New Forests
https://doi.org/10.1007/s11056-024-10055-9

RESEARCH

Organic matter additions for improved revegetation of arsenic-rich waste rock with planted boreal conifers: a three-year in situ monitoring study

Simon Taurines[1,2] · Marie Guittonny[1] · Armand Séguin[2]

Received: 16 January 2024 / Accepted: 18 May 2024

Abstract
Mining waste creates challenging soil conditions that hinder tree establishment for boreal forest restoration. This study investigated the effects of adding topsoil or ramial chipped wood (RCW) on the physicochemical properties of waste rock and the growth and survival of planted native tree species. A randomized-block setup with four replications of four treatments was established on a gold mine site in western Quebec, Canada in 2018, and planted with *Pinus banksiana* and *Abies balsamea*. Results demonstrated that topsoil addition significantly improved height and diameter growth, aerial and root biomasses, survival, and nutrient uptake (N, P, and S) in conifer seedlings. Concomitantly, water content increased, pH lowered and nutrient concentrations increased in the substrate with a topsoil layer. However, multivariate analysis revealed that these improved soil conditions alone did not determine the survival and growth of conifer seedlings. In contrast, the application of RCW-based treatments had no discernible impact on the growth and survival of the planted trees. Additionally, topsoil amendment effectively reduced the concentration of potentially phytotoxic elements in soil and needles, particularly arsenic. The total arsenic concentration in the mineral substrate (84.1 to 507 $\mu g.g^{-1}$) emerged as a growth-limiting factor for both conifer species. The total concentration of arsenic in the waste rock correlated positively with arsenic accumulation in the tree needles, indicating potential root uptake of this element. This study emphasizes the significance of addressing arsenic availability during reclamation efforts at mine sites. Nonetheless, further research is required to determine the phytotoxic thresholds of arsenic on conifers and its potential metabolic effects.

Keywords Ramial chipped wood · Topsoil · Mine waste afforestation · *Pinus banksiana* · *Abies balsamea* · Arsenic phytotoxicity

✉ Marie Guittonny
marie.guittonny@uqat.ca

[1] Institut de Recherche en Mines et Environnement, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, QC, Canada

[2] Centre de Foresterie des Laurentides, Ressources Naturelles Canada, Québec, QC, Canada

Published online: 30 May 2024

Introduction

The mining industry generates a large quantity of mining waste, including waste rock, which refers to the non-ore or rocky mineral material that is removed during mining operations (Bian et al. 2012). The rehabilitation of mine sites is essential to allow the reestablishment of the forest ecosystem and the recovery of the original ecological services and biodiversity (Bussière and Guittonny 2020; Macdonald et al. 2015; Tongway and Ludwig 2011). However, there has been limited research specifically targeting the reforestation of waste rock in the boreal context (Babi et al. 2018; Bouchard et al. 2018; Larchevêque et al. 2015).

Efforts to rehabilitate waste rock can be limited by soil conditions that constrain the establishment of trees (Bouchard et al. 2018; Macdonald et al. 2015; Tongway and Ludwig 2011). Among these conditions, the absence of organic matter often implies a low availability of micro and macro nutrients for plants, a low water retention capacity of the soil, and significant temperature variations during the period of plant growth (Bradshaw 1992; Lal 2001, 2020; Macdonald et al. 2015). Adding organic matter to waste rock can thus help afforestation.

In addition, the mobility of certain potentially phytotoxic elements contained in waste rock, especially arsenic, can reduce the chances of survival and growth of planted trees (Bradshaw 1992; Macdonald et al. 2015), and has implications for the food chain in the ecosystem (Peralta-Videa et al. 2009). Recent research has pointed towards the complex role that organic matter plays in the mobility of arsenic in mine wastes (Coudert et al. 2020; Wang and Mulligan 2009). The presence of organic matter has been found to promote arsenic mobilization under certain conditions.

Conifer species in the boreal forest are not all equally sensitive to poor quality soils with low organic matter and fast drainage like waste rock. Some species, such as jack pine (*Pinus banksiana* Lamb.), are pioneer species that can survive and grow on mainly mineral substrates, despite low water retention conditions (Chrosciewicz 1974, 1990; Weber et al. 1987). Other late-successional boreal conifers, such as balsam fir (*Abies balsamea* (L.) Mill.), are shade-tolerant and can survive and grow in forest conditions with high canopy cover (Asselin et al. 2001; Bergeron 2000; Chen and Popadiouk 2002). This canopy cover often implies a soil rich in organic matter and high water retention favorable to the development of these species (Gómez-Aparicio 2009; Keenan and Kimmins 1993; Wessman et al. 1988).

Several restoration approaches are possible on mine waste rock, including revegetation using an ameliorative approach (Bussière and Guittonny 2020; Huebner et al. 2022; Prach et al. 2001; Prach and Hobbs 2008; Singh et al. 2002). The ameliorative approach in a boreal forest context can consist of planting trees of native species combined with improving the substrate using organic matter, such as ramial chipped wood (RCW) or topsoil, as an amendment, mulch, or surface layer (Bussière and Guittonny 2020; Gastauer et al. 2018; Larcheveque et al. 2013; Maiti et al. 2021; Taurines 2019; Taurines et al. 2024).

Topsoil is a material that is sometimes available from borrow pits near mine sites in the boreal region or conserved after on-site excavations associated with mining works. Topsoil is the fertile portion of the soil profile containing organic matter, which, when mixed with a mineral substrate, can create favorable conditions for pedogenesis and lead to the formation of a soil (Brevik and Lazari 2014; Hugron et al. 2011). The addition of topsoil is a common approach to mine site reclamation, during the revegetation phase (Anderson et al. 2008; Barton et al. 2008; Boldt-Burisch and Naeth 2017; Bussière and Guittonny 2020; Charnock and Grant 2005; Drozdowski et al. 2012; Gagnon et al. 2021; Kneller et al. 2018; Larcheveque et al. 2013). However, the cost of this material is often too high to restore all the waste rock accumulation areas at large-scale mine sites. Moreover, this approach often involves borrowing soils from other ecosystems, which can lead to their disturbance.

Ramial chipped wood is a by-product of pruning cuts and is available at lower cost. RCW is a fresh or slightly decomposed organic material (Lemieux et al. 2000). RCW is used in agricultural and horticultural work, but very little mention has been found in the scientific literature for the revegetation of mine sites (Barthes et al. 2010; Germain and Eng 2007; Lemieux et al. 2000; Taurines 2019; Taurines et al. 2024). The use of RCW mulch as an alternative approach to topsoil during mine ecological restoration has shown promise in facilitating the natural colonization of plants (Taurines et al. 2024). However, its use for planting forest species directly in waste rock has not yet been tested. It is also unclear whether RCW should be mixed with the first cm of mineral substrate to facilitate the formation of an organic horizon and promote pedological processes, or whether it should be mulched on the surface of mineral substrates (Fortin Faubert et al. 2021; Lemieux et al. 2000; Soumare et al. 2004).

The main objective of this four-year study was to investigate the effects of an organic matter supply in the form of topsoil or RCW (as mulch or directly mixed with waste rock) on in situ survival and growth (height, diameter, and biomass) of *A. balsamea* and *P. banksiana* seedlings planted on waste rock, while determining the physicochemical conditions of the substrate that contributed to their growth and survival.

Three main hypotheses were formulated: (1) the supply of organic matter on waste rock increases the growth in diameter, height, and biomass, as well as the survival of seedlings of *A. balsamea* and *P. banksiana*, as compared to waste rock alone; (2) the supply of organic matter on waste rock improves the microclimatic conditions (volumetric water content and temperature) of the soil as compared to waste rock alone; and (3) the addition of organic matter to waste rock improves the chemical conditions (availability of nutrients, reduction of phytotoxicity risks) of the soil as compared to waste rock alone.

Materials and methods

Study area

The study was conducted on a mine site, located in Abitibi-Témiscamingue, Quebec, Canada (Fig. 1). The mine site was an underground gold mine that overlapped the Cadillac-Larder Lake fault zone. The mine site closed in 2018. The bioclimatic domain of the site is boreal mixedwood forest; more specifically, it is located in the balsam fir–white birch forest ecosystem (Québec 2019). Climate records from 1981 to 2010 indicate an average annual temperature of 1 °C, with average annual minimum and maximum values of −5 °C and 7.1 °C, respectively; this data was collected from the weather station closest to the site, at Mont-Brun, less than 40 km from the mine site. The mean monthly maximum and minimum values are −24.3 °C in January and 23.2 °C in July. The average annual precipitation is 707.7 mm of rain and 281.2 cm of snow (Québec 2010).

