, the results reveal that addressing pH alone, as with LF treatments, does not sufficiently promote natural successional processes or support short-term vegetation diversity. This study demonstrates that the application of industrial residuals, particularly ATB, can significantly improve soil conditions by enhancing pH, nutrient availability, and moisture retention while also moderating temperature extremes. The ATB-treated plots supported diverse and dynamic plant communities, including native mosses, grasses, and hardwood saplings, indicating that when both chemical (pH and slow-release nutrients) and physical (moisture and temperature regulation) soil factors are managed effectively, barriers to ecological succession can be lifted. In contrast, treatments such as pulp mill sludge and biomass boiler fly ash failed to support comparable levels of recolonization due to factors like elevated soil temperatures and poor moisture retention.

The results underscore the need for reclamation strategies that extend beyond pH correction to include the physical and biological properties of soil. By creating favourable microenvironments for native species establishment, industrial residuals like ATB can promote resilient, self-sustaining ecosystems. This research highlights the significant potential of industrial residuals to drive recolonization, restore biodiversity, and enhance long-term ecosystem functionality in severely disturbed landscapes. Future work should focus on optimizing amendment combinations and application methods to maximize ecological outcomes across diverse reclamation sites.

Chapter 6

Thesis Summary and Conclusions

Purpose and Contributions

The overarching objective of this doctoral thesis was to explore and advance our understanding of recolonization processes in severely disturbed landscapes, with a particular focus on soil organic matter (SOM) dynamics, plant functional traits, and the use of industrial residuals in reclamation. Situated in the distinct ecological context of Northeastern Ontario, this thesis addresses reclamation challenges associated with two primary types of environmental disturbance: abandoned borrow pits along the Highway17 corridor and metal-affected boreal forest ecosystems in Greater Sudbury. Both areas are characterized by depleted SOM, metal contamination, and disrupted nutrient cycling, conditions that challenge traditional reclamation methods.

This research contributes significant insights into the efficacy of reclamation approaches that incorporate industrial residuals—such as pulp mill sludge, biomass boiler fly ash, and lime-stabilized biosolids—to enhance soil fertility and support natural revegetation. By investigating the distinct roles that different soil amendments play in restoring key soil properties, the thesis provides evidence-based strategies for mitigating the impacts of mining and extraction activities on local ecosystems. These findings underscore the potential for residuals to increase soil pH, improve nutrient retention, and support the establishment of native and functionally diverse plant communities, ultimately facilitating ecosystem resilience and stability.

Moreover, this research highlights the importance of functional traits in the success of recolonization efforts, offering insights into which plant characteristics—such as drought tolerance, nitrogen fixation, and seed persistence—are best suited to foster recovery in nutrient-poor and highly disturbed environments. By connecting species' functional traits to their ecological roles in reclamation settings, this work supports a more nuanced approach to species selection in reclamation practices, promoting both biodiversity and ecosystem functionality.

The contributions of this thesis are twofold: practically, it provides actionable guidelines for enhancing reclamation success in highly disturbed landscapes; conceptually, it contributes to a deeper understanding of the ecological principles underlying recovery processes in Northern climates. These insights not only inform site-specific reclamation practices in Northeastern Ontario but also serve as a framework for broader applications in reclamation science, where similar ecological constraints are present.

This thesis provides an in-depth examination of the potential for recolonization and reclamation in severely disturbed landscapes in Northeastern Ontario, specifically in abandoned borrow pits and metal-affected boreal forest soils. By focusing on the roles of industrial residuals, plant functional traits, and site-specific ecological factors, each chapter contributes essential insights into effective and sustainable reclamation strategies.

Key Findings and Insights

Chapter 3 investigates the recolonization trends across distinct subzones within abandoned borrow pits, including True Remnant Communities (TRC), Recent Remnant Communities (RRC), Open Communities (OC), and Interface Communities (IC). These subzones house unique plant communities due to differences in soil properties, disturbance levels, and proximity to undisturbed vegetation, which create specific hierarchical filters that influence species composition. For example, the TRC areas, undisturbed islands within the pit, retain the original forest composition, providing stability and ecological continuity, while OC zones, frequently disturbed by human activity, are dominated by stress-tolerant and often exotic species. IC zones emerge as the most diverse, influenced by adjacent undisturbed forests as well as TRC, OC, and RRC zones, which enables them to support a complex community structure with species adapted to both disturbed and stable conditions. Perhaps most importantly, we highlight the primary limiting factor to passive recolonization in these sites: physical human disturbance - particularly from all terrain vehicles and small-scale extraction.

