Environmental Earth Sciences (2020) 79:422
https://doi.org/10.1007/s12665-020-09154-5

ORIGINAL ARTICLE

Addition of recyclable biochar, compost and fibre clay to the growth medium layer for the cover system of mine tailings: a bioassay in a greenhouse

Juha Heiskanen[1] · Marleena Hagner[2,3] · Hanna Ruhanen[4] · Kari Mäkitalo[5]

Received: 23 August 2019 / Accepted: 27 August 2020 / Published online: 15 September 2020

Abstract
Mine closures require landscape reclamation to reduce the environmental risks of tailings fields. However, information about the feasibility of recyclable waste materials as a growth medium layer for the cover systems of mine tailings and their effects on vegetation restoration and reforestation success is scant especially in the boreal climate. This study examines the use of various recyclable by-products in improving vegetation success on reclaimed mine tailings. The physical and chemical properties of two wood biochar types, fibre clay, compost, tailings soil and forest till soil as well as their effects as growth media on the growth of several plant species during one growing period in a greenhouse were examined. Marked differences in the properties (e.g. pH, element concentrations, water retention) as well as in plant growth among the growth media were found. Fresh non-oxidized tailings soil showed high salt contents and electrical conductivity which together with fine soil texture provided the poorest or nonexistent plant growth. Fibre clay was the coarsest and driest material and also showed poor plant growth. Root and shoot growth was greatest in pure compost. All media without compost additive showed relatively poor growth which indicates the lack of nitrogen. The results suggest that forest till soil and biochar are the most suitable growth media for the cover systems of mine tailings when added with compost or another nitrogen source. Scots pine container seedlings, willow cuttings and sown red clover showed to be the most feasible plant species to be grown on boreal tailings covers.

Keywords Land reclamation · Mine closure · Recyclates · Reforestation · Soil · Vegetation restoration

Introduction

After post ore-extracting activities, mine closures require landscape reclamation to reduce the environmental risks of tailings fields. As tailings fields store large amounts of mining waste, they can pose threats to the environment such as uncontrolled spills of tailings or the release of hazardous substances. In Europe, such devastating effects on humans and the environment have been seen following past accidents such as the aluminium sludge spill in Kolontar, Hungary, in 2010 (Thorpe 2010) or the accident at the Talvivaara Mining Company in Finland in 2012 (Kotilainen 2015; Leppänen et al. 2017).

Typically mine tailings are covered with low-permeability materials to prevent sulphide oxidation and minimize outflow of harmful effluents from reactive mine wastes into the surrounding environment (O'Kane and Wels 2003; MEND 2012; Kauppila et al. 2013). Commonly the most hazardous wastes are covered with geosynthetic clay liners (GCLs) to

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12665-020-09154-5) contains supplementary material, which is available to authorized users.

✉ Juha Heiskanen
juha.heiskanen@luke.fi

1 Natural Resources Institute Finland (Luke), Soil Ecosystems, Neulaniementie 5, 70150 Kuopio, Finland

2 Natural Resources Institute Finland (Luke), Plant Health, Tietotie 2C, 31600 Jokioinen, Finland

3 Ecosystems and Environment Research Programme, Faculty of Biological and Environmental Sciences, University of Helsinki, 15140 Lahti, Finland

4 Natural Resources Institute Finland (Luke), Experiment and Data Services, Juntintie 154, 77600 Suonenjoki, Finland

5 Natural Resources Institute Finland (Luke), Forest Management, Ounasjoentie 6, 96200 Rovaniemi, Finland

limit the oxygen flow through the cover layer into the waste material and to increase the alkalinity of the leaching water (Bouazza and Rahman 2007; Lange et al. 2010). As bentonite clay has to be imported to Northern Europe, there is a need to develop cheaper local materials and practices for tailings covers.

For a successful reclamation of abandoned mine sites effective revegetation is also required, in which the soil fertility is often the determining factor (Redente et al. 1997; Sydnor and Redente 2002; Dere et al. 2011). A good cover provides a growth medium for plants, retains water, prevents wind and water erosion, increases evapotranspiration and reduces oxygen flow to mine waste layers and oxidation of sulphide minerals (Tordoff et al. 2000; O'Kane and Wels 2003; Lottermoser 2007; INAP 2009; MEND 2012). In the long run, growing vegetation modifies microclimate and provides a source of carbon (C) to the soil profile thereby increasing the likelihood of natural vegetation succession. However, unfavourable substrate structure and nutrient composition require commonly soil amendments for successful vegetation restoration (Anawar et al. 2015).

There is a global augmentative need for recycling increasing amounts of organic by-products and wastes from households, energy plants and industries. Many of the recyclable waste materials, such as biochar (Bc), composted sewage sludge and waste paper sludge (fibre clay) have been suggested and are increasingly being used for landscaping, soil improvement and carbon sequestration (Méndez et al. 2015; Ali et al. 2017). Economic and ecological pressures have also led to the utilization of waste materials as growth media in horticulture (Kern et al. 2017). Recently, various waste materials have been tested and used in highly degraded lands and also in landscaping of mine reclamation areas (Fellet et al. 2011; Gwenzi et al. 2015; Peltz and Harley 2016). For instance, Bc addition into degraded soils has been indicated to improve soil fertility by supplying and retaining nutrients and water for plant growth and by improving physical, chemical and biological properties of the soil (Glaser et al. 2002; Lehmann et al. 2003; Verheijen et al. 2010; Arif et al. 2017). However, further research is required on the potential of Bc and other recyclable waste materials in reclamation and revegetation of mine tailings. Information about the feasibility of various recyclable waste materials as a growth medium layer for the cover systems of mine tailings and their effects on vegetation restoration and reforestation success is scarce especially in the boreal zone having a cool climate, a short growing season and limit vegetation growth.