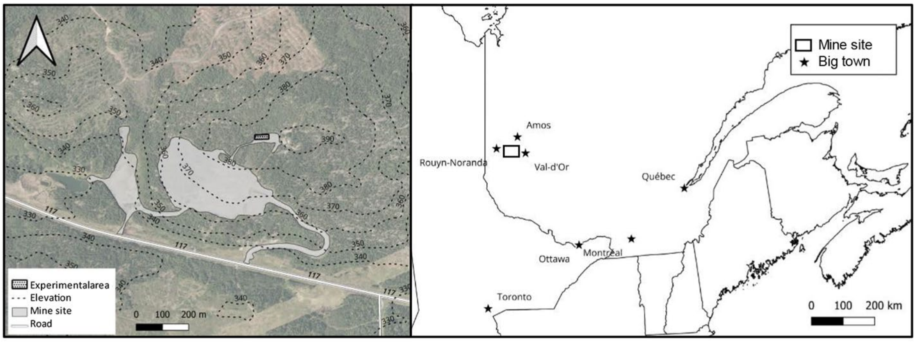

Fig. 1 On the left, the site map shows the position of the experimental setup, its proximity to the forest adjacent to the site, and the elevation. On the right, a rectangle indicates the approximate position of the mine site in the province of Quebec

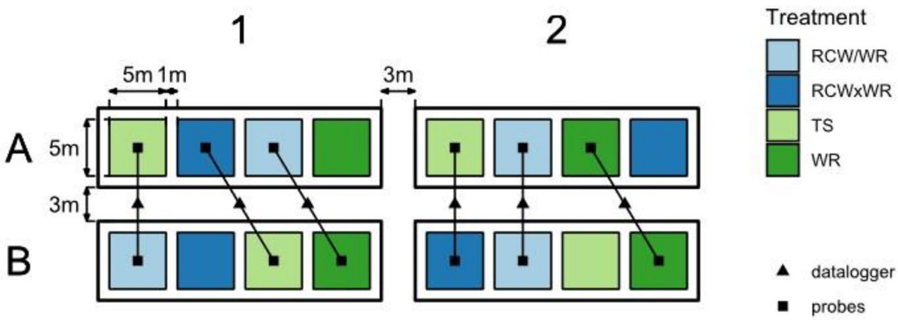

Fig. 2 Experimental setup with the four blocks (A1, A2, B1, and B2) containing the four treatments/cells (RCW/WR, RCW×WR, TS, and WR). The position of the volumetric water content and temperature probes is represented by squares and the position of the dataloggers connected to probes is represented by triangles. The spacing between the blocks was 3 m and the spacing of the cells within the blocks was 1 m. The cells measured 5 m square. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil

Experimental setup

Setup construction

The experimental setup was installed on August 22nd, 2018, on a waste rock deposit at an elevation of 393 m. The setup used a fully randomized block design with four blocks (replications). Each block included four cells measuring 5 m by 5 m, separated by a 1 m interval. Each cell included one of the four treatment types. The position of the treatments in each block was determined randomly (Fig. 2).

The treatments were as follows:

- WR: waste rock from the mine site, spread without slope;
- RCW/WR: fresh ramial chipped wood deposited as mulch to a thickness of 2 cm above

Table 1 Granulometric distribution of the waste rock. D_x corresponds to the mesh size of the sieve at which x % of the particles pass. The uniformity and curvature coefficients are calculated as follows:

$C_U = \frac{D_{60}}{D_{10}}$
and
$C_C = \frac{{D_{30}}^2}{D_{10} \times D_{60}}$

D_x	Particule size (mm)
D_{10}	0.315
D_{20}	2.5
D_{30}	5
D_{40}	10
D_{50}	14
D_{60}	20
D_{70}	28
Coefficients	-
Uniformity (C_U)	63.49
Curvature (C_C)	3.97

the waste rock;

- RCW×WR: fresh ramial chipped wood deposited as mulch to a thickness of 2 cm above the waste rock, then mixed with the waste rock using the crenellated edge of an excavator bucket manipulated by a mechanical shovel over 15 to 20 cm deep in the mineral material; and.
- TS: topsoil from an excavation company close to the site, deposited on the surface of the waste rock to a thickness of 10 cm.

The RCW was composed of 100% freshly cut trembling aspen (*Populus tremuloides*) twigs (chips varying in length between 2 and 4 cm; supplied by Émondage Abitibi Inc. ©); it was stored for less than a week before use.

Material characterization

The materials were characterized by various methods. The particle size distribution of the waste rock was determined using a Malvern Mastersizer 3000 laser diffraction analyzer for the < 80 µm fraction and a mechanical sieving device for the ≥ 80 µm fraction (ASTM 2007, 2022).

Based on the GSD (grain-sized distribution) parameters, the waste rock in the study area was considered "poorly graded gravel" (ASTM 2020) (Table 1).

The in situ bulk density of the materials was determined for each cell/treatment. A cylindrical soil sample with a diameter of 25 cm and a depth of 15 cm was extracted and the edges and bottom of the resulting hole were lined with a hydrophobic textile (Campbell 1994). The volume of the soil sample was calculated by measuring the amount of water required to fill the hole. The soil sample was then oven-dried at 60 °C for 48 h and its dry mass was recorded. The in situ bulk density was obtained by dividing the dry mass of the soil sample by its in situ volume (Table 2).

The soil water retention curve of the waste rock (alone or mixed with RCW) was obtained by fitting the Brooks and Corey equation to the measured data from a column experiment (Chapuis et al. 2007). A 70 cm-high column measuring 30 cm in diameter, containing waste rock placed at the average bulk density measured in situ, was used to determine the gravimetric water content (w) measurements following a water suction gradient (elevation) in the soil.

Table 2 Average bulk density of each treatment type ($n=4$). The standard error (S.E.) is indicated in parentheses

Treatment	Average bulk density (S.E.)
RCW/WR	1.81 (0.21)
RCW×WR	1.74 (0.08)
TS	0.61 (0.2)
WR	1.89 (0.12)

Conifer seedlings

Planting of seedlings

The choice of planted conifer species was made according to the plant composition of the bioclimatic subdomain of the study area. Since the area is in the balsam fir–white birch forest, two species of conifers belonging to different stages of succession were planted: *P. banksiana* Lamb. And *A. balsamea* (L.) Miller.

Seedlings were purchased in June 2018 and stored in an open warehouse until September 5th, 2018, the date of the planting. According to the survival of seedlings in the warehouse, the number of planted seedlings of each species was 12 per cell for *A. balsamea* and 26 for *P. banksiana*. The tree seedlings came from the Ministère des Forêts, de la Faune et des Parcs of Quebec (MFFP) nurseries (*P. banksiana* from Trécesson, QC, Canada and *A. balsamea* from the Abitibi-Témiscamingue Forestry Association). In each cell, the seedlings were divided into four groups (two groups of each species) and were randomly arranged in four uniform squares with randomly selected positions. Each seedling was planted with an inter-individual spacing of 1 m, ensuring appropriate space for growth and development.

Survival

After the first growing season (in 2019), a seedling was considered dead if its needles were no longer green or if no needles were left. However, if there were still green needles present, the seedling was considered alive. The number of live seedlings was counted at the end of each summer from 2018 to 2021 (mid-August, from planting to after the third growing season).

The study measured survival in two different ways for all planted seedlings. The first method (1) calculated survival difference ($\Delta_{Survival}$) by taking the difference between the number of seedlings observed in the previous year (N_{Y-1}) and the number observed in the current year (N_Y).

$$\Delta_{Survival} = N_{Y-1} - N_Y \tag{1}$$

The second method (2) calculated survival rate ($R_{Survival}$) by dividing the number of seedlings observed in the current year by the number observed in the previous year.

$$R_{Survival} = \frac{N_Y}{N_{Y-1}} \tag{2}$$

Aerial growth

Aerial growth was measured annually for all planted seedlings. The measurements always took place at the end of the summer from 2018 to 2021 (mid-August, from planting to after the third growing season). The initial measurements occurred in 2018, just after planting. Annual aerial growth was determined with two measurements on the living seedlings:

- Height from the base to stem apex, folding all the branches towards the top of the seedling to find its apical point (highest point of the seedling). This measurement was collected using a flexible measuring tape.
- Diameter at the base of the soil. This measurement was collected using a caliper.

Biomass

The total, aerial, and root biomasses were measured after three growing seasons by gently excavating with gardening shovels three randomly chosen seedlings per cell, in the last year of monitoring the experimental setup (2021). Only seedlings of *P. banksiana* were excavated because the survival of *A. balsamea* did not provide an adequate representation of the species in each cell of the setup.

Seedlings were first cut at the base of the stem and identified. Then, an excavation of the root system was carried out to recover all the roots, including the finest. The root samples were identified and associated with the corresponding aerial sample from each seedling.

The plant material was brought back to the laboratory where it was washed with tap water, then placed in an oven at 60 °C for 64 h to eliminate any residual water. A verification of the drying was carried out by ensuring that the mass no longer changed after 60 h. The mass of the different samples (root and aerial) was measured with a Mettler PM4800 DeltaRange © scale and an average whole seedling mass per cell was calculated (3, 4, 5).

$$m_a = \frac{m_{T_a}}{i} \tag{3}$$

$$m_r = \frac{m_{T_r}}{i} \tag{4}$$

$$m_i = \frac{m_{T_r} + m_{T_a}}{i} \tag{5}$$

Where m_a is the average seedling aerial mass in a cell, m_r is the average seedling root mass in a cell, m_i is the average whole seedling mass in a cell, m_{T_r} is the total mass of roots of the excavated seedlings, m_{T_a} is the total mass of aerial part of the excavated seedlings and i is the number of excavated seedlings in the cell.

Chemical composition of needles

In 2020, needles of the two species of conifers were collected from three randomly selected live seedlings in each cell. Needles from the three seedlings in a single cell were then combined to form a composite sample. Since there were a total of 16 cells in the experimental area and two species, this resulted in a total of 32 composite needle samples. After being cleaned, the samples were placed in an oven at 60 °C to dry for 48 h, until they no longer lost weight.

Samples were sent to the Lakehead University Forest Resources & Soils Testing Laboratory for analysis of total nitrogen (total N) and trace metal (Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, S, Sb, Se, Si, Sn, Sr, Ti, Tl, V, and Zn) concentrations in the needles. The method of analysis for total nitrogen was combustion combined with a nitrogen analyzer. The analytical method for trace metals was microwave assisted acid digestion followed by metal determination using inductively coupled plasma atomic emission spectroscopy (ICP-AES) (U.S.EPA 2007).

Environmental variables

Soil volumetric water content and temperature

The soil volumetric water content and the soil temperature were measured hourly from 2019 to 2021 (Fig. 2).

Two types of probes were used (Fig. 3):

- 5TM (Meter Environment ©), which measured the volumetric water content by volume and the temperature at a depth of 10 cm below the surface of the waste rock. The accuracy of these probes was ±2% after calibration and the temperature measurement ranged from −40 to +60 °C, with an accuracy of ± 1 °C.
- EC-5 (Meter Environment ©), which measured only the volumetric water content by volume at a depth of 25 cm below the surface of the waste rock. The precision of these probes was ±2% after calibration.

