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Phosphogypsum Stack Reclamation Using Soil Amendments and Short-Rotational Woody Species

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Abstract: Phosphogypsum (PG) is a by-product of phosphorus fertilizer production that is stored in large piles (stacks). Typically, PG stack reclamation focuses on topsoil caps vegetated with grass which has limited economic return. Therefore, a study was conducted using the short-rotational tree species (*Picea glauca*, *Populus balsamifera*) to determine their potential in PG stack reclamation. Five soil amendments (compost, compost with mycorrhizal fungi, manure pellets, black earth, mycorrhizal fungi) with a control (no amendment on PG) were used in a field experiment to determine whether they would enhance the growth of the planted species. After two years, amendments had little effect on the height, diameter or biomass of either species. *P. balsamifera* on PG (control) was significantly healthier than in amended soils. The healthiest and most successful trees for both species were found in the control treatment. Organic amendments (compost, manure) had significantly higher nitrate and phosphorus than most of the other treatments. Black earth and mycorrhizal fungi did not affect any soil properties relative to the control. This study suggests short-rotational forestry plantations of *Populus balsamifera* appear to be meeting reclamation objectives for PG stacks, similar to traditional grass covers; however, the built soil profile could limit tree success in future.

Keywords: biomass; survival; reclamation; soil amendments; *Picea glauca*; *Populus balsamifera*

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1. Introduction

Phosphogypsum (hereafter PG) is a by-product from the production of phosphorus fertilizer via the wet process [1–4], where sulfuric acid and water are mixed with phosphate rock. PG is commonly pumped as a slurry from the production facility and placed in large holding ponds; over time it accumulates and ponds become large stacks [5]. For every ton of phosphate fertilizer produced, an average of 4–6 tons of PG is produced, with a global estimate of 280 million tons produced per year [1,2,6]. PG is mostly comprised of gypsum and phosphoric acid with low concentrations of fluoride, trace elements and naturally occurring radioactivity from radionuclides in the parent ore [1], posing a risk of contaminating the surrounding environment and ground water through wind and water erosion [4,7]. Therefore, PG stack reclamation focuses on reducing erosion to prevent impact on the surrounding environment. Vegetation and soil create a barrier to reduce water infiltration into the stack and mitigate release from the stack to the atmosphere or nearby water bodies [8,9]. Typically, PG stacks are covered with grass at the initial stage of reclamation [4,10,11]. There is growing scientific evidence that tree or short-rotation plantations can have a catalytic effect [12] on plant community development in severely degraded sites, where ecological barriers would otherwise impede recolonization by a native species [13–17]. Thus, there is potential for use of short-rotational woody species in PG stack reclamation for ecosystem recovery.

Short-rotational forestry systems utilize rapidly growing woody plant species to grow large quantities of biomass on marginal land [16,18–20]. Typically, *Populus* (poplar), *Eucalypts* spp. (eucalypts) and *Salix* (willow) species are used in these plantations since they grow fast and can produce a large amount of biomass in a short time (10 years or less), have effective nutrient uptake, have a clone-specific capacity for taking up heavy metals and can tolerate marginal growing conditions [19–21]. These fast-growing tree plantations could benefit the regeneration of native species that cannot grow well in open environments or compete with herbaceous ground cover [14]. Fast-growing tree plantations could facilitate better understory microclimatic conditions [22,23], reduce competitive herbaceous species [23,24], improve soil fertility through the decomposing of litter [25] and reduce erosion through extensive root systems [26–28]. A large amount of biomass grown from these plantations may be used as fossil fuel substitutes and as carbon credits from carbon sequestration [29]. Several studies suggest that short-rotational plantations with hybrid and/or balsam poplar appear capable of accelerating reclamation success by enhancing understory colonization, suppressing competition from light-demanding herbaceous species and for the phytoremediation of contaminated soils [16,18–20]. Langholtz et al. [20] reported that the reclamation of phosphate-mined lands with a short-rotational woody species can be profitable at real rates of 10%, assuming moderately high yields, moderate-to-high stumpage prices and low operational costs.

Environmental regulations in Alberta require all industries to reclaim disturbed sites to pre-disturbance equivalent land capability; PG stack reclamation should be conducted with a 1 m soil cap after decommissioning, since uncovered PG can impact surrounding areas with its chemical compounds [4,9,30,31]. Thus, reclamation often requires large volumes of topsoil to reach the end land-use objectives if there are no stored soils available on the disturbed sites; this can be very expensive [32]. Soil amendment can be an important alternative approach to a 1 m soil cap. During operation, industries produce waste materials that are high in organic matter and plant nutrients such as black earth, municipal waste compost and animal manure which can be used as amendments for PG stack reclamation [33–35]. However, it is unknown whether such amendments contribute to the reclamation of PG stacks.

Other soil-building or amending materials include mycorrhizal fungi which can form symbiotic associations with the roots of host plants to increase nutrient uptake efficiency, provide access to unavailable minerals and increase productivity and stress resistance [9,36,37]. Therefore, symbiotic associations in mine reclamation sites are important for vegetation development and habitat formation [32,37,38]. PG with calcium sulfate is comparable to osmotic stress and ion-specific toxicity of sulfate [39], which are challenging for plant growth [40]. Mycorrhizal fungi inoculation could reduce plant-inhibiting effects of gypsum and sulfate in soils and increases leaf water content [41]. However, the relationship between host plants and fungi is often species-specific, where some hosts can be colonized by different fungal species and some fungi can colonize multiple host species [42].

Studies on reclaiming PG stacks are mostly limited to grass [4,9,11] or herbaceous plant [10,43] species, with an emphasis on reducing PG exposure to the environment or effective capping depth. Understanding the environmental drivers of short-rotational woody vegetation establishments on PG stacks that are undergoing reclamation remains unknown, and to our knowledge, this was among the first initiatives to incorporate short-rotational woody species in PG stack reclamation to determine whether PG can support tree growth with or without soil amendments. Addressing this knowledge gap, we conducted an experiment to provide evidence-based management options for PG stack reclamation. The objective of this study was to determine the effects of five soil amendments on aboveground biomass, height, vigour, stump diameter, number of branches and survival of two tree species (*Picea glauca* Voss. (white spruce) and *Populus balsamifera* L. (balsam poplar)), and on-soil properties and competing vegetation.

2. Materials and Methods

2.1. Study Location

Nutrien Nitrogen Operations is located 20 km northeast of Edmonton Alberta on the south bank of the North Saskatchewan River (53.73′ N, 113.19′ W) (Figure 1). The mean annual precipitation is 459 mm, with 353 mm as rain and 104 mm as snow [44]. The mean annual temperature is 2.4 °C; with the highest mean temperature in July at 17.1 °C and lowest in December at −10.4 °C. The site is located in the Central Parkland Subregion where large aspen parkland forests and grassland areas are intermixed. Very little native vegetation remains due to extensive vegetation control and anthropogenic disturbances. Non-native species such as *Bromus inermis* L. (smooth brome) and *Elymus repens* (L.) Gould (quack grass) are dominant.