The aim of this preliminary study was to examine the properties of various recyclable organic by-product and waste materials which are locally available and have potential to be used as cover material on Northern Finnish mine waste areas. In addition, the feasibility of the materials as growth media for vegetation restoration was evaluated. Thus, we examined the physical and chemical properties of two biochar (Bc) types (from wood of Norway spruce [*Picea abies* L. Karst.] and common silver birch [*Betula pendula* Roth], fibre clay (dried waste paper sludge), compost and forest till soil as well as their effects as growth media in varying mixing proportions on plant growth. Tailings soil was also examined as a control medium as such and mixed with other amendments. Some of the most typical northern Scandinavian forest plant species were tested during one growing period in a greenhouse: Scots pine [*Pinus sylvestris* L.] container seedlings, dark-leaved willow [*Salix myrsinifolia* Salisb.] cuttings and sowed red clover [*Trifolium pratense* L.], red fescue [*Festuca rubra* L.] and maiden pink [*Dianthus deltoides* L.].

Materials and methods

Media description

Tailings soils were dug in summer 2017 from the tailings field at the Rautuvaara iron enrichment plant (Kolari, Northern Finland 67°29′43.9″ N, 23°55′17.3″ E, mean yearly temperature 0.3 °C and precipitation 450–550 mm). The upper part (about 20 cm thick) of the soil was brownish and oxidized (Ta1), and the lower part grey and non-oxidized (Ta0). The forest till soil (Ti), which is commonly used in tailings covers, was dug from forest soil nearby the tailings field.

Biochars used in the experiments were received from RPK Hiili Oy (Mikkeli, Finland). The first biochar type (Bc1) was made from Norway spruce wood (porosity ca. 1.6 $cm^3\ g^{-1}$) and second (Bc2) from common silver birch wood (porosity ca. 1.1 $cm^3\ g^{-1}$). Due to the delivery difficulties the used biochar types in plant growing experiments 1 (Bc1a and Bc2a) and 2 (Bc2a and Bc2b) were obtained from different batches and has thus various physical characteristics (particle size distribution and specific surface area) (Table 1). Instead, due to the similar feedstock materials and process conditions the chemical characteristics were similar between batches (Tables 2, 3).

The used fibre clay type (FC) was light, dried fibre sludge from the effluent treatment plant of a paper mill (Stora Enso Oyj, Veitsiluoto, Finland). The paper mill produces fibre clay 35,000–40,000 t (in fresh mass) annually. The fibre clay contains mainly clay, filling ingredients and a slight amount of wood fibres (dry matter 50–55%). The filling substances are mainly calcium carbonate and less kaolin and talc (Finncao 2001; Niutanen and Korhonen 2002; Raivio 2013). The used compost (Co) was sewage sludge composted with peat, wood chips and sand (Levin vesihuolto Oy; Sirkka, Finland; Evira acceptance code FIC009-05135/2008NA).

Table 1 Growth media used in Exp. 1

Nr.	Medium (18 cm thick)	Code	Composition, vol. %	Legend
1	Tailings, non-oxidized	Ta0	100	Lower soil layer of tailings field at Rautuvaara
2	Tailings, oxidized	Ta1	100	Upper soil layer of tailings field at Rautuvaara
3	Till soil	Ti	100	Forest soil nearby Rautuvaara
4	Biochar1	Bc1	100	From Norway spruce by RPK Hiili Oy
5	Biochar1–till	Bc1–Ti	50 + 50	
6	Biochar1–compost	Bc1–Co	80 + 20	
7	Biochar1–fibre clay	Bc1–FC	50 + 50	
8	Biochar1–Biochar2	Bc1–Bc2	50 + 50	
9	Biochar2	Bc2	100	From silver birch by RPK Hiili Oy
10	Biochar2–till	Bc2–Ti	50 + 50	
11	Biochar2–compost	Bc2–Co	80 + 20	
12	Biochar2–fibre clay	Bc2–FC	50 + 50	
13	Compost	Co	100	Composted sewage sludge by Levin vesihuolto Oy
14	Till–compost	Ti–Co	80 + 20	
15	Fibre clay–compost	FC–Co	80 + 20	
16	Fibre clay	FC	100	Dried fibre sludge by Stora Enso Oyj, Veitsiluoto
17	Fibre clay–till	FC–Ti	50 + 50	

Table 2 Growth media used in Exp. 2 (proportions in vol%). The media of Bc1 and Bc2 are from different batches and are of different particle size than in Exp. 1

Nr	Ti	Bc1	Co	Nr	Ti	Bc2	Co	Nr	Ti	FC	Co
1	100	0	0								
2	90	10	0	**8**	90	10	0	**13**	90	10	0
3	80	0	20								
4	60	20	20	**9**	60	20	20	**14**	60	20	20
5	40	40	20	**10**	40	40	20	**15**	40	40	20
6	20	60	20	**11**	20	60	20	**16**	20	60	20
7	0	80	20	**12**	0	80	20	**17**	0	80	20

Bold values represent the number of different media

Table 3 Mean particle size distribution of the studied growth media (proportions in DM percentages from dry sieving; $n = 3$)

Fraction	Experiment 1							Experiment 2			
mm	Ta1	Ta0	Bc1	Bc2	Ti	Co	FC	Bc1	Bc2	Co	FC
> 20	0.0	0.0	0.0	0.0	0.0	1.0	14.9	4.5	0.0	1.3	14.9
10–20	0.0	0.2	1.6	2.4	3.7	10.9	51.0	24.9	4.2	22.2	42.5
5–10	0.6	2.7	7.9	36.6	5.9	21.1	25.0	22.2	29.3	25.0	29.1
2–5	1.7	4.7	39.9	33.9	11.8	27.1	8.3	20.7	30.1	30.8	12.3
0.6–2	2.4	3.7	22.6	13.5	22.8	26.9	0.7	13.7	20.3	17.9	1.1
0.2–0.6	8.2	4.2	7.5	7.5	26.1	10.5	0.1	4.6	9.8	2.5	0.0
0.06–0.2	59.9	58.6	6.0	4.2	23.5	2.4	0.1	3.5	5.0	0.2	0.0
< 0.06	27.2	25.9	14.5	1.9	6.2	0.1	0.0	5.8	1.3	0.0	0.0

Physical analyses

The particle size distribution for individual media components was measured ($n = 3$) using dry sieving with a series of sieves (from 20 to 0.06 mm). The bulk density (Db) was determined as the ratio of dry mass (dried at 105 °C) to near-saturated volume ($n = 3$). The particle density (Ds) was estimated using an average density of 2.65 g cm^{-3} for mineral and 1.5 g cm^{-3} for organic components. Loss-on-ignition at 550 °C for 2 h provided an approximate estimate of the organic matter for each medium ($n = 3$). The total porosity (TP) was estimated as ((Ds − Db)/Ds) * 100.