The study also identifies distinct functional traits within these communities. In IC zones, the influence of surrounding vegetation leads to a diversity of traits, including shade tolerance and nutrient-use efficiency, which could inform practitioners on the benefits of creating buffered, structurally complex areas to foster diverse species. RRC zones, which have recently undergone disturbance, favor early successional species with traits like drought tolerance and rapid growth, while OC zones support hardier, stress-tolerant species with traits geared toward survival under frequent disturbance. Understanding these trait distributions enables targeted rehabilitation strategies, suggesting, for example, that practitioners could leverage species with high drought tolerance and fast growth for initial stabilization in frequently disturbed zones, while focusing on shade-tolerant, structurally beneficial plants in areas adjacent to undisturbed stands.

Chapter 4 assesses the effects of various industrial residuals—pulp mill sludge (PMS), biomass boiler fly ash (BBFA), and lime-stabilized municipal biosolids (LSMB)—on tree seedling growth and soil improvement specifically within nutrient-poor borrow pit soils. Results demonstrate that PMS, with its neutral pH, effectively enhances SOM content and seedling performance, while also improving moisture retention, thus supporting early-stage plant growth in degraded soils. This pH neutrality is particularly notable in contrast with LSMB and BBFA, both of which significantly increased soil pH levels. The high pH induced by these residuals appears to disrupt stoichiometric balance, potentially hindering microbial communities and nutrient availability, indicating that while LSMB and BBFA can contribute to nutrient profiles, they may also lead to unintended ecological consequences without careful pH management. This chapter highlights that PMS is a more reliable amendment for such reclamation efforts, while LSMB and BBFA require adjustments to avoid creating overly alkaline conditions that could compromise soil microbial health and nutrient cycling.

Chapter 5 explores the use of industrial residuals in rehabilitating acid- and metal-stressed soils in Greater Sudbury, comparing the effectiveness of alkaline-treated biosolids (ATB) with PMS and BBFA. Results show that ATB application substantially improves soil conditions by moderating pH, enhancing moisture retention, and increasing nutrient availability, thus supporting the establishment of native species and fostering a more favorable microclimate. Moss species like Pohlia nutans and Polytrichum commune play a critical role in stabilizing the soil and enhancing moisture retention, creating conditions conducive to tree sapling growth and broader recolonization. In contrast, while PMS and BBFA also reduce soil acidity and alleviate metal stress, their application as a top-dressing significantly increases soil temperatures and decreases moisture retention due to higher albedo. This result is in sharp contrast to Chapter 3, where full incorporation of PMS and BBFA into the soil matrix was associated with more favorable outcomes for moisture retention and temperature stability. The findings underscore ATB's suitability as a primary treatment for severely disturbed soils, while highlighting the importance of application techniques, such as full incorporation versus top-dressing, in determining the microclimatic impact and overall effectiveness of each residual.

Implications for Reclamation Science

The findings of this research contribute valuable insights to the field of reclamation science, particularly in the context of Northern climates where harsh environmental conditions, nutrient-poor soils, and extended recovery times present unique challenges. By examining the role of industrial residuals and functional plant traits in aiding recolonization processes, this work highlights several key considerations for reclamation in cold, nutrient-limited environments, offering guidance that is applicable to similar disturbed sites globally.

Firstly, this research underscores the importance of site-specific amendments, particularly industrial residuals, in enhancing soil fertility and fostering ecosystem resilience. The effectiveness of PMS in maintaining a neutral pH, improving SOM content, and supporting moisture retention demonstrates that certain residuals can play an integral role in reclaiming nutrient-depleted soils, without the adverse pH effects seen with other amendments like LSMB and BBFA. In Northern climates where soils are often acidic and low in organic matter, such amendments provide critical support to initial vegetation establishment and soil stabilization. However, the variable impacts of LSMB and BBFA on soil pH and nutrient availability also reveal the potential risks of high-pH amendments in these contexts, pointing to the need for careful selection and calibration of residuals to avoid creating imbalances that could hinder microbial activity or nutrient uptake.

Furthermore, the identification of functional traits that support successful recolonization in disturbed Northern landscapes—such as drought tolerance, nitrogen fixation, and seed persistence—provides a practical framework for species selection in reclamation projects. Traits that align with specific environmental stressors allow practitioners to design plant communities that are resilient to the unique pressures of Northern climates, such as prolonged frost periods, short growing seasons, and low nutrient availability. By prioritizing species with traits suited to early successional stages in disturbed zones (e.g., rapid growth and drought tolerance in OC areas) and traits that promote ecological stability and structural complexity in less disturbed zones (e.g., shade tolerance and nutrient-use efficiency in IC zones), reclamation practitioners can more effectively guide ecosystem recovery toward self-sustaining, biodiverse communities.

Additionally, this thesis advances the understanding of microclimatic effects in reclamation, specifically how application methods (e.g., top-dressing vs. full incorporation) influence soil temperature and moisture retention. In Northern climates, where soil temperatures fluctuate significantly and frost cycles are frequent, managing these microclimatic variables is essential to maintaining favorable conditions for plant growth. The contrasting outcomes observed with PMS and BBFA when applied as topdressings versus fully incorporated highlight how such techniques can modify soil albedo and, consequently, temperature and moisture profiles. This insight into the importance of application technique offers practical guidance for reclamation projects in other cold and harsh climates, where managing soil surface conditions can directly impact early-stage plant survival and establishment.