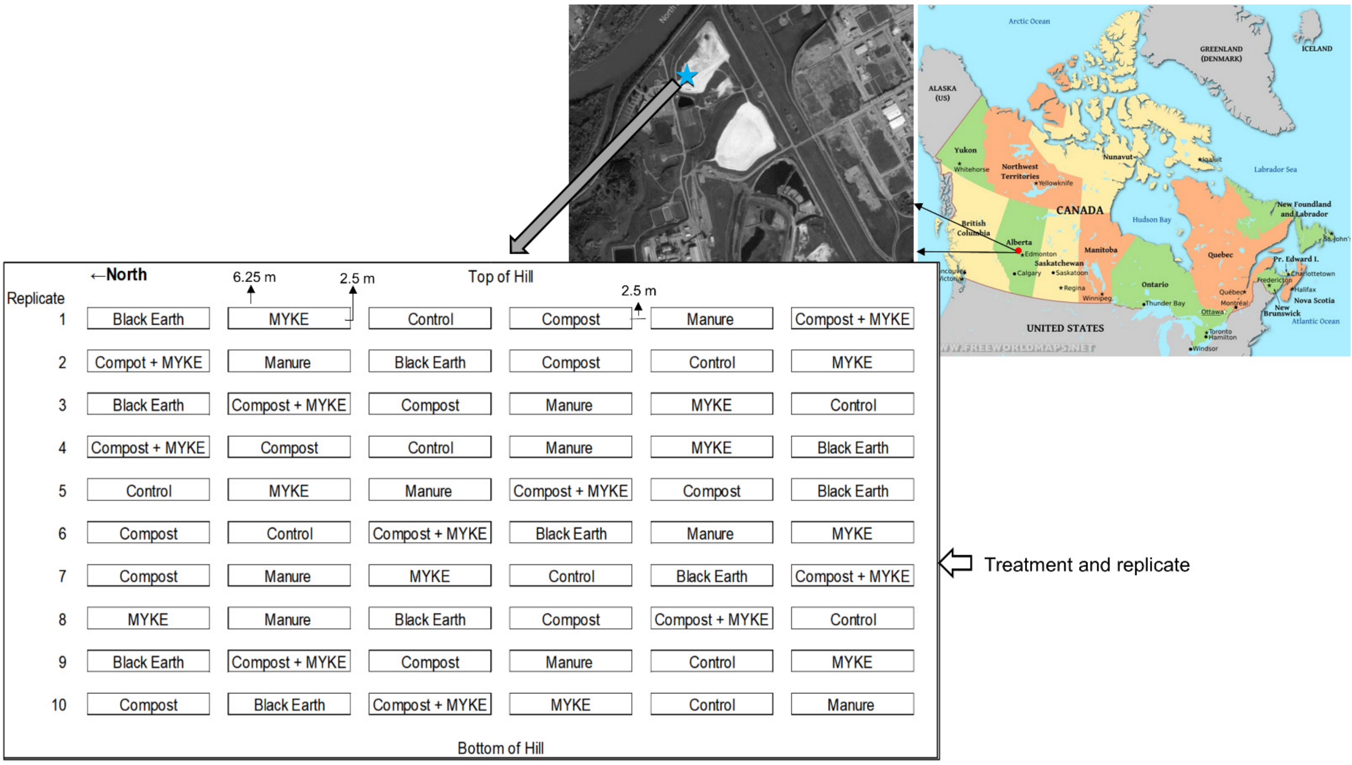

Figure 1. Location research sites with experimental design. Star indicates research site.

This experiment was conducted on a PG stack that was established in the 1970s and was recontoured in the fall of 2015 for this experiment. Approximately 20 cm of topsoil was placed on the entire stack and seeded in fall 2015 with a reclamation grass seed mix of 20% *Elymus trachycaulus* (Link) Gould ex Shinners, 20% *Pascopyrum smithii* (Rydb.) Á. Löve, 25% *Poa sandbergii* Vasey, 20% *Deschampsia cespitosa* (L.) *P. Beauv*. and 15% *Puccinellia distans* (Jacq.) Parl. to prevent soil erosion.

2.2. Experimental Design and Treatments

The experimental design was a randomized complete block with five amendment treatments (compost, compost with mycorrhizal fungi, manure pellets, black earth, mycorrhizal fungi) with a control (no amendment on PG) to determine survival and growth response of two tree species *Picea glauca* and *Populus balsamifera* (Figure 1). There were 10 replicates and each replicate was treated as a block. Each block consisted of six plots with 2.5 m × 6.25 m in size where amendment treatments were randomly assigned to plots and each plot contained 10 trees; five each of *P. balsamifera* and *P. glauca*. Trees were spaced 1.25 m apart in a grid with a total of 600 trees (6 amendments × 2 species × 5 trees × 10 replicates). A 2.5 m unplanted buffer was established between each plot.

Natural Resources Canada conducted research on several short-rotation woody species such as *Populus*, *Acacia*, *Pinus*, *Eucalyptus* and *Salix* as planting options. *P. balsamifera* provided the best option for fast growth and water utilization with the added benefit of obtaining crown closure within 3–5 years, reducing the requirement for long-term maintenance of the sites. Other short-rotation planting species were less suitable for the site in meeting the overall reclamation objectives of reducing long-term maintenance costs, improving ecosystem biodiversity and wildlife habitat, and enhancing long-term groundwater quality through the phytoremediation of excess nutrients and water in the rooting zone [45]. Therefore, *P. balsamifera* clones were selected for the site which were previously tested and proven to be frost-hardy and suitable for the Northern Alberta climate and able to withstand impacts associated with summer droughts and inconsistent winter conditions [46]. According to Rockwood et al. [21], effective phytoremediation of contaminated sites by short-rotational woody species depends on tree contaminant interactions and tree growth influenced by management and environmental factors. Therefore, locally adapted trees can be more successful in the reclamation of contaminated soils [21].

The five amendment treatments consisted of the following. Compost was procured from the City of Edmonton waste treatment facilities and applied at 20 tonne ha^{-1}. Manure was used as pellets produced by heating fresh manure above 315.6 °C to remove weed seeds, pathogens and unwanted chemical compounds; applied at 20 tonne ha^{-1}. Black earth is a mined product from naturally occurring oxidized coal that is rich in humified organic matter (80%) and humic and fulvic acids); coarse granule black earth was applied at 0.67 tonne ha^{-1}. MYKE® is a commercial-grade mycorrhizal fungal (hereafter MYKE) that can increase plant root development and efficient uptake of nutrients. It contains ectomycorrhizal fungi that were expected to colonize the exterior of *P. glauca* roots, and endomycorrhizal fungi which were expected to grow in the roots of *P. balsamifera*. It was applied at 125 mL plant^{-1}. In May 2016, amendments (compost, manure pellets, black earth) were hand spread evenly across the surface of each plot, then hand raked to spread to the full extent of the plot. After the amendments were spread in each replicate, they were incorporated into the top 10 to 15 cm of soil using a Power Dog 209 9 hp rear tine rototiller. This depth avoided incorporating the underlying PG. Buffers were rototilled in the same way as the plots. The mycorrhizal inoculant was added to individual trees during planting. Half of the MYKE was sprinkled on the root ball of *P. glauca* so that excess fell into the planting hole, and the other half was placed in layers with soil. For *P. balsamifera*, MYKE was placed in layers with soil during planting as cuttings did not have a root ball.

2.3. Soil Analyses

On June 2016, the soil was sampled in the center of each plot at a depth increment of 0–10 cm. Soil from three replicates of the same treatment was combined into a clean bucket and mixed into a single composite sample. This method was repeated 3 times for each treatment, creating 18 samples for analysis. Mycorrhizal fungi treatments were sampled the same way, except during mixing 250 mL of MYKE was added since the center of the plots did not receive inoculation. Samples were submitted to a commercial laboratory, and analyzed for total carbon and total nitrogen by Leco combustion [47], ammonium and available nitrate by extractable 2N KCl [48], available potassium and phosphorus by modified Kelowna [49], pH and electrical conductivity by saturated paste [50] methods.

2.4. Plant Stock and Management

Two-year-old *P. glauca* seedlings were collected from the Canadian Forest Service greenhouse in May 2016. *P. glauca* height was measured to document the beginning height and randomly placed on plots. *P. balsamifera* cuttings were taken from a nursery plantation at the University of Alberta Ellerslie Research Station. Long stems were harvested from a stool bed (nursery bed of woody plants propagated by layering), bagged and stored below −5 °C until taken from storage. Cuttings were 25 cm long, with approximately 1.0 cm diameter with 5–8 buds per cutting. Cuttings were bundled and soaked in water for approximately 12 h prior to planting. When planted, all cuttings appeared to be of the same health status with no obvious visible differences. Cuttings came in bundles of 25 and were randomly planted in the plots. *P. glauca* seedlings and *P. balsamifera* cuttings were planted on May 2016 within two days of the planting stocks being brought from the greenhouse or storage. *P. balsamifera* cuttings were placed so that at least one bud was above the surface and the buds were pointing upwards. *P. glauca* seedlings were planted so that the root ball was covered by 2.5 cm of soil. The grass mix was seeded for soil erosion control in the fall of 2015 prior to the experiment establishment. The entire experimental area was seeded equally to eliminate unequal treatment response. Mowing and weeding were conducted around individual trees; large weeds close to trees were hand-pulled throughout the experiment.