Since the probes were not buried in topsoil or RCW, we calibrated them for waste rock used in this study (waste rock alone and waste rock mixed with RCW), in the laboratory.

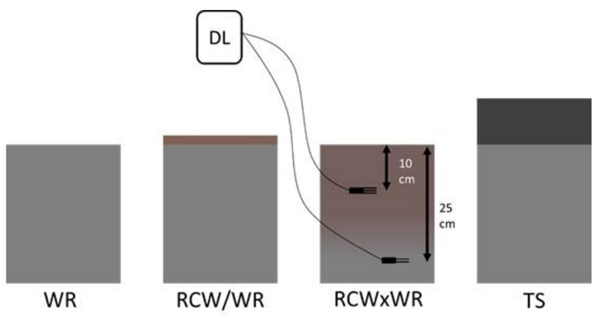

Fig. 3 Position of the probes in the soil. The 5TM (Meter Environment ©) probes, which measured volumetric water content and temperature, were located 10 cm below the surface of the mineral substrate, while the ECH$_2$O-EC5 (Meter Environment ©) probes, which measured the volumetric water content only, were located 25 cm below the surface. DL: data logger; WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil

Chemical analysis

Substrate samples were collected in September 2020 and sent to the Lakehead University laboratory for chemical analysis. The samples included bulk samples of topsoil and RCW mulch, and a sample of waste rock underlying each of the four treatments in each experimental cell (16 waste rock samples). The analyses carried out were as follows:

- electrical conductivity (1:1, H_2O: soil) with a conductivity meter;
- total nitrogen concentration by combustion with a nitrogen analyzer;
- total organic carbon concentration by combustion with a carbon analyzer;
- pH in saturated paste; and.
- trace metals (Al, As, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, Si, Sr, Ti, Tl, V, and Zn) with microwave assisted acid digestion followed by metal determination using ICP-AES (U.S.EPA 2007).

Colonizing plant cover

In 2021, during the dismantling of the experimental setup, the total and specific cover of spontaneously colonizing plants were measured by the method of point interceptions along a transect arranged diagonally on each cell. The measurement points were distributed every 5 cm along the transect. To facilitate the recognition of the plant species present, the *Pl@ntNet©* application was sometimes used (Bonnet et al. 2015). Total plant cover (C_T) corresponded to the quotient of the sum of the interception points (n_{T_s}) over the total number of measurement points (n_T) on the transect (6). Specific cover (C_s) corresponded to the quotient of the sum of interception points for a given species (n_s) over the total number of measurement points (n_T) on the transect (7).

$$C_T = \frac{n_{T_s}}{n_T} \tag{6}$$

$$C_s = \frac{n_s}{n_T} \tag{7}$$

Statistical analysis

The statistical analyses were conducted with the R language in the RStudio development environment (R, 2023). The scripts used can be found in the Supplementary Material. The significance level for the analyses was $\alpha = 0.05$.

When the assumptions were met (normality of residuals and homoscedasticity), a repeated custom analysis of variance was performed on the conifer variables (response variables) and environmental variables (explanatory variables), followed by a post-hoc test with Tukey's correction (Rupert Jr 2012) to test treatment effect. The treatment effect was tested for each species independently. When the assumptions were not met, a non-parametric Kruskal-Wallis test was performed (Hollander et al. 2013), followed by a non-parametric Dunn's multiple comparison test using Benjamini-Yekutieli adjustment (Benjamini and

Yekutieli 2001; Dunn 1961, 1964). Tables summarizing the analysis results are available in the Supplementary Material.

Multivariable linear regressions were also modeled to determine by stepwise selection the model that best explained the response of the seedlings, based on the Akaike criterion (AICc) of the different models and by analyzing all the models, from the full model to the null model (Sakamoto et al. 1986). The null model was composed of all the variables identified in the scientific literature as being able to influence the response variable, while considering the collinearity of these explanatory variables. To determine the collinearity of the variables, the variance inflation factor (VIF) was calculated for the full model, in addition to the correlation coefficient between the explanatory variables (Salmerón et al. 2018). A VIF less than 2 was considered acceptable for the variables included in the full model. When a variable had a VIF greater than 2, variables with a correlation coefficient greater than ± 0.5 were eliminated from the model (Fox and Monette 1992). Finally, the collinearity was checked graphically by principal component analysis (PCA) and using scatterplot to ensure the linearity of the variables and that the correlation coefficient was not fortuitous (De Marco and Nobrega 2018). The script for the analysis, as well as the data for the multivariate analysis, is provided in the Supplementary Material.

The *tidyverse* metapackage was used for the data cleaning, transformation, and visualization steps, as well as the functional programming steps (Wickham et al. 2019). The *multcomp*, *emmeans*, *lmerTest*, *lme4*, and *rstatix* packages were used for all statistical testing analysis steps (Bates et al. 2015; Hothorn et al. 2008; Kassambara 2023; Kuznetsova et al. 2017; Lenth et al. 2023). The stepwise selection was carried out with the *step()* function of the *stats* package, with a bidirectional search (*direction = "both"*) (Venables and Ripley 2002). The VIF was calculated using the *vif()* function of the *car* package (Fox and Weisberg 2018). The PCA and the correlations were carried out respectively using the *prcomp()* function and the *cor()* function, both from the *stats* package (R, 2023).

Results

Seedling responses

Seedling survival

The number of dead seedlings from year to year ($\triangle_{Survival}$) and the interannual survival rate ($R_{Survival}$) were significantly different between treatments only for *A. balsamea*. In 2021, the TS treatment showed a significantly lower $\triangle_{Survival}$ and a significantly higher $R_{Survival}$ for this species than the RCW×WR treatment (Table 3).

Table 3 Mean survival indices calculated in 2021 among treatments for *Abies balsamea*. $\triangle_{Survival}$: number of dead seedlings from year to year; $R_{Survival}$: interannual survival rate; WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil. The letters represent the results of the post-hoc test performed. Treatments that share the same letter do not differ significantly. The standard error is indicated in parentheses

	TS	RCW×WR	RCW/WR	WR
$\triangle_{Survival}$	1.5 (0.29) a	6.5 (1.66) b	4.75 (1.38) ab	2.5 (0.65) ab
$R_{Survival}$ (%)	83.6 (3.38) b	30.9 (14.93) a	44.9 (8.21) ab	70.5 (8.67) ab

Seedling height and basal diameter

At planting in 2018, the average height of *A. balsamea* on the site was 21.5 cm (SE = 0.3) and their average diameter was 4.3 mm (SE = 0.01). The height and diameter of *A. balsamea* began to significantly differ among treatments from 2020 onwards (Fig. 4). In 2020 and 2021, the TS treatment exhibited *A. balsamea* with a significantly larger diameter than the other three treatments. The TS and WR treatments had seedlings with a significantly greater height than the RCW×WR treatment in 2020. Then, in 2021, the TS treatment had a significantly greater height of *A. balsamea* than the other three treatments. The average diameter of *A. balsamea* in 2021 was 10.6 mm (SE = 0.7) for the TS treatment, which was about twice that of the other treatments: 4.8 mm (SE = 0.4) for RCW×WR, 5.1 mm (SE = 0.4) for RCW/WR, and 5.4 mm (SE = 0.3) for WR. The average height of *A. balsamea* in 2021 was also greater for the TS treatment, with 37.8 cm (SE = 1.9), as compared to 24.1 cm (SE = 1.6) for RCW×WR, 23.9 cm (SE = 1.4) for RCW/WR, and 27.5 cm (SE = 1.0) for WR.

The average height of *P. banksiana* at planting in 2018 was 23.5 cm (SE = 0.2), and their average diameter was 4.4 mm (SE = 0.04). *P. banksiana* seedlings exhibited a significantly greater diameter on the TS treatment than on the other three treatments from 2019 until 2021. They had a significantly greater height on the TS treatment than on the RCW×WR and WR treatments in 2019; in 2020 and 2021, the height of *P. banksiana* on the TS treatment was greater than on all three other treatments. The average diameter of *P. banksiana* in 2021 was 21.2 mm (SE = 0.3) for the TS treatment, three times greater than the average diameter of 7.1 mm (SE = 0.2) for RCW×WR, 6.6 mm (SE = 0.2) for RCW/WR, and 7.5 mm (SE = 0.2) for WR. The average height of *P. banksiana* in 2021 was 77.1 cm (SE = 2.0) for the TS treatment, 37.7 cm (SE = 0.9) for the RCW×WR treatment, 38.4 cm (SE = 0.8) for the RCW/WR treatment, and 39.6 cm (SE = 0.8) for the WR treatment.

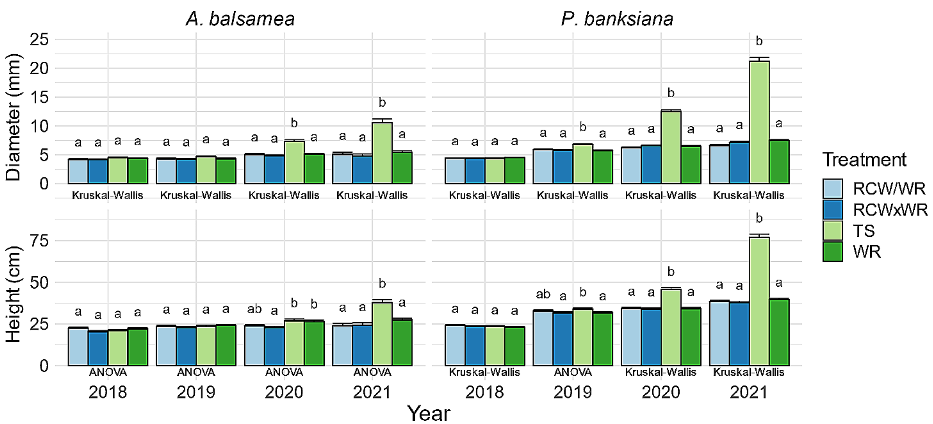

Fig. 4 Annual mean height (in cm) and basal diameter (in mm) of *A. balsamea* and *P. banksiana* planted seedlings among treatments. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil. The letters represent the results of the post-hoc test performed. Treatments that share the same letter do not differ significantly. The statistical comparison test is indicated under each bar chart. Error bars represent standard error

P. banksiana biomass

After excavation of *P. banksiana* seedlings in 2021, at the conclusion of three growing seasons, the aerial, root and whole seedling biomasses were found to all be significantly greater on the TS treatment than on the three other treatments. The average excavated seedling biomass was 300.82 g (SE = 43.8) on the TS treatment, more than 10 times greater than that on the other treatments: 20.53 g (SE = 2.59) on RCW×WR, 24.72 g (SE = 1.65) on RCW/WR, and 26.6 g (SE = 2.81) on WR.