Desorption water retention characteristics of the media were measured as water content (WC) at decreasing matric potentials using a pressure plate apparatus (Soilmoisture Equipment Corp., Santa Barbara, CA, USA) and standard methods (Klute 1986; Dumroese et al. 2011). Metal cylinders (height 60 mm, diameter 58 mm) were filled with each media, saturated, allowed to drain freely (to about − 0.3 kPa), and then exposed to successive matric potentials from − 1 to − 100 ($n=3$). WC at wilting point potential (− 1500 kPa) was measured from parallel loose samples. Saturated hydraulic conductivity was measured by applying the constant-head method ($n=3$) (Klute 1986; Dumroese et al. 2011).

Specific surface areas of biochars were analysed. Samples (200 mg) were pretreated at low pressures and high temperatures to clean the surfaces. Sample tubes were immersed in liquid N (− 197 °C) and N gas was added to the samples in small steps and the resulting isotherms were obtained. Specific surface areas were calculated from adsorption isotherms according to the BET method (Brunauer et al. 1938).

Chemical analyses

Total C and N were measured (ISO 10694 1995; ISO 13878 1998) from sieved and air-dried samples on a CHN analyzer (LECO-1000, LECO Corp., St. Joseph, MI, USA). Samples for other elements (SFS-ISO 11466, 2007) were digested by the closed wet HNO_3-HCl digestion method in a microwave (CEM MDS-2000; CEM Corp., Matthews, NC, USA) and the extract was analysed on an iCAP 6500 Duo ICP-emission spectrometer (Thermo Scientific Ltd., Cambridge, UK).

To assess soluble sulphur (S), acid ammonium acetate (pH 4.65) extractant was used (Vuorinen and Mäkitie 1955). The quantification was done using the previously described ICP-emission spectrometer. Soil ammonium (NH_4-N), nitrate (NO_3-N), and total N were determined from a KCl-extract on a FIA-analyzer (Lachat QuickChem 8000, Lachat Instruments, Milwaukee, WI, USA) (Kalra and Maynard 1991). Using a microwave (CEM MDS-2000 described above), we used the hot water refluxing method to extract easily soluble boron, quantified using the previously described ICP-emission spectrometer.

For cation exchange capacity (CEC), substrates were prepared as for soluble nutrients (ISO 11260 2018). We used a 0.1 M $BaCl_2$ solution to extract exchangeable cations, and their total concentrations in the filtrate were determined using the previously described ICP-emission spectrometer. To determine exchangeable acidity, the 0.1 M $BaCl_2$ extract was titrated with a 0.05 M NaOH solution up to pH 7.8. Effective CEC [ECEC(cmol kg^{-1})] was then calculated as ECEC (in cmol kg^{-1}) = Na + K + Ca + Mg + ACI_E, where ACI_E is exchangeable acidity from $BaCl_2$ extract. Percentage base saturation was calculated as the sum of the bases (Na, K, Ca, Mg) divided by ECEC.

In addition, Bc samples were analysed (Fagernäs et al. 2015) by Eurofins Nab Labs Ltd (Finland) for 16 PAH (polyaromatic hydrocarbons) compounds usually monitored by the US Environmental Protection Agency EPA Extraction (ISO 16703 2004). The PAH components were analysed from *n*-hexane extract of the sample. The sample was transferred to the extraction funnel and the internal deuterated PAH standards were added. The extract was then cleaned using DMSO liquid–liquid partitioning. The PAH compounds were analysed from the cleaned *n*-hexane extract using gas chromatography–mass spectrometry (GC/MS) running in SIM-mode. The quantitation was made using the Internal Standard Method. Four deuterated PAH compounds were used (d8-naphthalene, d10-anthracene, d12-chrysene and d14-dibenzo[a,h]anthracene. The limit of detection for the method is 10 µg kg^{-1} sample and the repeatability ± 20–40% depending on the concentration of the individual component present in the sample.

Plant growing experiment 1

Forest till soil, tailings soil (oxidized and non-oxidized), two various biochar types, compost and fibre clay were used either alone or as a component of various growth media mixtures (Table 1). The growth media were mixed and packed into 3 L pots (Soparco, Condé-sur-Huisne, France) by hand. The depth of the media in the pots during the experiment was 18 cm and the volume 2700 cm^3. There were in all 17 different growth media combinations with 4 replicates for 5 different plant species in the pots (total of 340 pots).

Seeds of some of the most common grass species were selected for the experiment. Red clover, red fescue and maiden pink were sown into the pots on 22nd November 2017 in the greenhouse (Luke, Suonenjoki, Finland). 15 seeds were sown per pot to determine the germination rate at 7, 14 and 21 day after sowing with frequent irrigation from above. Two germinants per pot were then left to grow. Two common tree species were also used: dark-leaved willow cuttings with two clones (K2183, E6778) and 1-year-old containerized Scot pine seedlings (from local central Finnish seed) were gradually thawed after cold storage, acclimatized to ambient conditions and then transplanted into the pots on 24th November (one clone per pot, i.e. two willow cuttings per pot; one pine seedling per pot).