2.5. Vegetation Assessment

P. glauca and *P. balsamifera* vigor were assessed once a month during the growing season, using a 1–5 scale for an overall health score. The scale used 1 (very high vigor) = <5% of tree appears dead, 2 (high vigor) = 5 to 30% of tree appears dead, 3 (moderate vigor) = 30 to 60% of tree appears dead or conditions of 2 with significant wilting, 4 (low vigor) = 60 to 99% of tree appears dead, 5 (dead) = tree appears 100% dead. The percent of the tree deemed dead was determined from necrotic leaves or needles. Healthy leaves and needles were green with no chlorosis or wilting. Vigor was assessed on 10 June, 29 June, 20 July and 23 August in 2016 and on 23 May, 28 June, 10 August and 17 September in 2017. Midway through and the end of the growing season, the height of each tree was measured from the base of the trunk to the end of the tallest branch. Three height measurements were taken in August 2016 and in May and September 2017. In September 2017, final measurements of each tree were taken for the base stem diameter, branching pattern and number of living branches. The base stem diameter was measured using a tree caliper at the ground surface. In each treatment and species, 6 poor (vigor = 3 or 4) and 6 healthy (vigor = 1 or 2) individuals were selected for above-ground biomass assessment at the time of final measurements to represent all vigor groups. While excavating a tree, measuring rooting depth was not possible; however, any occurrence of roots penetrating the PG layer was recorded. Above-ground biomass was clipped at the soil surface, bagged and brought to the laboratory for estimation. Above-ground biomass was dried at 80 °C for 48 h or to constant weight.

The competition between planted tree seedlings and the competing vegetation (all vegetation except the planted trees) were estimated for each plot in June 2017, prior to plot management activities. A 0.1×1.0 m ($0.1\ m^2$) quadrat was placed in the center of each plot and percent canopy cover of grass, forb and bare ground were visually assessed. Any vegetation rooted within the quadrat had all above-ground biomass clipped at ground level and bagged. Biomass was oven dried at 80 °C for 24 h or to constant weight, then weighed.

2.6. Statistical Analyses

All statistical analyses were completed using R version 3.4.2 [51] with significance at $\alpha = 0.05$. Data collected at the end of the 2017 growing season were used for most of the analyses. Mixed models were used to detect the significance of treatment on tree height, stump diameter, number of branches, above-ground biomass and vigor. Replicates were treated as a random effect in the mixed models. A repeated measure mixed model was used to detect the significance of treatment on vigor over time. The Shaprio–Wilk test and residual plots observation were used to determine data normality. Soil data, grass biomass and cover in each treatment were assessed using analysis of variance (ANOVA) since all assumptions of normal distribution, the equal variance between treatments and independence of samples were met. All significant effects were followed by pairwise comparisons using the HSD Tukey method. Tree survival in each treatment was compared using a chi-squared test and pairwise z-tests. The p values were adjusted using the Holm method for pairwise comparisons. Correlation between tree survival and competing grass biomass were analyzed using Pearson correlation coefficient.

3. Results

3.1. Effect of Amendments on Planted Species

Vigor ($p = 0.015$), tree height ($p > 0.048$) and stump diameter ($p > 0.042$) change showed significant soil amendment effects for *P. balsamifera*, whereas no significant effects were detected for *P. glauca*. When the dead trees were removed from the data, there was no significant treatment effect found for *P. balsamifera*. The greatest vigor for *P. balsamifera* was found in the control (no amendment or grown on PG) (33% highly vigor to less vigor) and the lowest in compost + MYKE (10% highly vigor to less vigor) with a significant difference from the control (Figure 2). Although no significant difference was found, *P. glauca* had better vigor across the treatments than *P. balsamifera* with a 60–39% (highly vigor to less vigor); and the control was best (60%) followed by black earth (58%) (Figure 2). Soil amendment treatment had no significant effect on tree vigor over time for either species, and both species were healthiest in the control by the end of the study (Figure 2).

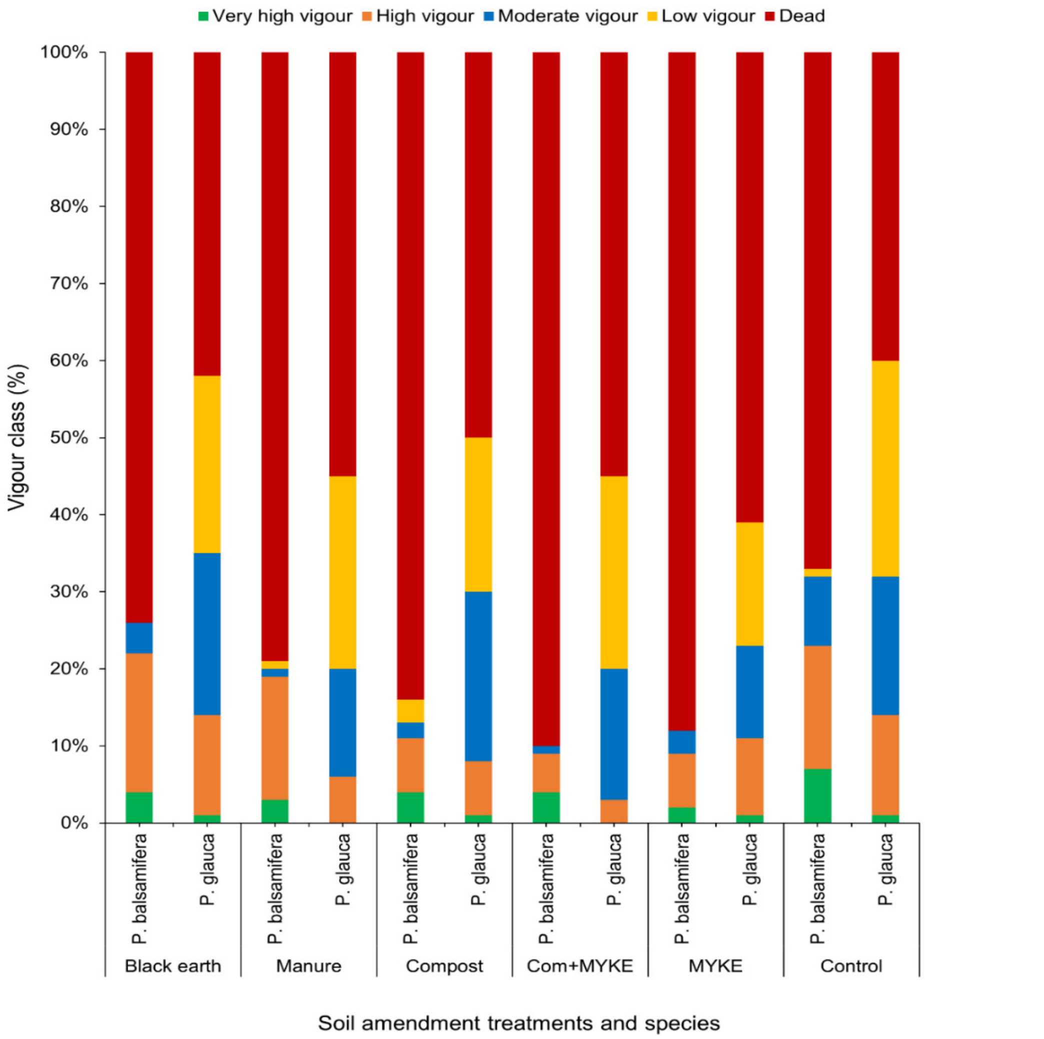

Figure 2. Vigor class percentages of planted *P. glauca* and *P. balsamifera* by soil amendment treatments.