In sum, this research not only contributes to the specific context of Northeastern Ontario but also provides a framework for other reclamation projects facing similar environmental challenges. By integrating an understanding of industrial residual efficacy, functional trait-based species selection, and microclimatic management, these findings offer a holistic approach to supporting long-term ecosystem stability and recovery in Northern disturbed landscapes. This approach emphasizes that tailored, site-specific interventions—particularly those that leverage locally adapted species and optimize soil amendments—are critical for achieving sustainable reclamation outcomes in challenging environments.

Future Works and Personal Endeavors

Building upon the findings and implications of this research, several directions for future work are essential to advancing reclamation science and addressing the unique challenges faced in disturbed Northern landscapes. These directions align closely with my career aspirations, as I seek to contribute meaningfully to sustainable land management, industrial collaboration, and ecological restoration across Canada.

Monitoring reclaimed sites over extended periods is crucial for understanding the durability and ecological stability of improvements in SOM, vegetation establishment, and biodiversity Mutitire et al., 2024). To this end, I am currently spearheading a federally and industrially funded study that seeks to incorporate the industrial residuals tested in Chapters 4 and 5 into degraded landscapes similar to those discussed in Chapter 3. This large-scale, site-specific trial will combine the application of industrial residuals with earthwork techniques, particularly mounding and trenching, alongside tree planting and herb and grass sowing. Over the next four years, we will monitor the vegetation response—including planted, sown, and passively colonizing species—to better understand the dynamic interactions among reclamation techniques. Additionally, this project includes a focus on the mobility of metals and pharmaceuticals and personal care products (PPCPs) within the reclaimed soils, especially critical in long-term applications where these substances might migrate into groundwater. To address these risks, we will install lysimeters across the study site to capture groundwater samples and assess the potential contamination profile of these materials over time. This initiative not only aligns with the sustainability goals of reclamation science but also provides essential data for understanding the long-term implications of using industrial residuals in sensitive environments.

Comparative studies in regions with similar disturbances—such as coarse-textured, infertile, and potentially acidified soils—will be vital for expanding the applicability of our findings. These studies could specifically target industrial aggregate mines or mine tailings, where similar soil challenges exist and where the buffering capacity of specific industrial residuals may offer remediation solutions. By exploring how our techniques perform in these additional contexts, we can assess whether site-specific modifications are necessary or whether our findings represent broader best practices. This direction aligns with the current study mentioned above, where we aim to track plant responses to industrial residuals in degraded environments, enabling us to establish whether these methods are adaptable across various disturbed sites in Canada.

The demonstrated effectiveness of industrial residuals in this research highlights the need to explore additional reclamation methods that could enhance site resilience. For example, microbial inoculations that promote plant-microbe interactions could bolster nutrient cycling, enhance plant stress tolerance, and accelerate SOM accumulation, especially in nutrient-poor soils (Zvoyuma et al., 2008). Additionally, bioengineered soil amendments that combine organic matter with beneficial additives, such as biochar or activated carbon, could help stabilize contaminants, increase water retention, and support long-term soil health. Integrating organic composting and decomposition techniques alongside industrial residuals could introduce a balanced nutrient profile, providing a steady, longer-term supply of SOM to complement the faster-acting benefits of residuals. These approaches collectively represent a promising avenue for increasing site-specific reclamation options, adapting to unique environmental pressures, and fostering more resilient plant communities.

My ultimate goal is to standardize the use of industrial residuals for reclamation in Canada. Currently, the variability in industrial residuals presents both an opportunity and a challenge. On the one hand, their diverse properties can be tailored to address specific environmental issues; on the other, the lack of consistent regulation and approval processes limits their potential applications. I envision collaborating with major producers of pulp mill sludge (PMS), along with provincial and federal agencies, to develop a regulatory framework that ensures residuals are shelf-stable, possess consistent properties, and are safe for a wide range of reclamation applications. This framework would facilitate the use of PMS and similar materials as SOM proxies in both residential, commercial, and large-scale industrial environments.

Following the completion of my PhD, I plan to pursue a position with the Canadian Forestry Service (CFS) in Sault Ste. Marie, ON, to strengthen relationships between industry, government, and academia in the region. Key partnerships could include the new municipal GoreTex facility that will convert municipal biosludge into compost for landfill covers, as well as the local steel mill that faces challenges regreening its slag heaps. With the CFS's background in experimental applications of BBFA, PMS, and LSMB, I aim to integrate my expertise into these ongoing projects, potentially collaborating with post secondary institutions in Northern Ontario to support local HQP training in reclamation practices. I am also considering the possibility of establishing a consulting firm to serve as an intermediary between these institutions, providing expertise that connects industrial, governmental, and academic resources to achieve sustainable reclamation solutions across Northern Ontario.