Chemical composition of needles

For both planted species, the concentrations of total K, P, S, and N (essential elements that make up proteins) were significantly higher in the seedlings growing on the TS treatment than on the other treatments (Fig. 5.A).

For *P. banksiana*, the concentrations of potentially phytotoxic elements in the needles, such as Cr or As, were generally lower in the plants growing on the TS treatment than on the other treatments (not significant for As, partly significant for Cr) (Fig. 5.B). Nickel concentrations were not significantly different among the treatments. The variance of concentrations on each treatment was too large for the statistical comparison analysis to detect a possible significant difference among the treatments. Average As concentrations in the needles ranged from 2.25 to 6.43 µg/g for *A. balsamea* and from 3.73 to 17.4 µg/g for *P. banksiana*.

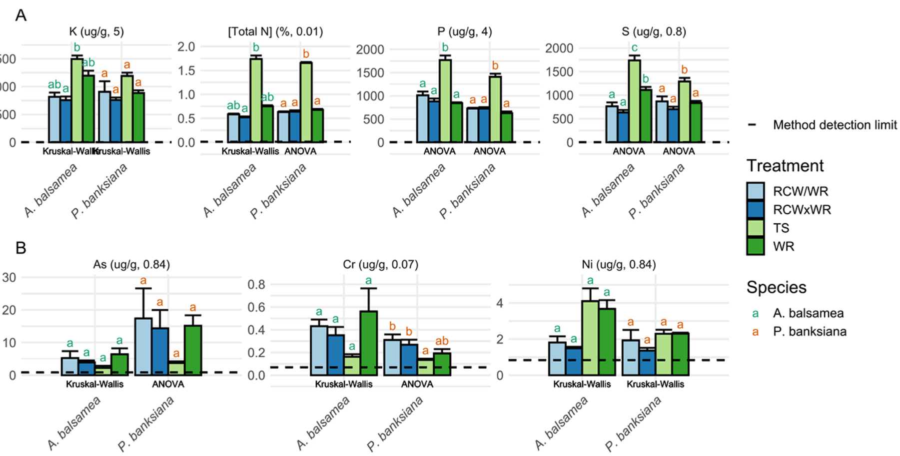

Fig. 5 Mean element concentrations in the needles of *A. balsamea* and *P. banksiana* seedlings in 2020, compared among treatments. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil. The bar charts in A present the concentrations of essential elements (macronutrients), while the bar charts in B present the concentrations of potentially phytotoxic elements. The name of the element is indicated above the bar chart. The units are specified in parentheses, as well as the method detection limit (MDL). The MDL is also represented by a dashed line. The statistical comparison test is indicated under each bar chart. The letters are the results of the post-hoc test, in blue for *A. balsamea* and in red for *P. banksiana*. Treatments that share the same letter do not differ significantly. Error bars represent standard error

Environmental variables

Microclimatic variables

Water content The average volumetric water content measured at a depth of 10 cm in the waste rock was significantly different among treatments from 2019 to 2021 (Fig. 6). In 2019, the average volumetric water content was significantly higher in the TS treatment than in the RCW/WR treatment. In 2020, the TS treatment had a significantly higher average volumetric water content than the other three treatments. In 2021, the average volumetric water content was significantly higher in the TS treatment than in the RCW/WR and WR treatments.

Water retention curve results are presented in the Supplementary Material. The number of days when the suction exceeded 100 kPa during the periods of volumetric water content measurement at a 10 cm depth were significantly different among the treatments in 2019 and 2021. In general, the TS treatment had the fewest number of days when the soil suction at a 10 cm depth was above 100 kPa.

The volumetric water content was not significantly different among the treatments at a depth of 25 cm. Average volumetric water contents at this depth in the waste rock during the measurement period (June to late September) were 12% (SE=1.64) in 2019, 14.1% (SE=2.37) in 2020, and 12.7% (SE=2.83) in 2021.

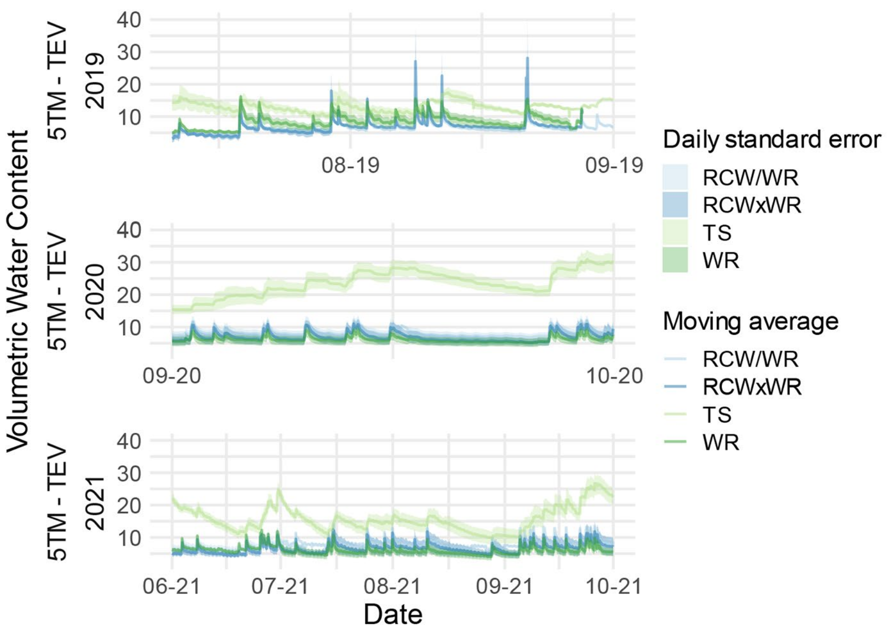

Fig. 6 Volumetric water content at a depth of 10 cm in the waste rock substrate for each treatment, measured during the growing season in 2019, 2020, and 2021. The periods correspond to those where all the measurements were of sufficient quality. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil

Temperature The mean temperature variation (difference between daily maximum and minimum temperature) at a 10 cm depth in the soil was significantly different among treatments in 2021. The difference between the daily maximum and minimum temperature was significantly lower on the TS treatment than on the other treatments in 2021 ($p<.05$). The average daily temperature differences were 7.73 °C (SE = 0.08) on WR, 6.97 °C (SE = 0.68) on RCW/WR, 7.02 °C (SE = 0.04) on RCW×WR, and 4.38 °C (SE = 0.89) on TS.

Chemical composition of mineral substrate

Nutrients The total concentration of nitrogen in the waste rock substrate was significantly higher in the TS treatment than in the other treatments. The topsoil layer contained 1.2% total N on average. The total concentration of phosphorus was significantly higher in the TS treatment than in WR only. In contrast, the K concentration in the TS treatment was significantly lower as compared to the other treatments. The concentrations of potential micronutrients (Cu, Fe, Mn, Mo, and Zn) were not necessarily different among the treatments, with the exception of Fe, which was lower in the TS treatment than in the other treatments. The average concentrations of all these elements are presented in Table 3 in the Supplementary Material.

Potentially phytotoxic elements The pH of the waste rock substrate under the TS treatment was significantly lower (slightly acidic) than the other three treatments (neutral) (Fig. 7), due to an acidic average pH of 4.5 in the topsoil layer.

The average total As concentrations in the waste rock substrates of all the treatments exceeded the regulatory thresholds (criterion C, for industrial land use) of Schedule 1 of the Land Protection and Rehabilitation Regulation (Quebec Environmental Quality Act Q-2, r.37). The average total Cr concentrations exceeded the residential regulatory thresholds (criterion B) in the waste rock substrates of the RCW/WR, RCW×WR, and WR treatments. The total Ni concentrations in the waste rock substrates of all the treatments also exceeded the residential regulatory thresholds (criterion B). Although not significant, the mean As, Cr, and Ni concentrations were lower in the TS treatment than the other three treatments. The topsoil layer showed total As concentrations (12 $\mu g.g^{-1}$ on average) below the B criterion for residential land use, but the average total Hg concentration reached 90 $ng.g^{-1}$, which is above the C criterion for industrial land use.