Manure treatment had greater change (height 130 cm, diameter 25.1 mm) which was significantly greater from black earth (height 70.9 cm, diameter 12.2 mm) for *P. balsamifera*; whereas, height and diameter changes were very low for *P. glauca* across treatments, slightly higher in the control (height 2.7 cm, diameter 8.2 mm) (Figure 3).

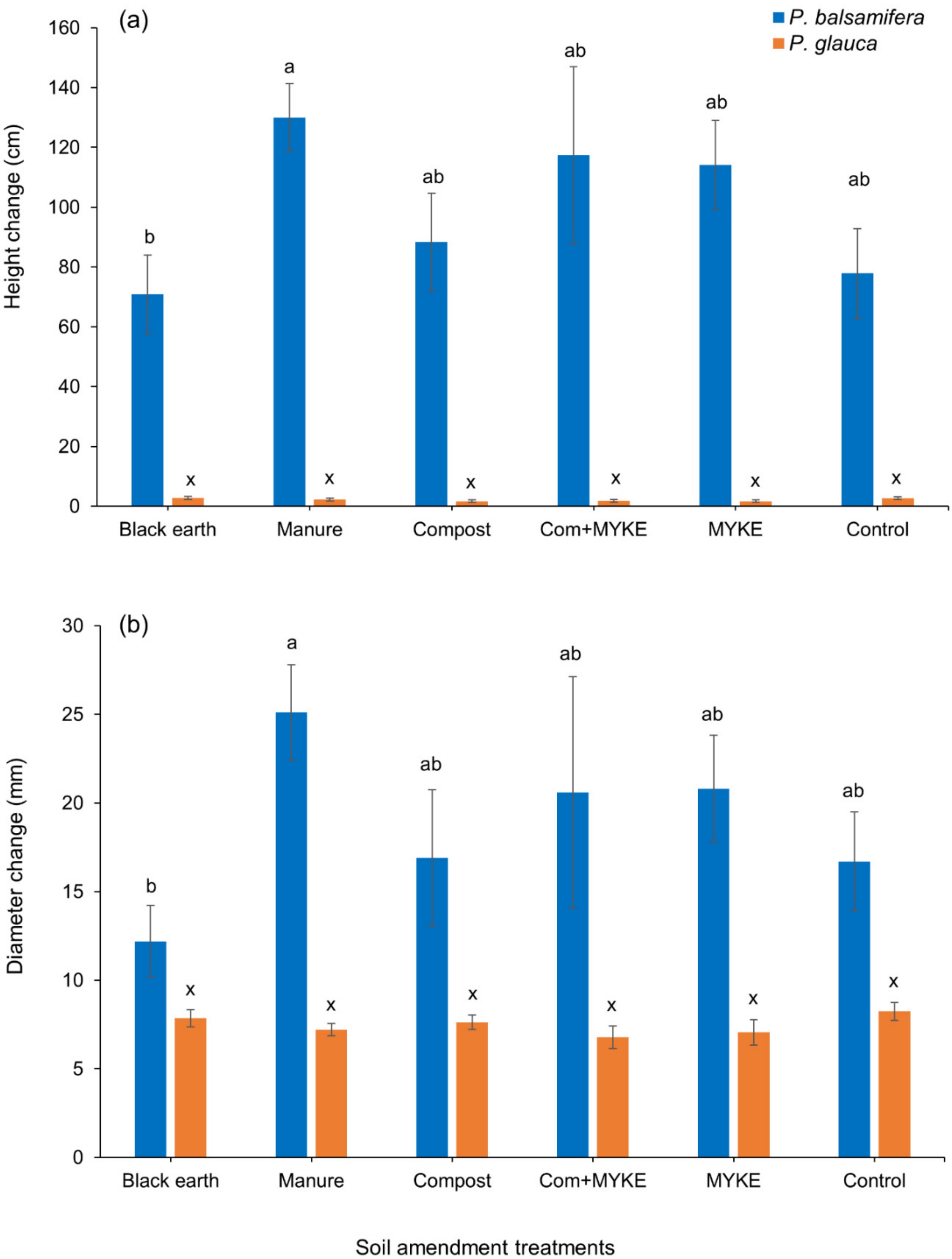

Figure 3. Mean (±SE) (**a**) height (**b**) stump diameter change of planted *P. glauca* and *P. balsamifera* by amendment treatments. Different letters indicate significant differences at $p = 0.05$ in the Tukey HSD post hoc comparisons.

Above-ground biomass was highly variable and greatest with compost + MYKE (Figure 4). For *P. glauca*, the control tended to have greater biomass than other treatments where new growth, old growth and total growth biomass were similar for all treatments except the control which had a slightly greater amount of biomass (Figure 4). The number of branches for *P. balsamifera* was highly variable and the greater number of branches was found in MYKE (8.8 per plant), followed by manure (7.4 per plant), compost (6.1 per plant), control (5.9 per plant), with the lowest in black earth (3.6 per plant).

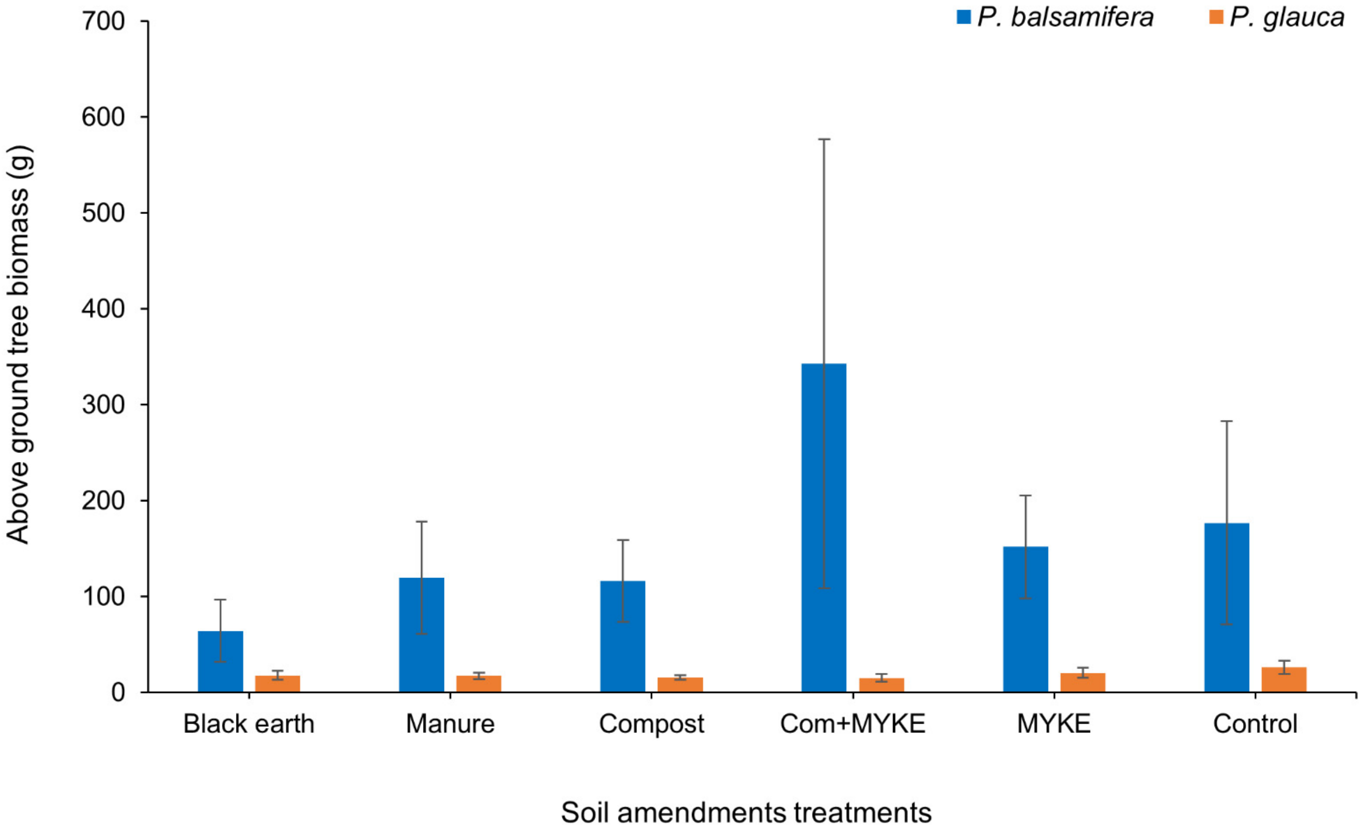

Figure 4. Mean (±SE) above-ground tree biomass of planted *P. glauca* and *P. balsamifera* by amendment treatments. BE = Black earth.