Plants were grown in a greenhouse, where the natural light was supplemented with artificial diurnal light for 18 h (high-pressure sodium lamps were on from 5 to 23 h). During the night, one interruption lamp was lit to prevent too early bud formation. The temperature was set to 20 °C (day) and 15 °C (night). Actual daily temperatures at seedling shoots were 20–32 °C due to light warming. Full light yielded photosynthetically active radiation at the seedling shoot level of 380–450 µE m^{-2} s^{-1}. Relative humidity varied between 30 and 70%, being about 10% higher with no light. The interruption light was shut off after 1.5 months and temperature was lowered 4–5 degrees and light cycle was shortened to 16 h and 14 h after 2 and 2.4 months from the start, respectively. During the experiment, pot positions were changed once a week to reduce spatial variation in growing conditions.

Irrigation was done manually first for 2 weeks by spraying pure tap water from above and then using tap water added with 700 nitrogen (N) and 30 µg l^{-1} phosphorus (P) (using urea and NaH_2PO_4) to mimic the average N and P concentrations in rain water in northern Finland (Järvinen and Vänni 1998; Vuorenmaa et al. 2001). No other added nutrients were used. Irrigation need was estimated twice a month by weighing the pot masses. The target pot mass after irrigation was determined for each pot as the volumetric WC of about 0.55*TP, where TP is the total porosity of the medium (Heiskanen 2013; Dumroese et al. 2018). Each medium was aimed to be irrigated before the WC limit of 0.35*TP was achieved. Once a month, pots were watered similarly over the target masses so that a percolated water sample of equal amount could be taken from the bottom of the pots for monitoring pH and electrical conductivity (EC) (from three samples per treatments).

Plant quality and height were measured every second week. Plant shoot quality was estimated using a 5-category visual classification (0 dead, 1 dying, 2 weakened, 3 slightly symptomatic, 4 vigorous). On 2nd February 2018, plants were harvested and measured for morphological attributes: height, visual vigour (i.e. greenness and chlorotic tone), and dry mass of shoot. The greenness tone was estimated using a chlorophyll content meter (CCM-300, Opti-Sciences, Hudson, New Hampshire, USA). Root volumes were estimated visually using a 5-category classification (0 dead or non-existent roots, 1 little viable roots, 2 some long roots, 3 many long, spiralled roots, 4 pot full of long and thick roots) and measuring the maximum root length per pot.

Plant growing experiment 2

The second growing experiment was carried out with red fescue to find out suitable application proportions of Bc1, Bc2 or FC in growth media because in Exp. 1 the effect of Co was found to be the most pronounced. Each new mixture contained a Co proportion of 0 or 20 vol% (Table 2); for example, a medium code Ti80Bc10Co20 denotes mixture of till soil (80 vol%), Bc1 (0 vol%) and Co (20 vol%). Bc1, Bc2, Co and FC were of different batch and particle size than in the growing experiment 1 (Table 3). The media were packed into 2-L pots (OS Plastic A/S, Denmark) by hand. The medium volume is 1770 cm^3 when the surface is 1 cm below the upper rim of the pot. Red fescue seeds were sown on 5th March 2018, grown and measured as in the first plant growing experiment. There were 68 pots in all (17 media × 4 replicates). The experiment was ceased, and the plants harvested on 3rd May 2018.

Statistical analyses

Data were analysed with IBM SPSS Statistics (Version 25.0). Two-way (Exp. 1) and one-way (Exp. 2) analysis of variance were used to compare the effect of plant species and growth medium on the shoot dry mass. Homogeneity of variance was tested using Levene's test of equality of error variance. The least significance difference pairwise method (LSD) at a significance level of $p < 0.05$ was used for post hoc multi-comparison tests of the differences between means. Because of the small number of replicates (4), categorical variables (0–4; plant vigour and root volume) could not be analysed or tested with ordinal or binary logistic regression.

Results

Physical properties

In Exp. 2, Bc1 and Co were somewhat coarser while Bc2 and FC were finer in particle size than in Exp. 1 (Table S3). Highest bulk density was in Ti and Ta0, and lowest in FC (Table 4). Largest available water content released between matric potentials − 0.3 (near saturation) and − 9.81 kPa (field capacity) was in FC–Co and lowest in Ta0 (Table 4). Bc1 and Bc2 had intermediate water release, but Bc2 released negligible water in drier conditions between − 9.8 and − 98.1 kPa. Saturated hydraulic conductivity was variable being highest in FC–Co (mean 0.441 cm min^{-1}) and lowest in Ta0 (0.002 cm min^{-1}). In Bc1 it was lower (0.092) than in coarser Bc2 (0.179 cm min^{-1}). The specific surface area as BET-area of Bc1 (in Exp. 1 and 2) and Bc2b (in Exp. 2) were 180, 61 and 0.26 m^2 g^{-1}. BET-area of Bc2 (in Exp. 1) could not be detected due to the tars in the sample.

Chemical properties

Tailings soil contained much different elements and especially Ca, Mg, Fe, S, Cr, Cu and Ni (Table 5). Ta1 contained the highest amounts of Cd and As. Co contained much P as well as Cu, Pb and Zn. Co (compost) contained the most Al. Ca was the highest in FC. C/N ratio was highest in Bc1, Bc2 and FC. N was the highest in Co. Extractable elements were clearly on a lower level compared to the total amounts (Tables 5, 6). FC contained Ca and P the most. Bc1 had clearly the highest K content. Co contained Ntot and NO_3

Table 4 Mean bulk (Db) and particle densities (Ds), loss on ignition (LOI) and water retention at different matric potentials of the studied growth media ($n = 3$). Water retention at − 0.01 kPa indicates total porosity