Colonizing plant cover

The total and specific cover of colonizing plants had no effect on seedling response. Only the TS treatment had a total cover greater than 1%, with an average value of 70.5% (SE = 4.84). No alien species were observed on any of the cells in the experimental setup (Colautti and MacIsaac 2004). The species present on the TS treatment were *Agrostis* spp., *Anaphalis* spp., *Artemisia* spp., *Cirsium* spp., *Eutamia graminifolia*, *Iris foetidissima*, *Leucanthemum vulgare*, *Linaria* spp., *Potentilla norvegica*, *Rumex* spp., *Solidago canadensis*, *Solidago* spp., *Taraxacum* spp., *Trifolium repens*, *Trifolium pratense*, and *Vicia sativa*. No woody

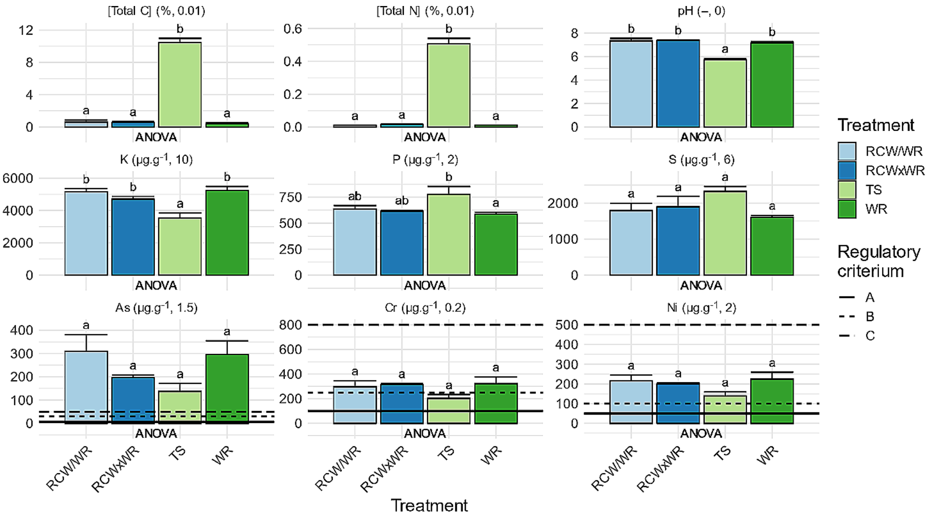

Fig. 7 Average total element concentrations in the waste rock substrate of all treatments in 2020. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil. The units are specified in parentheses, as well as the method detection limit (MDL). The Quebec regulatory criteria (A, B, and C) are represented by the different type of lines (Quebec Environmental Quality Act Q-2, r.37). The statistical comparison test is indicated under each bar chart. The letters are the results of the post-hoc test. Treatments that share the same letter do not differ significantly. Error bars represent standard error

species were observed among the colonizing plants in 2021, three years after the construction of the experimental setup.

Multivariate relationships

The microclimatic variables (volumetric water content, temperature, and number of days when the suction exceeded 100 kPa) of the substrate did not explain the dynamics of the response variables. On the other hand, after having observed several correlations between response variables and physicochemical variables of the substrate, the analysis using a multivariate linear regression model and a stepwise selection based on the Akaike criterion made it possible to determine the model comprising the explanatory variables that best explained the response of the plants.

The model that best explained the seedling responses (cumulative diameter of *A. balsamea* and average height of *P. banksiana*) contained only one explanatory variable: the total As concentration in the substrate. The bivariate linear relations of the modeled seedling responses are represented graphically in the form of scatterplot in Fig. 8. The observed number of dead seedlings for *P. banksiana* was notably lower than for *A. balsamea*. Consequently, the selected response variable for *P. banksiana* was the mean height of its seedlings in 2020. For this species, height appeared to be more impacted by arsenic concentrations than diameter. For *A. balsamea*, the cumulative diameter—defined as the sum of diameters of living seedlings on each experimental cell—was chosen as the response variable. This approach effectively highlights the combined influence of both mortality and diameter in relation to arsenic soil concentrations in 2020.

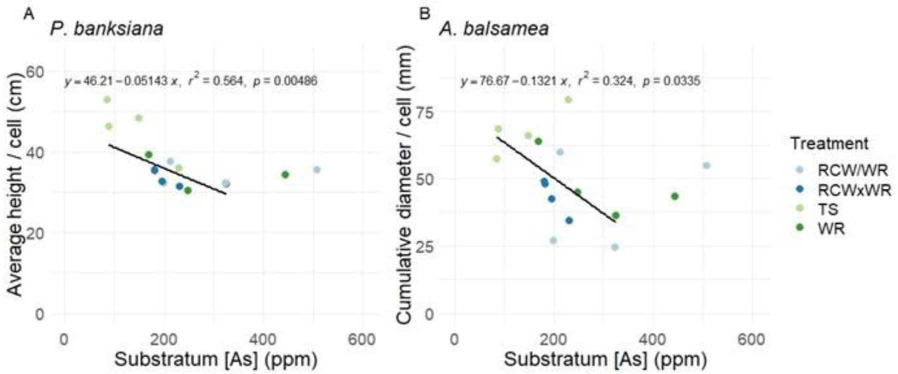

Fig. 8 Responses of the two seedling species to the total arsenic concentrations of the waste rock substratum. (A) Average height of *P. banksiana* seedlings as a linear function of the arsenic concentrations of the mineral substrate. (B) Cumulative diameter of *A. balsamea* seedlings as a linear function of the arsenic concentrations of the mineral substrate. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil

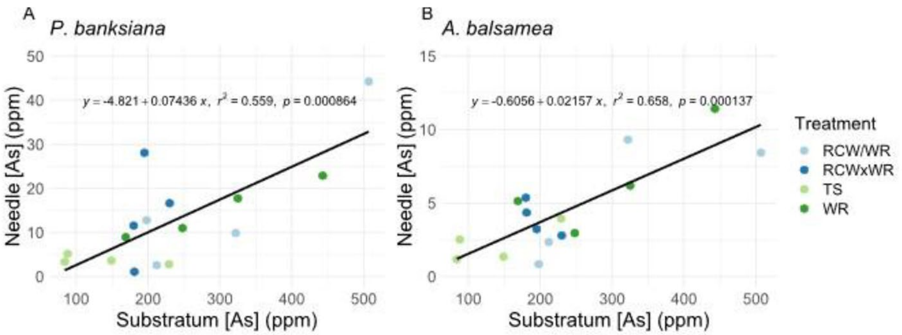

Fig. 9 Arsenic concentration in the needles of *P. banksiana* (**A**) and *A. balsamea* (**B**) seedlings in 2020 as a linear function of the total arsenic concentration in the waste rock substrate. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil

To illustrate that the total arsenic concentration in the substrate significantly influenced the morphological response of the seedlings, two scatterplots depict the relationship between the total arsenic concentration in the substrate and the arsenic concentration in the needles of coniferous seedlings (Fig. 9). Linear regressions with coefficients of determination over 0.5, combined with visible linear patterns among the data points and a gradation of arsenic concentrations, reveal clear linear relationships between these soil and plant variables.

Finally, the total phosphorus and sulfur concentrations in the waste rock substrate showed negative correlations with the total arsenic concentration in the same substrate (Pearson correlations of −0.53 and −0.55, with *p*-values of 0.04 and 0.03, respectively). The concentrations of total P and S were also correlated with the arsenic concentrations in the needles of *A. balsamea* (Pearson correlations of −0.56 and −0.64, with *p*-values of 0.03 and 0.01, respectively). Additionally, a mild negative correlation was observed between the total phosphorus concentrations in the waste rock substrate and the arsenic concentration in the needles of *P. banksiana* (Pearson correlation of − 0.5 and *p*-value of 0.048).

The biplot (Fig. 10), which illustrates the associations among the principal correlated variables, effectively projects a point cloud that is based on a reduction of the two primary components derived from the PCA. This visual representation delineates the relationships between the chemical composition of the substrate and that of the needles from the two studied species. Notably, it underscores the impact of the total As concentration in the waste rock substrate on the corresponding As concentration in the plant needles. Arsenic concentrations appeared to be independent of treatment type, although the stepwise selected model previously showed that plants growing on the TS treatment seemed to accumulate less As than on the other treatments. The figure also shows that the TS treatment was characterized by greater accumulation of nutrients (N, P, K, S) in the needles of the seedlings.

Discussion

Positive effect of topsoil layer on waste rock substrate and development of planted seedlings

In agreement with our first hypothesis, a significant supply of organic matter (10 cm-thick layer) in the form of topsoil promoted growth in aerial and root biomasses, diameter, and height, and the survival of *A. balsamea* and *P. banksiana* seedlings planted in waste rock.

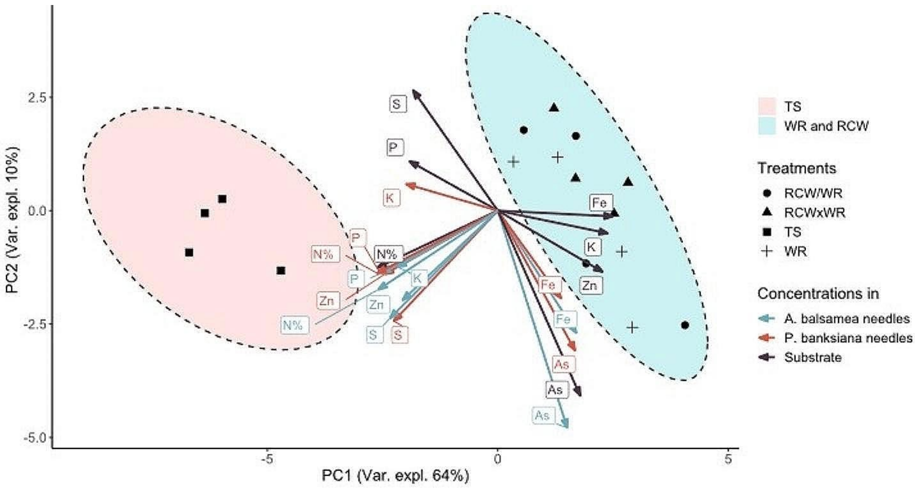

Fig. 10 PCA biplot showing the relationships between chemical variables with the strongest relationships to each other (Pearson correlation |R| > 0.5). Correlations between the element concentrations of the needles of the two species were not considered to avoid biasing the interpretation of PCA. The ellipses represent the multivariate t-distributions of two groups (TS cells and other treatment cells). The arrows represent the correlation between element concentrations in each group (*A. balsamea* needles, *P. banksiana* needles, and waste rock substrate). Finally, treatments are represented by different shapes: RCW/WR by circles, RCW×WR by triangles, TS by squares, and WR by crosses. WR: waste rock; RCW/WR: RCW over waste rock; RCW×WR: RCW mixed with waste rock; TS: topsoil. The cumulative proportion of variance explained by the graphical representation of the first two components is 74.6% (PC1: 64.4%, PC2: 10.2%)

However, the RCW-based treatments (mixed or mulch) affected neither the growth of the planted seedlings nor their survival, while the topsoil treatment had a considerable effect on these variables. As expected, *P. banksiana* suffered less than *A. balsamea* from the early successional conditions present at the experimental site, in terms of survival and growth (Asselin et al. 2001; Bergeron 2000).