Soil amendment treatments had significant effects on survival for both species. The control treatment (*P. balsamifera* 36%, *P. glauca* 58%) had significantly greater survival than treatment with MYKE (*P. balsamifera* 12%, *P. glauca* 36%), manure (*P. balsamifera* 18%, *P. glauca* 38%), compost + MYKE (*P. balsamifera* 10%, *P. glauca* 38%) and compost for *P. balsamifera* (14%) (Figure 5). The lowest survival was in the compost + MYKE for both species. *P. glauca* had significantly higher survival than *P. balsamifera* in all treatments (Figure 5).

3.2. Effect of Competing Vegetation on Planted Species

Grass cover and biomass were not significantly affected by soil amendments. The control had the lowest grass cover (59%) and biomass (Figure 5). Although a visible relationship between tree survival and grass biomass was evident, grass biomass was not significantly correlated with tree survival. Nevertheless, *P. balsamifera* (R = −0.69) and *P. glauca* (R = −0.40) both had negative Pearson correlation coefficients, which were stronger in *P. balsamifera* than *P. glauca*. All amended treatments had increased grass yield and decreased tree survival (Figure 5). Grass biomass was similar in MYKE, black earth and control treatments, but grass cover was 10% lower in the control than in black earth (69%), compost (69%) and MYKE (60.5%).

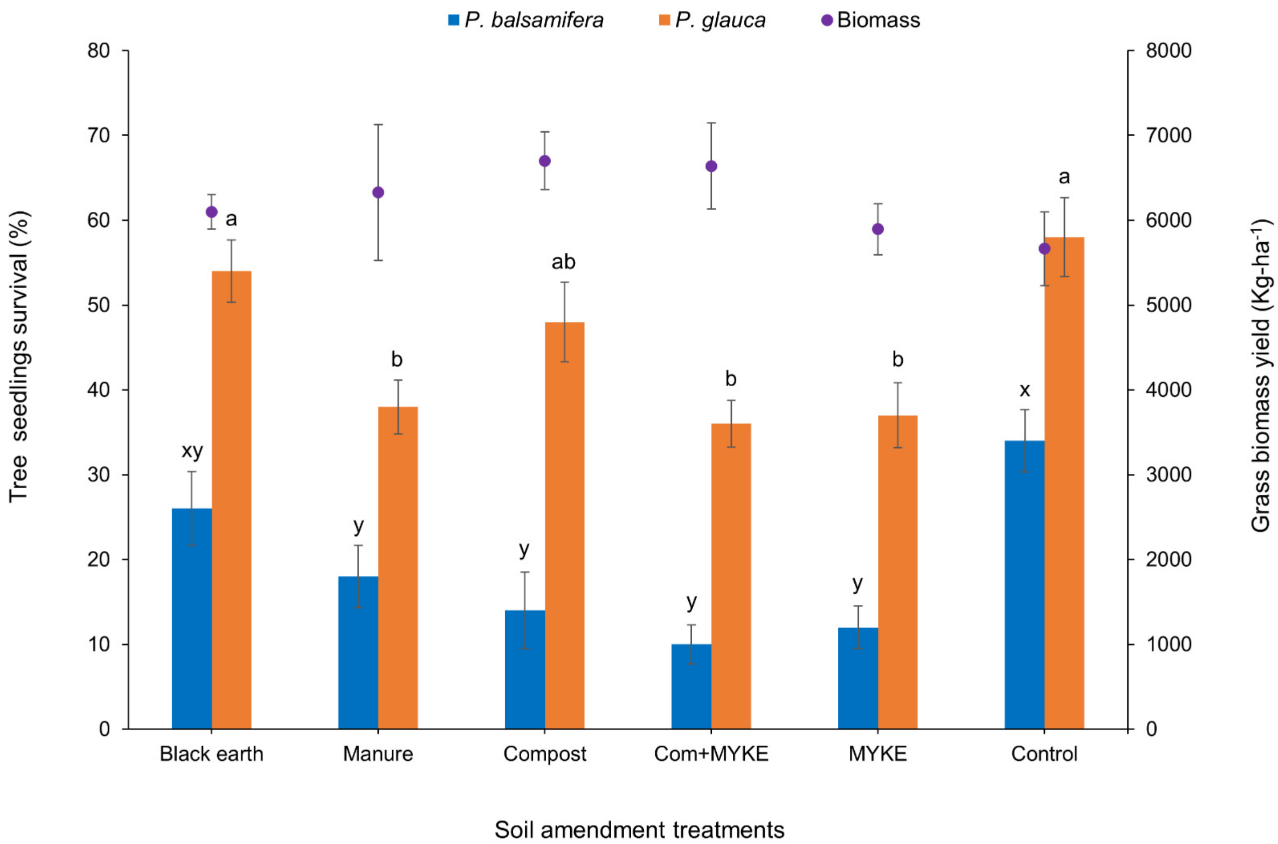

Figure 5. Mean (±) percent tree survival of *P. balsamifera* and *P. glauca* by amendment treatment including mean (±) grass yield shown with dots. Different letters indicate significant differences at $p = 0.05$ in pairwise Z-tests.

3.3. Effect of Amendments on Soil Parameters

Some soil properties were affected by amendments, with soil nutrients increased with organic amendments, compost and manure, and very little change to soil pH or electrical conductivity (Table 1). Black earth and MYKE had no effect on any soil properties relative to the control. Both compost and manure treatments had significantly higher nitrate and phosphorus than black earth, control and MYKE (Table 1). Potassium in the manure treatment was significantly greater than with any other amendment. Ammonium had high variability within replicates of compost and MYKE. The carbon nitrogen (C:N) ratio was higher in MYKE treatments and significantly lower in compost and compost + MYKE (Table 1). Organic matter, inorganic carbon, organic carbon, pH and electrical conductivity were not affected by soil amendments (Table 1).

Table 1. Mean (±SE) soil properties for each soil amendment treatment at the reclamation site of phosphogypsum stake.

Soil Parameter	Black Earth	Manure	Compost	Compost + MYKE	MYKE	Control
Nitrate (ugg^{-1})	3.3 (1.5) b	12 (4.4) ab	19.7 (5.0) a	18 (2.6) a	3.3 (0.6) b	3.3 (2.1) b
Phosphorus (ugg^{-1})	40.7 (6.0) bc	53.3 (6.1) ab	61.3 (1.2) a	64 (7.8) a	35.7 (2.5) c	36 (6.1) c
Potassium (ugg^{-1})	88.3 (6.5) b	216 (67.9) a	128.3 (5.5) b	128 (16.5) b	87 (3.0) b	85 (1.0) b
Ammonium (ugg^{-1})	1 (0.9)	0.4 (0.0)	1.2 (0.6)	2.9 (2.3)	0.8 (0.6)	0.7 (0.5)
C:N Ratio	12.3 (0.1) ab	12 (0.2) ab	11.7 (0.0) b	12 (0.1) ab	12.5 (0.1) a	12.3 (0.2) ab
Total nitrogen (%)	0.2 (0.0)	0.2 (0.0)	0.2 (0.0)	0.2 (0.0)	0.2 (0.0)	0.2 (0.0)
Organic matter (%)	4 (0.4)	4.1 (0.4)	4.4 (0.2)	4.4 (0.3)	4.1 (0.3)	4 (0.7)
Inorganic carbon (%)	0.1 (0.0)	0.1 (0.0)	0.1 (0.0)	1 (0.0)	0.1 (0.0)	0.1 (0.0)
Organic carbon (%)	2 (0.2)	2 (0.2)	2.2 (0.1)	2.2 (0.2)	2 (0.1)	2 (0.4)
Soil pH	7.4 (0.1)	7.5 (0.1)	7.4 (0.1)	7.4 (0.1)	7.4 (0.1)	7.5 (0.2)
Electrical conductivity (ds m^{-1})	2.4 (0.1)	2.2 (0.7)	2.3 (0.7)	2.4 (0.4)	2.3 (0.1)	1.8 (1.0)

Letters denote significant differences at $p = 0.05$.