				Water retention at different matric potentials, vol. %							
Medium	Db	Ds	LOI	− 0.01	− 0.3	− 1.0	− 4.9	− 9.8	− 33.0	− 98.1	− 1500
Unit	g cm^{-3}	g cm^{-3}	%	kPa	kPa	kPa	kPa	kPa	kPa	kPa	kPa
Ta0	1.647	2.646	0.4	–	40.5	37.9	36.9	36.1	29.2	19.3	5.1
Ta1	1.176	2.633	1.5	55.3	52.1	48.4	44.5	41.6	20.4	12.1	6.5
Ti	1.848	2.644	0.6	30.1	25.4	21.5	18.9	16.8	9.5	6.1	5.4
Bc1	0.225	1.708	82.0	86.8	68.7	62.8	58.2	53.7	22.9	21.5	10.0
Bc1–Ti	1.015	2.545	9.1	60.1	47.8	42.9	39.7	37.5	18.3	9.4	5.7
Bc1–Co	0.269	1.762	77.2	84.7	69.9	61.2	57.7	53.0	38.3	35.9	14.5
Bc1–FC	0.229	1.828	71.4	87.5	73.1	63.9	56.3	53.7	51.9	50.4	17.5
Bc1–Bc2	0.239	1.610	90.4	85.1	35.0	30.5	28.2	25.8	21.5	19.3	13.2
Bc2	0.272	1.680	84.3	83.8	36.0	23.9	22.0	20.6	20.3	20.2	17.3
Bc2–Ti	1.119	2.521	11.2	55.6	37.8	31.2	22.4	19.0	13.2	10.9	4.4
Bc2–Co	0.268	1.753	78.0	84.7	41.7	29.2	25.1	23.4	22.5	21.9	17.0
Bc2–FC	0.215	1.853	69.3	88.4	44.0	33.9	31.6	30.3	28.2	26.8	17.8
Co	0.304	2.130	45.2	85.7	64.2	48.8	44.4	42.1	37.3	33.1	18.7
Ti–Co	1.671	2.621	2.5	–	39.0	31.8	27.7	24.5	17.4	12.7	9.0
FC–Co	0.186	2.019	54.9	90.8	70.2	49.9	38.9	34.4	27.7	24.3	13.5
FC	0.179	2.034	53.6	91.2	57.7	46.5	43.7	39.9	35.5	29.4	10.3
FC–Ti	1.069	2.635	1.3	59.4	53.3	39.8	31.4	27.5	22.8	17.8	8.1

Table 5 Total element concentrations of the growth media components (from combined sample, extractant aqua regia: $HNO3 + HCl$)

Element	Unit	Ta0	Ta1	Ti	Bc1	Bc2	Co	FC
Al	mg/kg	9 760	4 730	8 570	177	1 180	38 200	12 700
Ca	mg/kg	50 700	48 100	5 020	7 900	13 800	11 400	150 000
Fe	mg/kg	79 300	68 400	16 300	440	5 220	53 600	676
K	mg/kg	4 000	1 010	1 180	2 950	3 330	1 620	144
Mg	mg/kg	33 400	19 000	2 820	594	1 710	3 960	944
Mn	mg/kg	822	642	187	211	897	351	41
Na	mg/kg	405	280	363	109	114	483	253
P	mg/kg	429	499	482	269	789	19 800	243
S	mg/kg	18 800	21 500	46	83	411	6 070	603
B	mg/kg	5.19	11.8	1.01	8.7	20.9	19.3	30.3
Cd	mg/kg	1.29	9.59	< 0.07	< 0.2	1.11	0.178	0.185
Cr	mg/kg	144	46.8	24.4	1.03	9.11	27.5	13.2
Cu	mg/kg	152	199	9.46	3.94	16.2	275	3.21
Ni	mg/kg	419	554	9.78	1.39	10.1	16.7	3.91
Pb	mg/kg	4.33	5.43	1.92	< 2.28	4.3	12.8	< 2.06
Zn	mg/kg	29.9	14.4	12.9	63.1	338	277	15.7
As	mg/kg	101	651	3.13	< 2.28	< 2.17	9.65	2.6
C	% DM	2.73	2.26	0.161	95.1	81.5	20.2	29.3
N	% DM	< 0.080	< 0.080	< 0.080	0.17	0.79	1.88	0.23
C/N	–	> 34.1	> 28.3	> 2.0	562.7	103.2	10.7	130.2

and the most. Ti had the lowest ECEC. Total PAH concentrations of biochars varied from 0.7 to 2.4 (Bc1) and 40 to 57 mg kg^{-1} (Bc2) (Supplementary Table 1).

Plant growing experiment 1

pH and EC of the percolate from pots were all within 5.0–9.7 pH and 0.04–16.4 mS cm^{-1} during the experiment, respectively (Fig. 1). EC tended to lower during the experiment except in Ta0, where it elevated to as high as 16.4 mS cm^{-1}.

Table 6 Extractable nutrients of the growth media components (from combined sample, extractant $BaCl_2$). ECEC denotes effective cation exchange capacity and BS base saturation

Element	Unit	Ta0	Ta1	Ti	Bc1	Bc2	Co	FC
Al	mg/kg	1.82	< 0.25	4.11	< 1.55	< 0.989	238	133
Ca	mg/kg	1 610	2 100	182	1 580	1 280	4 500	6 860
Fe	mg/kg	3.27	0.396	2.65	< 0.309	0.966	5.36	< 1.54
K	mg/kg	291	95.5	13.1	1 930	746	469	44.3
Mg	mg/kg	1 180	417	41.8	59.9	112	582	313
Mn	mg/kg	7.88	0.458	1.48	22.4	10.4	60.8	2.34
Na	mg/kg	97	17.4	6.96	16.5	15.2	97.3	226
P	mg/kg	< 0.635	< 0.417	< 0.331	< 2.58	2.01	1.44	< 12.9
S *)	mg/kg	3 260	7 360	13.0	17.6	55.8	2 270	156
Ntot **)	mg/kg	2.59	3.65	1.91	1.35	29.2	1 820	80.8
NO_3 **)	mg/kg	< 0.104	0.629	< 0.1	< 0.112	< 0.107	1 800	0.492
NH_4 **)	mg/kg	1.9	1.07	1.04	< 1.12	3.7	5.46	9.35
ECEC	cmol/kg	18.9	14.2	1.3	13.4	9.3	32.1	37.9
BS	%	100	100	100	100	100	90	100

*Extractant AAc pH 4.65

**Extractant KCl

Acidity was highest at the start of the growing in Co percolate (pH 5.0) where it lowered later on (pH 6.7). Acidity was lowest in Bc1 percolate, where it decreased from pH 9.7 to 9.3 during the growing.