At the soil level, the TS treatment had greater water retention capacity, lower pH and total concentrations of potentially phytotoxic elements, and greater soil essential nutrient concentrations (except potassium). Our hypothesis concerning the improvement of the microclimatic and physical conditions of the mineral substrate by organic matter addition is supported by the results of the volumetric water content, the number of days when the matrix pressure was higher than 100 kPa, and the soil temperature at a depth of 10 cm. These findings could be attributed to the ability of organic matter to improve soil structure, thus increasing water-holding capacity, which can support plant growth and improve overall soil health (Libohova et al. 2018; Naeth et al. 1991). However, based on the multivariate analysis, improving these conditions was not a determining factor in the survival or growth in biomass, height, or diameter of conifer seedlings.

As expected, the total concentrations of elements that can constitute macronutrients in plants were higher when a supply of already decomposed organic matter was present over the waste rock, such as topsoil. Although total element concentrations are not necessarily a good indicator of the availability of nutrients in the soil, it was noted that the total concentrations of these macronutrients were linearly related to the concentrations found in the needles of the seedlings, exwcept for K. Accordingly, the concentrations of essential elements such as P, K, S, and N were significantly higher in the needles of the planted seedlings in the topsoil treatment. This suggests that, in this case, the total concentration of essential elements found in the soil reflected the concentration bioavailable to plants. Interestingly, despite the lower concentrations of total K in the waste rock of the TS treatment, a higher concentration was observed in the seedling needles. This phenomenon could potentially be attributed to K not acting as a limiting factor within the context of this study (van der Ploeg et al. 1999). Furthermore, the concentration of K in the needle proteins may be influenced by the concentration of other constituent elements of these proteins, thus explaining the observed discrepancy.

Our results also revealed that the average pH in the TS treatment was around 5, compared to approximately 7.5 in the other treatment groups. The pH level in the TS treatment closely aligns with the optimum soil acidity range for the growth of both *P. banksiana* and *A. balsamea*, as documented in existing research. A review pointed out that *A. balsamea* grows in cooler, wet-mesic sites with acidity between 5.1 and 6.0 (Frank 1990). *P. banksiana* is adaptable to different soil conditions, including slightly acidic environments (Rudolph and Laidly 1990). Therefore, the lower pH substrate provided by the TS treatment appeared more conducive for the growth of these species when compared to the other treatments with higher pH values.

RCW mulch did not improve microclimatic and nutrient soil conditions and did not change the colonizing plant composition compared to waste rock alone. It would therefore appear that the used RCW mulch (*P. tremuloides*) at the tested dose (2 cm) did not provide a more favorable environment for seedling growth than the waste rock. Fehmi et al. (2020) showed that a thin RCW layer had no effect on soil water content but did stimulate soil microbial activity of a gravel soil (including topsoil), resulting in increased plant growth, but their experiment was conducted under arid and semi-arid conditions with conifer RCW (*Juniperus sp.*). Taurines et al. (2024) also showed that the use of a thin layer of willow RCW mulch over sand increased the abundance of *Salix* sp. and *Picea glauca* seedlings, with greater aerial biomasses of *P. glauca* compared to sand alone, however, these effects were not present over waste rock. It is possible that a greater application rate of RCW mulch would be necessary to induce seedling response on waste rock.

Arsenic in waste rock and accumulation in seedlings

The concentrations of potentially phytotoxic elements such as chromium or arsenic were generally lower in the plants growing on the TS treatment (even if not statistically significant for As). However, for Cr, the needle concentrations were far below the 5 $\mu g.g^{-1}$ concentration reported to possibly induce phytotoxicity (Kabata-Pendias 2010; Kabata-Pendias et al. 2017). The total arsenic concentrations were high in the waste rock, which constitutes the mineral growing substrate for the treatments. This is an important consideration as the mining industry increasingly exploits refractory ore deposits to extract gold, which often results in the release of a substantial proportion of arsenic (Coudert et al. 2020). Adding organic matter in the form of topsoil to the surface of the waste rock appeared to reduce the transfer of arsenic to planted seedling needles. The root volume growing in the 10 cm-thick topsoil was indeed not in direct contact with the As-bearing waste rock. Moreover, total As concentrations were lower in the waste rock under the topsoil. Recent research has shown that adding organic cover material in the form of peat with an acidic pH can decrease the concentration of arsenic in desulfurized gold mine tailings with neutral-alkaline pH by making it mobile and more leachable, especially in the form of As(III) (Rakotonimaro et al. 2021).

Total arsenic concentrations are generally not a good indicator of the availability of this element for plant uptake since it may be non-leachable and retained in gangue. However, the accumulation of As in the needles of the sampled seedlings that appeared proportional to the total As concentrations in the waste rock substrate suggests that, in this case, As was available for root uptake. In the supplementary material of a recent PhD thesis (Kalonji 2020), the author reported averaged arsenic concentrations of 0.2 mg/L in leachates from a waste rock sample originating from the same mine site. These results were obtained through column leaching tests, which suggests that arsenic may be released into the water upon contact with the waste rock (Kalonji 2020). This finding could potentially explain the uptake of arsenic by *P. banksiana* observed in our own investigation, as the arsenic may have been leached into the water and subsequently absorbed by the plants. However, it was noted that in another experimental setup on the same site, the waste rock did not contain any detectable total As (Taurines et al. 2024).

In the scientific literature, arsenic concentrations in the needles of conifers of the genus *Pinus* grown on disturbed sites never exceeded 8 ppm on average (Juranović Cindrić et al. 2018; Popovic et al. 2022; Shin et al. 2019; Wang et al. 2022; Yu et al. 2020). In natural forests (including forests adjacent to disturbed sites), the concentrations in *Pinus* spp. never exceeded 1 ppm (Juranović Cindrić et al. 2018; Shin et al. 2019). Data from this non-exhaustive literature review are presented in the Supplementary Material. In our study, the highest average arsenic concentration found in the needles was 17.4 ppm (±9.21) for

P. banksiana. Arsenic concentrations were therefore high in the needles of the seedlings in our experiment.

Arsenic phytotoxicity

The accumulation of arsenic in *A. balsamea* and *P. banksiana* needles negatively impacted their growth in diameter and height, respectively. Few research studies have focused on the phytotoxicity thresholds of arsenic on conifers of the genus *Pinus* and it is difficult to determine the effect of the concentrations attained here on the metabolism of the genus (Juranović Cindrić et al. 2018). Moreover, very few studies present information on arsenic concentrations in needles for the genus *Abies*. According to our analysis of the variables that can explain the response of conifer seedlings (diameter of *A. balsamea* and height of *P. banksiana*), the growth-limiting factor seemed to be the presence of high arsenic concentrations in the waste rock.

In agreement with recent research on the bioavailability of arsenic in contaminated agricultural soils in India (Singh and Srivastava 2020), the higher total P and S concentrations found in the waste rock of the TS treatment could be concomitant with a decrease in the bioavailability of arsenic for the plants. The authors of that study identified that an increase in the availability of phosphorus in the soil was correlated with a decrease in the bioavailability of arsenic, because phosphorus and arsenic compete for sorption sites in the soil (Singh and Srivastava 2020). They also found that the arsenic concentrations in the soil decreased with the sulfur concentrations. Sulfur and arsenic have similar and often interconnected biogeochemical cycles (Singh and Srivastava 2020).

When conducting revegetation work in waste rock including soil improvement techniques with organic matter addition, it is recommended that the speciation of As and its available concentration to plants be considered. Topsoil application, especially if it contains available phosphorus, can effectively improve the physicochemical growing conditions for *P. banksiana* and *A. balsamea* on waste rock, potentially reducing certain phytotoxicity risks to some extent.

Conclusion

This study demonstrated that the addition of organic matter in the form of topsoil to coarse mineral substrates on mine sites can enhance the growth and survival of conifer seedlings such as *A. balsamea* and *P. banksiana*, resulting in improved access to water and nutrients from the substrate. However, mulched or mixed aspen RCW treatments had no effect on seedling growth after three years of follow-up. RCW also did not have a major impact on improving the physicochemical and microclimatic conditions of the substrate favorable to the growth of the two species. Moreover, the results suggested that high concentrations of arsenic in gold mine waste rock may be an important factor limiting the growth of conifer seedlings. Further research should be conducted to explore the potential of organic matter-based treatments and phosphorus fertilization for improving the revegetation of arsenic-bearing gold mine waste rock. The development of substrate quality indicators reflecting As availability to planted seedlings should also be investigated to anticipate a possible decrease of afforestation success for mine sites in the longer term.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11056-024-10055-9.

Acknowledgements We acknowledge the financial support from Mitacs, Agnico Eagle Mines Limited and the Research Institute on Mines and the Environment (RIME-UQAT-Polytechnique). We thank the Centre d'Étude de la Forêt (CEF) and Natural Resources Canada, as well as the laboratory facilities at the Research Institute on Mines and the Environment (RIME-UQAT). We are grateful to our research team, colleagues, participants, and supporters for their valuable contributions. We thank J. Jamieson-Hanes for English editing of the manuscript.

Author contributions S.T., M.G., and A.S. designed the experiment and obtained funding. S.T. achieved data curation, formal analysis, investigation, validation, visualization, and wrote the original draft of the article. M.G. administrated and supervised the project. All authors reviewed and edited the manuscript.