4. Discussion

The study results suggest that PG stack reclamation can be possible using a short-rotation tree species, such as *P. balsamifera,* without using any soil amendments, as the control treatment tended to have the best overall tree growth and survival relative to the other treatments. However, differences in *P. balsamifera* height and diameter among soil treatments might be due to soil properties from amendments which may contribute to the growth and survival of the trees. Fortier et al. [52] found that different soil nutrients at different sites lead to significantly different growth of *Populus* spp. (hybrid poplar) clone over a six-year study. In another reclamation study, Miller and Naeth [53] reported that black earth amendment had a low effect on plant growth which might be due to its lesser impact on a substrate structure. Amendments likely had an unintentionally greater influence on competing vegetation than on the planted trees, as exemplified by equal or better overall tree growth in the control than in amendment treatments. Increased nutrients from the addition of amendments, particularly nutrient-rich compost and manure, may have given the surrounding vegetation a competitive advantage in amended plots, relative to the control. Over the two-year study, the grass likely reduced potential tree growth despite efforts to control vegetation. Competition not only reduced the nutrients available to trees, but also water, sunlight and root space at the early stage of tree establishment [32,54,55] and thus, the control had higher survival and good growth for planted tree species.

Removing understory (forb, graminoid) vegetation from around each tree (within a 15 cm radius) may not be the most effective way to reduce competition as it had a negative impact on tree survival. This method is likely effective with larger stock or in older plantations, but for small cuttings and seedlings used in this experiment, it is likely not close enough since the root systems are not well developed. A similar observation was reported by Henkel-Johnson et al. [56] in a hybrid poplar plantation in northern Alberta, where understory vegetation control near hybrid poplar did not affect the survival of trees, although herbicide treatments led to a significantly higher basal area than herbaceous vegetation control near the tree. All treatments had a substantially higher survival (92.3–100%) than our study after three growing seasons. Landhausser and Lieffers [57] found a significant decrease in height, stem caliper growth and stem and leaf dry weight of *Populus tremuloides* Michx. (aspen) when grown in competition with *Calamagrostis canadensis* Michx. (blue joint grass) in a greenhouse experiment. Dhar et al. [58] concluded that removing understory vegetation within a 1 m radius may not be enough to reduce neighborhood competition effects for *Pinus contorta* Dougl. Ex Loud. Var. *latifolia Engelm*. Similar results have been reported by other studies in Alberta, Canada [59,60]. Thus, removing competition between the adjacent understory and planted trees should be improved for the establishment and growth of trees in future PG reclamation studies.

Competition around each tree was likely a key driver of poor tree survival, other factors could contribute. Although mortality of both species was significant in winter 2016–2017 in all treatments, temperature and precipitation did not differ considerably relative to the climate normals. Mean total precipitation and mean air temperature from November to March in 2016–2017 on the PG stack were 81.2 mm and −7.1 °C, respectively, similar to the Canadian Climate Normals for 1981–2010 (98.1 mm and −7.4 °C) [44]. This could mean trees were stressed by the end of the 2016 growing season and did not have stored resources to tolerate winter. Poor tree growth could be related to a shallower soil profile than in a natural system. An average of 20 cm of topsoil was placed across the stack with relatively high sand content. High sand content in soil reduces water holding capacity and rapidly drains following precipitation events. These soil conditions could result in periods of water stress when precipitation is infrequent. Under the topsoil horizon, PG is compacted to prevent water infiltration into the stack. This boundary layer may have restricted tree rooting depth relative to natural soil. Removing vegetation or plant biomass from the surface exposes dark soil to direct sunlight, resulting in higher soil temperatures and greater evaporation of water from the soil [61]. The combination of these factors could have resulted in low water availability for trees. Organic amendments used in this study improve water-holding capacity but may not have been applied in high enough proportions or incorporated deep enough to affect water-holding capacity.

Despite being marketed to improve tree growth, MYKE did not improve tree parameters of either tree species relative to the control. Root assessments conducted in a companion study on the same site found 14 different fungal species colonizing *P. balsamifera* and 23 for *P. glauca*; MYKE significantly reduced colonization and intensity of mycorrhizal fungi [62]. According to Boldt-Burisch [62], healthy trees had significantly higher mycorrhizal colonization and intensity than unhealthy trees in the same treatment. A decrease in colonization and intensity of fungi from MYKE could be attributed to competition between native fungi and what was added from the inoculant. Many fungal pathogens including *Fusarium* sp., a known tree pathogen, were found on both species' roots in all treatments [62]. The percentage of pathogenic fungi was significantly correlated with tree health. This suggests that the poor health of trees could be the result of a fungal infection and reduced mycorrhizal abundance. It is possible the infection came from either the sample collection location or the soil cap at the study site. The source of infection could be confirmed by growing trees in both soils in a greenhouse setting with further studies.

The results from this study were interesting and should not discredit the possibility of using amendments for establishing short-rotational forestry plantations. While Zalesny et al. [63] reported that short-rotation *Populus* can be used for phytoremediation because of its rapid juvenile growth, ease of hybridization and vegetative propagation, others found this species can also regrow after multiple harvests [64,65]. The chemical and physical attributes of PG likely did not impact the trees during this short study; however, the soil profile built could limit tree success in future. Although some studies found that *Populus* or *Salix* can effectively remove inorganic components from contaminated soil [64–67], long-term soil impact and trace element uptake by the tree species should be monitored. Altering depths and horizons in the soil profile may also improve the success of trees in future studies. Adjusting the proportions of different soil building materials could be an effective way to better test the effect of amendments on trees. Altering the amount of soil amendment and incorporating organic matter into the PG layer could improve the rooting depth and soil water holding capacity. Using a herbicide at the start of the study to remove understory from the seed bank could be a more effective way to control vegetation in the early stages of a plantation. Comparing the effectiveness of herbicide and vegetation control may be useful in the first few years of tree establishment.

5. Conclusions

After two years, soil amendments had little effect on either *P. glauca* or *P. balsamifera* for measured growth parameters. Tree species grew on PG (control), with significantly healthier *P. balsamifera* trees than in amended soils. In general, the healthiest and most successful trees for both species were found in the control treatment. Organic amendments, compost and manure, had significantly higher nitrate and phosphorus than most treatments. Black earth and MYKE did not affect any soil properties relative to the control. Despite efforts to control unwanted vegetation, the use of amendments inadvertently benefited competing vegetation more than the planted trees. This study showed good potential for PG stack reclamation using short-rotational tree species, such as *P. balsamifera*, which could provide similar results to traditional grass covers. This study will advance our understanding of alternative revegetation methods for PG stack reclamation.