All the measured plant variables, germination/burst rate, development of plant vigour, shoot and root growth, differed by species and growth media but showed parallel results. Less than 50% of red clover germinated in 21 days in Ta0, Ta1 and Bc2 (Fig. 2). On red fescue, the germination was below 50% in Ta0, Ta1, Ti and Ti–Co, while it was as high as 98% in Bc1. Maiden pink germinated poorest on the average, but was best in Ti (78%) and FC (80%), and poorest in Bc2 (0%). At least 50% of willow cuttings were burst in all growth media in 21 days. On pine seedlings, the bud burst was gradual and similar in all media except in Ta0, where it was delayed about one week. Development of plant vigour (classes 0–4) was best in pine and willow although it decreased during growing. Overall, the poorest vigour was in Ta0 while it was best in Bc1–Co, Bc2–Co, Co and Ti–Co especially in the grass species (Supplementary Fig. 1).

Shoot dry mass after the growing season differed highly significantly by the growth medium and plant species but most by the growth medium (Table 7). There was also a significant interaction effect of species and medium. Shoot growth was the greatest in Co and good in Bc1–Co, Bc2–Co, and Ti–Co (Fig. 3). In Bc1–Co growth was equal or slightly better than in Bc2–Co. Pine and willow were able to grow also in the other growth media, but the grass species were not. However, no shoot growth occurred in Ta0 except on pine. Shoot growth of plant species decreased, on average, in the order pine, willow, red clover, red fescue and maiden pink. There was no root growth in Ta0 (Fig. 4). The grass species showed no roots in Bc1 either. Roots grew best in Bc1–Co, Bc2–Co, Co and Ti–Co. Mean root mass after one growing period deceased in the order willow, pine, red clover, red fescue and maiden pink.

Plant growing experiment 2

pH and EC of the percolate from pots were all within 6.2–8.0 pH and 0.05–1.75 mS cm^{-1} during the experiment, respectively. EC tended to lower during the experiment (to less than 0.8) except in Ti0FC80Co20 where it reached 1.75 mS cm^{-1}. Acidity tended to decrease slightly during the experiment (mean pH from 7.2 to 7.5).

Red fescue germinated fairly in all media. The germination rate was within 63–95% after 21 days in the media. Also shoot growth (as shoot mass) differed significantly by the growth medium (Table 8). Growth was good in media amended with Co except in FC, where the growth was minimal (Fig. 5). Ti soil with Co but without Bc grew intermediately. Bc2 mixtures yielded somewhat better growth than Bc1 mixtures. Similarly, root growth (as root volume class) was poor in media with FC and media without Co (Fig. 6). In Bc2 mixtures also root growth was somewhat better than in Bc1 mixtures. Both shoot and root biomass tended to increase when Bc concentration increased from 10 > 20 > 40 to 60% of growth media.

Discussion

The studied pure tailings soils (Ta0 and Ta1) had high metal/metalloid in the order Fe > Mg > S > Al > Mn > Ni > Cr > Cu and low N concentrations. Especially EC was high in Ta0 and concentrations of Cd and As were high in