Data availability Data can be provided upon reasonable request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

References

Anderson JD, Ingram LJ, Stahl PD (2008) Influence of reclamation management practices on microbial biomass carbon and soil organic carbon accumulation in semiarid mined lands of Wyoming [Article]. Appl Soil Ecol 40(2):387–397. https://doi.org/10.1016/j.apsoil.2008.06.008

Asselin H, Fortin M-J, Bergeron Y (2001) Spatial distribution of late-successional coniferous species regeneration following disturbance in southwestern Québec boreal forest. For Ecol Manag 140(1):29–37. https://doi.org/10.1016/s0378-1127(00)00273-5

ASTM (2022) *E3340-22: Standard Guide for Development of Laser Diffraction Particle Size Analysis Methods for Powder Materials*

ASTM (2020) *D2487-17e1: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*

ASTM (2007) *D854-06: Standard test method for specific gravity of soil solids by water pycnometer: annual book of ASTM standards*

Babi K, Guittonny M, Larocque GR, Bussière B (2018) Effects of spacing and herbaceous hydroseeding on water stress exposure and root development of poplars planted in soil-covered waste rock slopes. Écoscience 26(2):149–163. https://doi.org/10.1080/11956860.2018.1538591

Barthes BG, Manlay RJ, Porte O (2010) Effects of ramial wood amendments on crops and soil: a synthesis of experimental results. Cahiers Agricultures 19(4):280–287. https://doi.org/10.1684/agr.2010.0412

Barton CD, Sweigard RJ, Marx D, Barton W (2008) Evaluating spoil amendment use and mycorrhizal inoculation on reforestation success in the eastern and western kentucky coalfields. In. 25th Annual Meetings of the American Society of Mining and Reclamation and 10th Meeting of IALR 2008. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84865433667&doi=10.21000%2fjasmr08010098&partnerID=40&md5=dc206ff16e4420ca3db561440b9b730f

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting Linear mixed-effects models using lme4. J Stat Softw 67(1):1–48. https://doi.org/10.18637/jss.v067.i01

Benjamini Y, Yekutieli D (2001) The control of the false discovery rate in multiple testing under dependency. Ann Stat, 1165–1188

Bergeron Y (2000) Species and stand Dynamics in the mixed Woods of Quebec's Southern Boreal Forest. Ecology 81(6):1500–1516. https://doi.org/10.1890/0012-9658(2000)081[1500:Sasdit]2.0.Co;2

Bian Z, Miao X, Lei S, Chen SE, Wang W, Struthers S (2012) The challenges of reusing mining and mineral-processing wastes. Science 337(6095):702–703. https://doi.org/10.1126/science.1224757

Boldt-Burisch K, Naeth MA (2017) Early colonization of root associated fungal communities on reclamation substrates at a diamond mine in the Canadian sub-arctic. Appl Soil Ecol 110:118–126. https://doi.org/10.1016/j.apsoil.2016.10.006

Bonnet P, Joly A, Goëau H, Champ J, Vignau C, Molino J-F, Barthélémy D, Boujemaa N (2015) Plant identification: man vs. machine. Multimedia Tools Appl 75(3):1647–1665. https://doi.org/10.1007/s11042-015-2607-4

Bouchard H, Guittonny M, Brais S (2018) Early recruitment of boreal forest trees in hybrid poplar plantations of different densities on mine waste rock slopes. For Ecol Manag 429:520–533. https://doi.org/10.1016/j.foreco.2018.07.003

Bradshaw AD (1992) The biology of land restoration. In S. K. Jain et L. W. Botsford (dir.), *Applied Population Biology* (pp. 25–44). Springer Netherlands. https://doi.org/10.1007/978-0-585-32911-6_2

Brevik EC, Lazari AG (2014) Rates of Pedogenesis in Reclaimed lands as compared to Rates of Natural Pedogenesis. Soil Horizons 55(1). https://doi.org/10.2136/sh13-06-0017. sh13-06-0017

Bussière B, Guittonny M (2020) Hard rock mine reclamation: from prediction to management of acid mine drainage. CRC

Campbell DJ (1994) Determination and Use of Soil Bulk Density in Relation to Soil Compaction. In B. D. Soane et C. van Ouwerkerk (dir.), *Soil Compaction in Crop Production* (vol. 11, pp. 113–139). Elsevier. https://doi.org/10.1016/b978-0-444-88286-8.50014-3

Chapuis RP, Masse I, Madinier B, Aubertin M (2007) A drainage column test for determining unsaturated properties of coarse materials. Geotech Test J 30(2):83–89. https://doi.org/10.1520/GTJ100385

Charnock NR, Grant CD (2005) Assessing various rehabilitation strategies for coarse coal washery reject dumps in the Hunter Valley, Australia. I. Chemical characteristics. Int J Surf Min Reclam Environ 19(2):108–131. https://doi.org/10.1080/13895260500158077

Chen HY, Popadiouk RV (2002) Dynamics of North American boreal mixedwoods. Environ Reviews 10(3):137–166. https://doi.org/10.1139/a02-007

Chrosciewicz Z (1974) Evaluation of fire-produced seedbeds for Jack Pine Regeneration in Central Ontario. Can J for Res 4(4):455–457. https://doi.org/10.1139/x74-067

Chrosciewicz Z (1990) Site conditions for Jack Pine Seeding. Forestry Chron 66(6):579–584. https://doi.org/10.5558/tfc66579-6

Colautti RI, MacIsaac HJ (2004) A neutral terminology to define 'invasive' species. Divers Distrib 10(2):135–141. https://doi.org/10.1111/j.1366-9516.2004.00061.x

Coudert L, Bondu R, Rakotonimaro TV, Rosa E, Guittonny M, Neculita CM (2020) Treatment of As-rich mine effluents and produced residues stability: current knowledge and research priorities for gold mining. J Hazard Mater 386:121920. https://doi.org/10.1016/j.jhazmat.2019.121920

De Marco PJ, Nobrega CC (2018) Evaluating collinearity effects on species distribution models: an approach based on virtual species simulation. PLoS ONE 13(9):e0202403. https://doi.org/10.1371/journal.pone.0202403

Drozdowski BL, Anne Naeth M, Wilkinson SR (2012) Evaluation of substrate and amendment materials for soil reclamation at a diamond mine in the Northwest territories, Canada. Can J Soil Sci 92(1):77–88. https://doi.org/10.4141/cjss2011-029

Dunn OJ (1961) Multiple comparisons among means. J Am Stat Assoc 56(293):52–64. https://doi.org/10.1080/01621459.1961.10482090

Dunn OJ (1964) Multiple comparisons using rank sums. Technometrics 6(3):241–252. https://doi.org/10.1080/00401706.1964.10490181

U.S.EPA (2007) *Method 3051A (SW-846): Microwave Assisted Acid Digestion of Sediments, Sludges, Soils, and Oils*

Fehmi JS, Rasmussen C, Gallery RE (2020) Biochar and woodchip amendments alter restoration outcomes, microbial processes, and soil moisture in a simulated semi-arid ecosystem. Restor Ecol 28(4):S355–S364. https://doi.org/10.1111/rec.13100

Fortin Faubert M, Hijri M, Labrecque M (2021) Short rotation Intensive Culture of Willow, spent mushroom substrate and Ramial Chipped Wood for Bioremediation of a contaminated site used for Land Farming activities of a former Petrochemical Plant. Plants 10(3). https://doi.org/10.3390/plants10030520. article

Fox J, Monette G (1992) Generalized collinearity diagnostics. J Am Stat Assoc 87(417):178–183. https://doi.org/10.1080/01621459.1992.10475190

Fox J, Weisberg S (2018) An R companion to applied regression. Sage

Frank RM (1990) Abies balsamea (L.) Mill. balsam fir. In *Silvics of North America* (vol. 1, pp. 26–35)

Gagnon A, Fenton NJ, Sirois P, Boucher J-F (2021) Plant Community Diversity at Two Reclaimed Mine Tailing Storage Facilities in Québec, Canada. Land 10(11). https://doi.org/10.3390/land10111191

Gastauer M, Silva JR, Junior C, Ramos CF, Souza Filho SJ, Furtini Neto PWM, A.E. and, Siqueira JO (2018) Mine land rehabilitation: modern ecological approaches for more sustainable mining. J Clean Prod 172:1409–1422. https://doi.org/10.1016/j.jclepro.2017.10.223

Germain D, Eng P (2007) *Ramial chipped wood: the clue to a sustainable fertile soil*

Gómez-Aparicio L (2009) The role of plant interactions in the restoration of degraded ecosystems: a meta-analysis across life-forms and ecosystems. J Ecol 97(6):1202–1214. https://doi.org/10.1111/j.1365-2745.2009.01573.x

Hollander M, Wolfe DA, Chicken E (2013) Nonparametric statistical methods. Wiley

Hothorn T, Bretz F, Westfall P (2008) Simultaneous inference in general parametric models. Biom J 50(3):346–363. https://doi.org/10.1002/bimj.200810425

Huebner L, Al-Quraishi F, Branch AM, O. and, Gaznayee HAA (2022) New approaches: use of assisted natural succession in revegetation of inhabited arid drylands as alternative to large-scale afforestation. SN Appl Sci 4(3):80. https://doi.org/10.1007/s42452-022-04951-y

Hugron S, Andersen R, Poulin M, Rochefort L (2011) Natural plant colonization of borrow pits in boreal forest highlands of eastern Canada. Botany 89(7):451–465. https://doi.org/10.1139/b11-036

Juranović Cindrić I, Zeiner M, Starčević A, Stingeder G (2018) Metals in pine needles: characterisation of bio-indicators depending on species. Int J Environ Sci Technol 16(8):4339–4346. https://doi.org/10.1007/s13762-018-2096-x

Kabata-Pendias A (2010) *Trace Elements in Soils and Plants* (4th[th] ed.). https://doi.org/10.1201/b10158