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References

1. Tayibi, H.; Choura, M.; Lopez, F.A.; Alguacil, F.J.; Lopez-Delgado, A. Environmental impact and management of phosphogypsum. *J. Environ. Manag.* **2009**, *90*, 2377–2386. [CrossRef] [PubMed]
2. Saadaoui, E.; Ghazel, N.; Romdhane, C.B.; Massoudi, N. Phosphogypsum: Potential uses and problems. *Int. J. Environ. Stud.* **2017**, *74*, 558–567. [CrossRef]
3. Bituh, T.; Petrinec, B.; Skoko, B.; Babić, D.; Rašeta, D. Phosphogypsum and its potential use in Croatia: Challenges and opportunities. *Arh. Hig. Rada. Toksikol.* **2021**, *72*, 93–100. [CrossRef]
4. Turner, L.E.; Dhar, A.; Naeth, M.A.; Chanasyk, D.S.; Nichol, C.K. Effect of soil capping depth on phosphogypsum stack revegetation. *Environ. Sci. Pollut. Res.* **2022**, *29*, 50166–50176. [CrossRef] [PubMed]
5. Rutherford, P.M.; Dudas, M.J.; Samek, R.A. Environmental impacts of phosphogypsum. *Sci. Total Environ.* **1994**, *149*, 1–38. [CrossRef]
6. Yang, J.; Liu, W.; Zhang, L.; Xiao, B. Preparation of load-bearing building material from autoclaved phosphogypsum. *Constr. Build. Mater.* **2009**, *23*, 687–693. [CrossRef]
7. Chernysh, Y.; Yakhnenko, O.; Chubur, V.; Roubík, H. Phosphogypsum recycling: A review of environmental issues, current trends, and prospects. *Appl. Sci.* **2021**, *11*, 1575. [CrossRef]
8. Patel, S.K.; Ericson, W.A.; Kelley, M.P. *Phosphogypsum Stack Closure: Evaluation of Phosphogypsum as an Alternative Final Cover*; BCI Engineers and Scientists Inc.: Lakeland, FL, USA, 2002; p. 122.
9. Boldt-Burisch, K.; Naeth, M.A. Phosphogypsum significantly alters root growth and fungal colonization of smooth brome and sheep fescue on a reclamation site. *Rhizosphere* **2019**, *9*, 106–109. [CrossRef]
10. Hallin, I.L.; Naeth, M.A.; Chanasyk, D.S.; Nichol, C.K. Assessment of a reclamation cover system for phosphogypsum stacks in Central Alberta. *J. Environ. Qual.* **2010**, *39*, 2160–2169. [CrossRef]
11. Jackson, M.; Naeth, M.A.; Chanasyk, D.S.; Nichol, C.K. Phosphogypsum capping depth affects revegetation and hydrology in western Canada. *J. Environ. Qual.* **2010**, *40*, 1122–1129. [CrossRef]
12. Parrotta, J.A.; Turnbull, J.W.; Jones, N. Catalyzing native forest regeneration on degraded tropical lands. *For. Ecol. Manag.* **1997**, *99*, 1–7. [CrossRef]
13. Guariguata, M.R.; Rheingans, R.; Montagnini, F. Early woody invasion under tree plantations in Costa Rica: Implications for forest restoration. *Restor. Ecol.* **1995**, *3*, 252–260. [CrossRef]
14. Parrotta, J.A. Influence of overstory composition on understory colonization by native species in plantations on a degraded tropical site. *J. Veg. Sci.* **1995**, *6*, 627–636. [CrossRef]
15. Carnevale, N.J.; Montagnini, F. Facilitating regeneration of secondary forests with the use of mixed and pure plantations of indigenous tree species. *For. Ecol. Manag.* **2002**, *163*, 217–227. [CrossRef]
16. Boothroyd-Roberts, K.; Gagnon, D.; Truax, B. Can hybrid poplar plantations accelerate the restoration of forest understory attributes on abandoned fields? *For. Ecol. Manag.* **2013**, *287*, 77–89. [CrossRef]
17. Bouchard, H.; Guittonny, M.J.; Brais, S. Early recruitment of boreal forest trees in hybrid poplar plantations of different densities on mine waste rock slopes. *For. Ecol. Manag.* **2018**, *429*, 520–533. [CrossRef]
18. Laureysens, I.; Bogaert, J.; Blust, R.; Ceulemans, R. Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. *For. Ecol. Manag.* **2004**, *187*, 295–309. [CrossRef]
19. Rockwood, D.L.; Cardellino, R.; Alker, G.; Lin, C.; Brown, N.; Spriggs, T.; Tsangaris, S.; Isebrands, J.; Hall, R.; Lange, R.; et al. Fast-growing trees for heavy metal and chlorinated solvent phytoremediation. In Proceedings of the Seventh International In Situ and On-Site Bioremediation Symposium, Orlando, FL, USA, 2–5 June 2003; Battelle Press: Columbus, OH, USA; p. F-12.
20. Langholtz, M.; Carter, D.R.; Rockwood, D.L.; Alavalapati, J.R.R. The economic feasibility of reclaiming phosphate mined lands with short-rotation woody crops in Florida. *J. For. Econ.* **2007**, *12*, 237–249. [CrossRef]
21. Rockwood, D.L.; Naidu1, C.V.; Carter, D.R.; Rahmani, M.; Spriggs, T.A.; Lin, C.; Alker, G.R.; Isebrands, J.G.; Segrest, S.A. Short-rotation woody crops and phytoremediation: Opportunities for agroforestry? *Agrofor. Syst.* **2004**, *61*, 51–63.
22. Lugo, A.E. The apparent paradox of reestablishing species richness on degraded lands with tree monocultures. *For. Ecol. Manag.* **1997**, *99*, 9–19. [CrossRef]