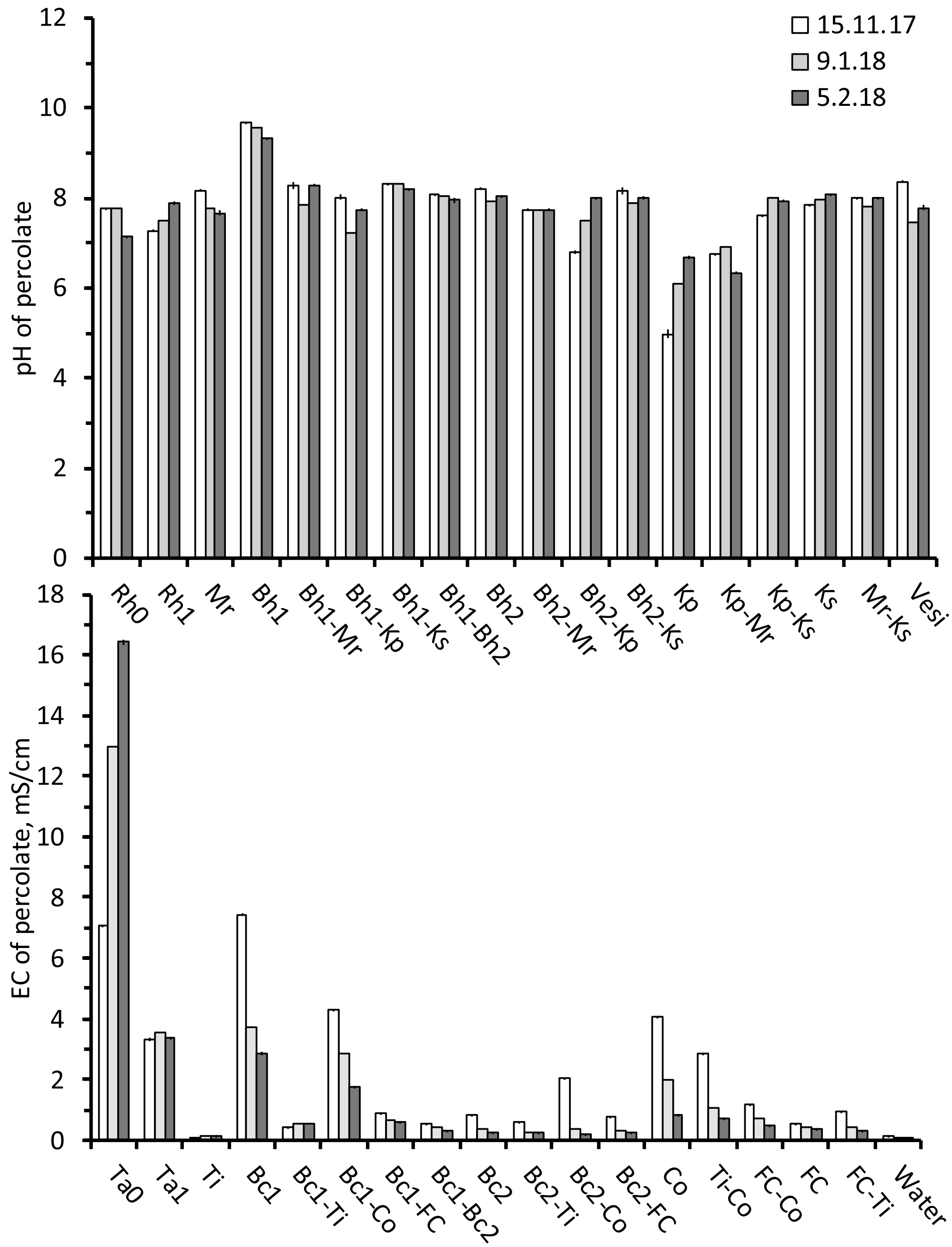


Fig. 1 Development of acidity (pH) and electrical conductivity (EC, mS cm^{-1}) from one combined percolate sample per treatment during Exp. 1 (on three dates as dd.mm.yy) (mean ± s.d.). On 9th January 2018, measurements were made from a pooled percolate from 5 pots. Water denotes the added irrigation water

Ta1. However, only the marginal proportions of the concentrations were in water-extractable form which suggests low leaching risk of these metals in the neutral or alkaline conditions at Rautuvaara tailings. Bc addition can further increase soil pH and alkalinity and reduce phytoavailability of Cd, Zn, and Pb (Martins et al. 2018). Compost (Co) originating from sewage sludge exhibited high concentrations of Al and P, which indicates that P in the sewage sludge has been precipitated using Al. Also, concentrations of P as well as Cu, Pb and Zn were high in compost medium. However, concentrations of metals in the used compost and biochar types were all below the limit values of Finnish Fertilizer product Act (539/2006; Cd 1.5, Cr 300, Cu 600, Ni 100, Pb 100 and Zn 1500 mg kg^{-1}) showing that the products are suitable to be used as a part of growth media.

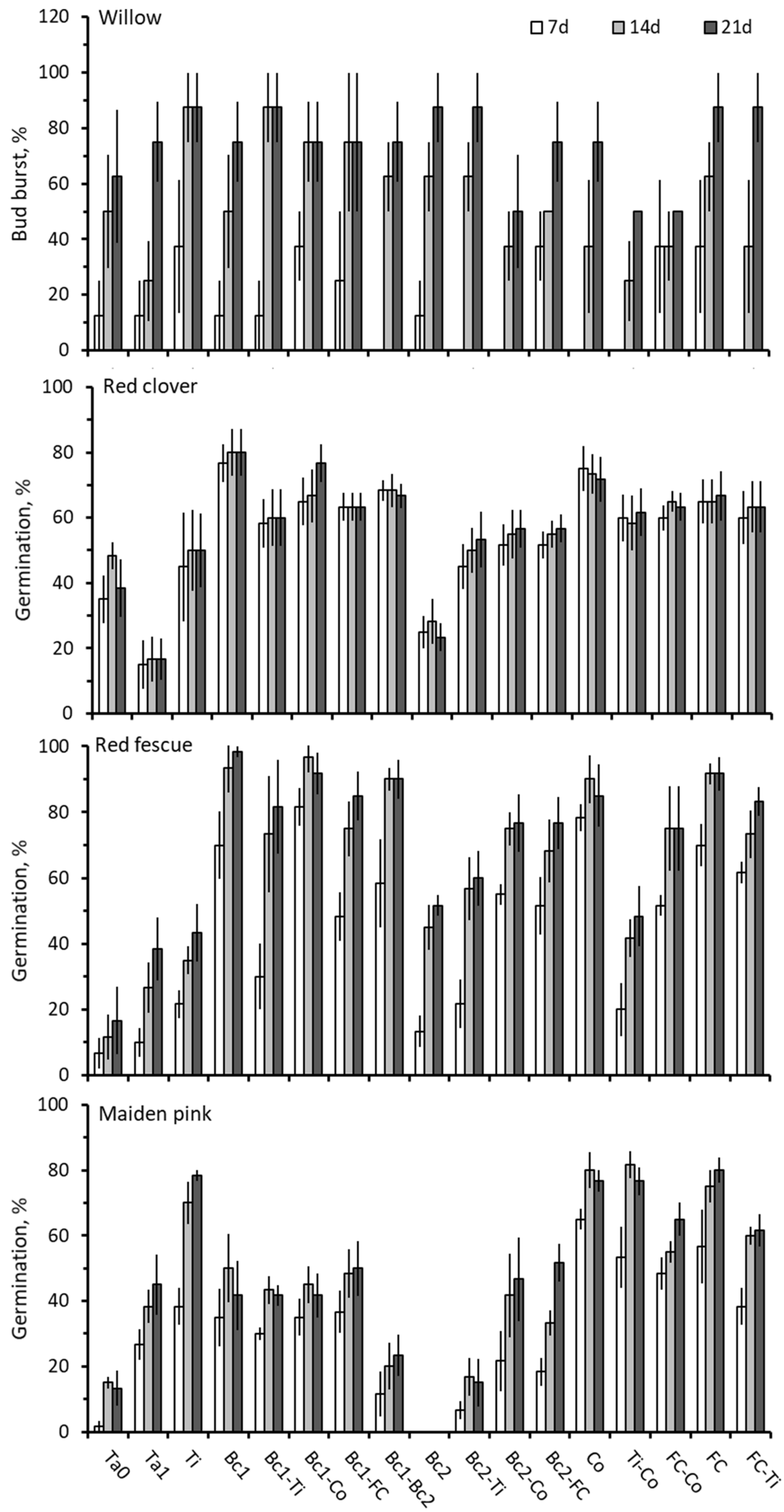


Fig. 2 Mean (± s.e.) germination rate and, on willow cuttings, bud burst rate at 7, 14 and 21 days from the start of Exp. 1. On pine seedlings, the bud burst was gradual and similar in all media except in Ta0, where it was delayed about one week