Kabata-Pendias A, Dudka S, Chlopecka A (2017) Background levels and environmental influences on trace metals in soils of the temperate humid zone of Europe. Biogeochemistry of trace metals. CRC, pp 73–96

Kalonji AK (2020) *Évaluation du comportement hydrogéologique et géochimique de recouvrements faits de matériaux miniers pour contrôler la contamination provenant de résidus miniers fortement réactifs* [PhD Thesis, Polytechnique Montréal]. https://publications.polymtl.ca/5488/

Kassambara A (2023) rstatix: Pipe-friendly framework for basic statistical tests (version 0.7.2) [R package]. https://rpkgs.datanovia.com/rstatix/

Keenan RJ, Kimmins JP (1993) The ecological effects of clear-cutting. Environ Reviews 1(2):121–144. https://doi.org/10.1139/a93-010

Kneller T, Harris RJ, Bateman A, Muñoz-Rojas M (2018) Native-plant amendments and topsoil addition enhance soil function in post-mining arid grasslands. Sci Total Environ 621:744–752

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest Package: tests in Linear mixed effects models. J Stat Softw 82(13):1–26. https://doi.org/10.18637/jss.v082.i13

Lal R (2001) Soil degradation by erosion. Land Degrad Dev 12(6):519–539. https://doi.org/10.1002/ldr.472

Lal R (2020) Soil organic matter and water retention. Agron J 112(5):3265–3277. https://doi.org/10.1002/agj2.20282

Larcheveque M, Desrochers A, Bussiere B, Cartier H, David JS (2013) Revegetation of non-acid-generating, thickened tailings with boreal trees: a greenhouse study. J Environ Qual 42(2):351–360. https://doi.org/10.2134/jeq2012.0111

Larchevêque M, Desrochers A, Bussière B, Cimon D (2015) Planting trees in soils above non-acid-generating wastes of a boreal gold mine. Écoscience 21(3–4):217–231. https://doi.org/10.2980/21-(3-4)-3697

Lemieux G, Germain D, Environnement H (2000) Ramial Chipped Wood: the Clue to a sustainable fertile soil. Laval University, Coordination Group on Ramial Wood

Lenth RV, Bolker B, Buerkner P, Giné-Vázquez I, Herve M, Jung M, Love J, Miguez F, Riebl H, Singmann H (2023) emmeans: Estimated Marginal Means, aka Least-Squares Means (version 1.8.9) [R package]. https://cran.r-project.org/web/packages/emmeans/index.html

Libohova Z, Seybold C, Wysocki D, Wills S, Schoeneberger P, Williams C, Lindbo D, Stott D, Owens PR (2018) Reevaluating the effects of soil organic matter and other properties on available water-holding capacity using the National Cooperative Soil Survey characterization database. J Soil Water Conserv 73(4):411–421. https://doi.org/10.2489/jswc.73.4.411

Macdonald SE, Landhäusser SM, Skousen J, Franklin J, Frouz J, Hall S, Jacobs DF, Quideau S (2015) Forest restoration following surface mining disturbance: challenges and solutions. New Forest 46(5–6):703–732. https://doi.org/10.1007/s11056-015-9506-4

Maiti SK, Bandyopadhyay S, Mukhopadhyay S (2021) Importance of selection of plant species for successful ecological restoration program in coal mine degraded land. In K. Bauddh, J. Korstad et P. Sharma (dir.), *Phytorestoration of Abandoned Mining and Oil Drilling Sites* (pp. 325–357). Elsevier. https://doi.org/10.1016/b978-0-12-821200-4.00014-5

Naeth M, Bailey A, Chanasyk D, Pluth D (1991) Water holding capacity of litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta. J Range Manag 44(1):13–17. https://doi.org/10.2307/4002630

Peralta-Videa JR, Lopez ML, Narayan M, Saupe G, Gardea-Torresdey J (2009) The biochemistry of environmental heavy metal uptake by plants: implications for the food chain. Int J Biochem Cell Biol 41(8–9):1665–1677. https://doi.org/10.1016/j.biocel.2009.03.005

Popovic V, Seslija Jovanovic D, Miletic Z, Milovanovic J, Lucic A, Rakonjac L, Miljkovic D (2022) The evaluation of hazardous element content in the needles of the Norway spruce (Picea abies L.) that originated from anthropogenic activities in the vicinity of the native habitats. Environ Monit Assess 195(1):109. https://doi.org/10.1007/s10661-022-10732-2

Prach K, Hobbs RJ (2008) Spontaneous succession versus Technical Reclamation in the Restoration of Disturbed sites. Restor Ecol 16(3):363–366. https://doi.org/10.1111/j.1526-100X.2008.00412.x

Prach K, Bartha S, Joyce CB, Pyšek P, Diggelen R, Wiegleb G (2001) The role of spontaneous vegetation succession in ecosystem restoration: a perspective. Appl Veg Sci 4(1):111–114. https://doi.org/10.1111/j.1654-109X.2001.tb00241.x

Québec Gd (2010) *Normales climatiques du Québec 1981–2010 - Station Mont-Brun (Abitibi-Témiscamingue)*. https://environnement.gouv.qc.ca/climat/normales/sommaire.asp?cle=7085106

Québec Gd (2019) *Forêt Ouverte*. https://www.foretouverte.gouv.qc.ca/

R. (2023) R: A Language and Environment for Statistical Computing (version 4.3.1 Beagle Scouts). R Foundation for Statistical Computing. https://www.R-project.org/

Rakotonimaro TV, Guittony M, Neculita CM (2021) Compaction of peat cover over desulfurized gold mine tailings changes: Arsenic speciation and mobility. Appl Geochem 128:104923. https://doi.org/10.1016/j.apgeochem.2021.104923

Rudolph T, Laidly P (1990) Pinus banksiana Lamb. Jack pine. Silvics North Am 1:280–293

Rupert Jr G (2012) *Simultaneous statistical inference*

Sakamoto Y, Ishiguro M, Kitagawa G (1986) *Akaike information criterion statistics* (vol. 81)

Salmerón R, García C, García J (2018) Variance inflation factor and condition number in multiple linear regression. J Stat Comput Simul 88(12):2365–2384. https://doi.org/10.1080/00949655.2018.1463376

Shin JH, Yu J, Wang L, Kim J, Koh S-M (2019) Investigation of Spectral Variation of Pine needles as an Indicator of Arsenic Content in Soils. Minerals 9(8):article. https://doi.org/10.3390/min9080498

Singh SB, Srivastava PK (2020) Bioavailability of arsenic in agricultural soils under the influence of different soil properties. SN Appl Sci 2(2):153. https://doi.org/10.1007/s42452-019-1932-z

Singh AN, Raghubanshi AS, Singh JS (2002) Plantations as a tool for mine spoil restoration. Curr Sci 82(12):1436–1441. http://www.jstor.org/stable/24106177

Soumare M, Mnkeni P, Khouma M (2004) Effects of ramial chipped wood and litter compost of Casuarina equisetifolia tomato growth and soil properties in Niayes, Senegal. Biol Agric Hortic 385. https://doi.org/10.1080/01448765.2002.9754955

Taurines S (2019) *Utilisation de bois raméal fragmenté pour faciliter la colonisation naturelle de stériles miniers par des essences boréales* [MSc thesis, Université du Québec en Abitibi-Témiscamingue]. https://depositum.uqat.ca/id/eprint/805

Taurines S, Guittonny M, Séguin A (2024) Facilitating early boreal forest succession on waste rock using Ramial Chipped Wood mulch: a five-year study. For Ecol Manag 561:121860. https://doi.org/10.1016/j.foreco.2024.121860

Tongway DJ, Ludwig JA (2011) Restoration of Mine-Site Waste-Rock Dumps. In D. J. Tongway et J. A. Ludwig (dir.), *Restoring Disturbed Landscapes* (pp. 65–73). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-007-1_6

van der Ploeg RR, Böhm W, Kirkham MB (1999) On the origin of the theory of Mineral Nutrition of Plants and the Law of the Minimum. Soil Sci Soc Am J 63(5):1055–1062. https://doi.org/10.2136/sssaj1999.6351055x

Venables W, Ripley B (2002) Exploratory multivariate analysis. In *Modern applied statistics with S* (pp. 301–330)

Wang S, Mulligan CN (2009) Effect of natural organic matter on arsenic mobilization from mine tailings. J Hazard Mater 168(2–3):721–726. https://doi.org/10.1016/j.jhazmat.2009.02.088

Wang J, Huang Y, Beiyuan J, Wei X, Qi J, Wang L, Fang F, Liu J, Cao J, Xiao T (2022) Thallium and potentially toxic elements distribution in pine needles, tree rings and soils around a pyrite mine and indication for environmental pollution. Sci Total Environ 828:154346. https://doi.org/10.1016/j.scitotenv.2022.154346

Weber MG, Wagner CEV, Hummel M (1987) Selected parameters of Fire Behavior and Pinus banksiana Lamb. Regeneration in Eastern Ontario. Forestry Chron 63(5):340–346. https://doi.org/10.5558/tfc63340-5

Wessman CA, Aber JD, Peterson DL, Melillo JM (1988) Remote sensing of canopy chemistry and nitrogen cycling in temperate forest ecosystems. Nature 335(6186):154–156. https://doi.org/10.1038/335154a0

Wickham H, Averick M, Bryan J, Chang W, McGowan LDA, François R, Grolemund G, Hayes A, Henry L, Hester J (2019) Welcome to the Tidyverse. J open Source Softw 4(43):1686. https://doi.org/10.21105/joss.01686

Yu P, Sun Y, Huang Z, Zhu F, Sun Y, Jiang L (2020) The effects of ectomycorrhizal fungi on heavy metals' transport in Pinus massoniana and bacteria community in rhizosphere soil in mine tailing area. J Hazard Mater 381:121203. https://doi.org/10.1016/j.jhazmat.2019.121203