23. Otsamo, R. Secondary forest regeneration under fast-growing forest plantations on degraded Imperata cylindrica grasslands. *New For.* **2000**, *19*, 69–93. [CrossRef]
24. Powers, J.S.; Haggar, J.P.; Fisher, R.F. The effect of overstory composition on understory woody regeneration and species richness in 7-year-old plantations in Costa Rica. *For. Ecol. Manag.* **1997**, *99*, 43–54. [CrossRef]
25. Filcheva, E.; Noustorova, M.; Gentcheva-Kostadinova, S.; Haigh, M. Organic accumulation and microbial action in surface coal-mine spoils, Pernik, Bulgaria. *Ecol. Eng.* **2000**, *15*, 1–15. [CrossRef]
26. Wilkinson, A. Poplars and willows for soil erosion control in New Zealand. *Biomass Bioenergy* **1999**, *16*, 263–274. [CrossRef]
27. Douglas, G.B.; McIvor, I.R.; Potter, J.F.; Foote, L.G. Root distribution of poplar at varying densities on pastoral hill country. *Plant Soil* **2010**, *333*, 147–161. [CrossRef]
28. Espigares, T.; Moreno-de las Heras, M.; Nicolau, J.M. Performance of vegetation in reclaimed slopes affected by soil erosion. *Restor. Ecol.* **2011**, *19*, 35–44. [CrossRef]
29. Samson, R.; Girouard, P.; Zan, C.; Mehidi, B.; Martin, R.; Henning, J. The Implications of Growing Short Rotation Trees Species for Carbon Sequestration in Canada. Final Report. National Climate Change Process, Solicitation no. 23103-8-0253/N. 1999, p. 91. Available online: https://www.reap-canada.com/online_library/ghg_offsets_policy/20%20The%20Implications.pdf (accessed on 9 August 2022).
30. Alberta Environment. *Operating Approval under the Environmental Protection and Enhancement Act*; Approval No. 20477-01-00; Agrium Products Inc.: Fort Saskatchewan, AB, Canada; Government of Alberta: Edmonton, AB, Canada, 2008; p. 27.
31. Government of Alberta. Environmental Protection and Enhancement Act (EPEA). Revised Statutes of Alberta 2000 Chapter E-12. 2019. Available online: https://www.qp.alberta.ca/documents/Acts/E12.Pdf (accessed on 8 August 2022).
32. Dhar, A.; Comeau, P.G.; Karst, J.; Pinno, B.D.; Chang, S.X.; Naeth, A.M.; Vassov, R.; Bampfylde, C. Plant community development following reclamation of oil sands mine sites in the boreal forest: A review. *Environ. Rev.* **2018**, *26*, 286–298. [CrossRef]
33. Shiralipour, A.; McConnell, D.B.; Smith, W.H. Physical and chemical properties of soils as affected by municipal waste compost application. *Biomass Bioenergy* **1992**, *3*, 261–266. [CrossRef]
34. Moore, P.A.; Daniel, T.C.; Sharpley, A.N.; Wood, C.W. Poultry manure management: Environmentally sound options. *J. Soil Water Conserv.* **1995**, *50*, 321–327.
35. Black Earth. Mini-Granule Coarse: Product Brochure. Ryley Alberta. 2014, p. 4. Available online: http://www.hortimax.biz/BlackEarth/BlackEarth-MiniGranule_Coarse.pdf (accessed on 12 July 2022).
36. Bonfante, P.; Anca, I.A. Plants, mycorrhizal fungi, and bacteria: A network of interactions. *Annu. Rev. Microbiol.* **2009**, *63*, 363–383. [CrossRef]
37. Asmelash, F.; Bekele, T.; Birhane, E. The potential role of arbuscular mycorrhizal fungi in the restoration of degraded lands. *Front. Microbiol.* **2016**, *7*, 1095. [CrossRef] [PubMed]
38. Wang, F. Occurrence of arbuscular mycorrhizal fungi in mining-impacted sites and their contribution to ecological restoration: Mechanisms and applications. *Crit. Rev. Environ. Sci. Technol.* **2017**, *47*, 1901–1957. [CrossRef]
39. Parsons, R.F. Gypsophily in plants. A review. *Am. Midl. Nat.* **1976**, *96*, 1–20. [CrossRef]
40. Guerrero-Campo, J.; Alberto, F.; Maestro Martınez, M.; Hodgson, J.; Montserrat Martı, G. Plant community patterns in a gypsum area of NE Spain. II. Effects of ionwashing on topographic distribution of vegetation. *J. Arid Environ.* **1999**, *41*, 411–419. [CrossRef]
41. Khabou, W.; Hajji, B.; Zouari, M.; Rigane, H.; Abdallah, F.B. Arbuscular mycorrhizal fungi improve growth and mineral uptake of olive tree under gypsum substrate. *Ecol. Eng.* **2014**, *73*, 290–296. [CrossRef]
42. Linderman, R.G.; Call, C.A. Enhanced rooting of woody plant cuttings by mycorrhizal fungi. *J. Am. Soc. Hortic. Sci.* **1977**, *102*, 629–632. [CrossRef]
43. Prysedskyi, Y.; Mashtaler, M. Growth parameters of herbaceous plants on phosphogypsum dumps with using soil coverings based on sewage sludge. *J. Ecol. Eng.* **2021**, *22*, 20–26. [CrossRef]
44. Environment Canada. Canadian Climate Normals 1981–2010 Station Data. 2022. Available online: http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&txtStationName=Fort+McMurray&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentraLongSec=0&stnID=2519&dispBack=1 (accessed on 12 July 2022).
45. Government of Canada. Canadian Biomass Innovation Network. Natural Resources Canada. 2015. Available online: http://www.nrcan.gc.ca/energy/renewable-electricity/bioenergy-systems/17160 (accessed on 26 October 2022).
46. Keddy, T.; (Canadian Wood Fibre Center). Personal communication, 2017.
47. Sparks, A.L.; Helmke, P.A.; Loeppert, R.H. *Methods of Soil Analysis. Part 3—Chemical Methods*; Soil Science Society of America, American Society of Agronomy: Madison, WI, USA, 1996, 1996; pp. 961–1010.
48. McKeague, J.A. *Manual on Soil Sampling and Methods Analysis*; Canadian Society of Soil Science: Ottawa, ON, Canada, 1981; p. 212.
49. Ashworth, J.; Mrazek, K. Modified kelowna test for available phosphorus and potassium in soil. *Commun. Soil Sci. Plant Anal.* **1995**, *26*, 731–739. [CrossRef]
50. Carter, M.R.; Gregorich, E.G. *Soil Sampling and Methods of Analysis*, 2nd ed.; Taylor & Francis Group: Boca Raton, FL, USA, 2008; p. 1264.
51. R Core Team. *R: A Language and Environment for Statistical Computing. R Foundation 110 for Statistical Computing*; Vienna, Austria, 2021. Available online: http://www.R-project.org/ (accessed on 1 August 2021).

52. Fortier, J.; Gangon, D.; Truax, B.; Lambert, F. Biomass and volume yield after 6 years in multiclonal hybrid poplar riparian buffer strips. *Biomass Bioenergy* **2010**, *34*, 1028–1040. [CrossRef]
53. Miller, V.S.; Naeth, M.A. Amendments and substrates to develop Anthroposols for northern mine reclamation. *Can. J. Soil Sci.* **2017**, *97*, 266–277. [CrossRef]
54. Messier, C.; Parent, S.; Bergeron, Y. Effects of overstory and understory vegetation on the understory light environment in mixed boreal forests. *J. Veg. Sci.* **1998**, *9*, 511–520. [CrossRef]
55. Lieffers, V.J.; Messier, C.; Stadt, K.J.; Gendron, F.; Comeau, P. 1999. Predicting and managing light in the understory of boreal forests. *Can. J. For. Res.* **1999**, *29*, 796–811. [CrossRef]
56. Henkel-Johnson, D.; Macdonald, S.E.; Bork, E.W.; Thomas, B.R. Influence of weed composition, abundance, and spatial proximity on growth in young hybrid poplar plantations. *For. Ecol. Manag.* **2016**, *362*, 55–68. [CrossRef]
57. Landhausser, S.M.; Lieffers, V.J. Growth of *Populus tremuloides* in association with *Calamagrostis canadensis*. *Can. J. For. Res.* **1998**, *28*, 396–401. [CrossRef]
58. Dhar, A.; Wang, R.J.; Hawkins, C.D.B. Interaction of Trembling Aspen and Lodgepole Pine in a Young Sub Boreal Mixedwood Stand in Central British Columbia. *Open J. For.* **2015**, *5*, 129–138. [CrossRef]
59. Lieffers, J.V.; Pinno, D.B.; Stadt, J.K. Light Dynamics and Free-to-Grow Standards in Aspen Dominated Mixedwood Forests. *For. Chron.* **2002**, *78*, 37–45. [CrossRef]
60. Lieffers, V.J.; Stadt, K.J.; Feng, Z. Free-to-Grow Regeneration Standards Are Poorly Linked to Growth of Spruce in Boreal Mixedwoods. *For. Chron.* **2007**, *83*, 818–824. [CrossRef]
61. Weil, R.R.; Brady, N.C. *Elements of the Nature and Properties of Soil*, 4th ed.; Pearson Education: Cranbury, NJ, USA, 2021; p. 768.
62. Boldt-Burisch, K.; (Brandenburg University of Technology, Cottbus, Germany). Personal communication, 2022.
63. Zalesny, R.S., Jr.; Stanturf, J.A.; Gardiner, E.S.; Perdue, J.H.; Young, T.M.; Coyle, D.R.; Headlee, W.L.; Bañuelos, G.S.; Hass, A. Ecosystem services of woody crop production systems. *BioEnergy Res.* **2016**, *9*, 465–491. [CrossRef]
64. Baldantoni, D.; Cicatelli, A.; Bellion, A.; Castiglione, S. Different behaviours in phytoremediation capacity of two heavy metal tolerant poplar clones in relation to iron and other trace elements. *J. Environ. Manag.* **2014**, *146*, 94–99. [CrossRef]
65. Laureysens, I.; Blust, R.; De Temmerman, L.; Lemmens, C.; Ceulemans, R. Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture: I. Seasonal variation in leaf, wood and bark concentrations. *Environ. Pollut.* **2004**, *131*, 485–494. [CrossRef]
66. Rogers, E.R.; Zalesny, R.S., Jr.; Hallett, R.A.; Headlee, W.L.; Wiese, A.H. Relationships among Root–Shoot Ratio, Early Growth, and Health of Hybrid Poplar and Willow Clones Grown in Different Landfill Soils. *Forests* **2019**, *10*, 49. [CrossRef]
67. Dutton, M.V.; Humphreys, P.N. Assessing the Potential of Short Rotation Coppice (Src) for Cleanup of Radionuclide contaminated Sites. *Int. J. Phytoremedia.* **2005**, *7*, 279–293. [CrossRef] [PubMed]