Table 7 Two-way analysis of variance for the effects of plant species and growth medium on shoot dry mass in Exp. 1

Source	SS	df	MS	F	*p*
Corrected model	5763.57	84	68.61	79.21	< 0.0005
Intercept	2466.98	1	2466.98	2848.00	< 0.0005
Plant	707.03	4	176.76	204.06	< 0.0005
Medium	4462.30	16	278.89	321.97	< 0.0005
Plant * medium	594.23	64	9.29	10.72	< 0.0005
Error	220.89	255	0.866		
Total	8451.43	340			
Corrected total	5984.44	339			

$R^2 = 0.963$, adjusted $R^2 = 0.951$

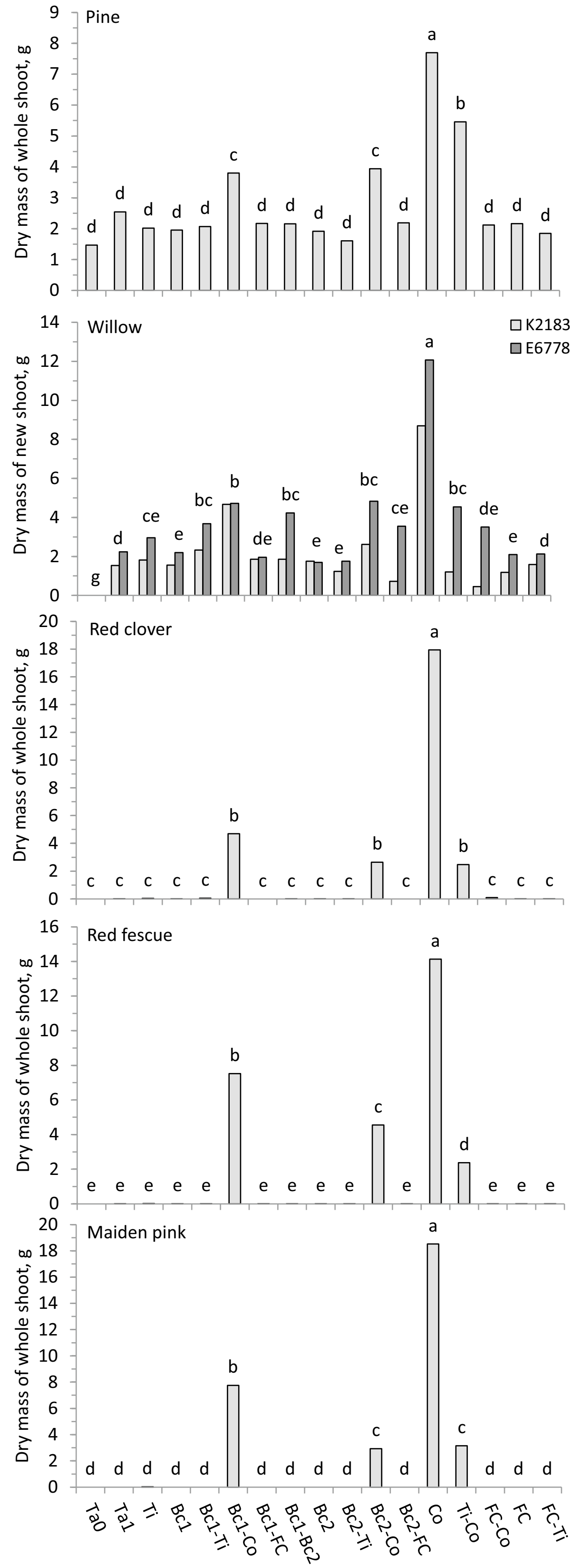
The overall seed germination with abundant irrigation was best in treatments Co, Bc1, FC and Ti, while it was poorest in pure Ta0, Ta1 and Bc2 (Exp. 1). The need for amended growth layer in the tailings soil to plant growth is evident as all the tested plant species showed poor or no germination and growth in Ta0 and Ta1. This is in accordance with field observations in Rautuvaara tailings area, where the early success of vegetation is negligible in the tailings soil without any amendments. Even though the total concentrations of toxic metals as Cd and As were much lower in Ta0 than in Ta1, Ta0 showed much higher phytotoxicity on plants i.e. lower germination and no root growth. Poor growth in Ta0 was presumably also contributed by very limited oxygen availability owing to the soil compactness and wetness. Growth prerequisites of Ti soil were significantly improved by the amendment due to the increased amount of nutrients (esp. N) and improved soil structure, which enhanced growth of all tested plant species. Instead, FC addition gave no advantages on plant growth.

Previously, also in temperate Appalachian region, afforestation of coal-mined areas is found successful with topsoil covers (Zipper et al. 2011, 2013). Successful afforestation of non-acidic (low S level) mine waste areas have been found with at least 20–50-cm-thick topsoil layer in boreal conditions in Canada (Larchevêque et al. 2014). Bc and other additives such as peat and sewage sludge mixed in mine covers have also been used to enhance vegetation restoration (Drozdowski et al. 2012; Dietrich et al. 2017; Miller and Naeth 2017). Compost, clay and new recyclable materials such as dried waste paper sludge (FC) have been somewhat studied as growth media components in mine cover systems and bottom sealing layers (Nurmesniemi and Pöykiö 2006; Nurmesniemi et al. 2007; Pöykiö et al. 2007; Kuokkanen et al. 2008; Kukkonen et al. 2011; Raivio 2013; Tuomisto et al. 2016). Addition of organic materials to coarse or compact mineral soil has generally shown to improve soil CEC, water retention and aeration and thus availability of water and nutrients to plants (Bunt 1988). Varying effects of composted sewage, paper mill sludges and other composts have been found on vegetation restoration and tree seedling growing (Hernández-Apaolaza et al. 2005; Heiskanen 2013; Chong and Lumis 2017). In this study, the poor plant growth in FC media after successful germination, was probably due to the poor wettability and rapid subsurface drainage caused by its coarse particle size. FC has generally shown a good liming effect increasing soil pH and concentrations of P, K, Ca and Mg but, in high quantities, high pH and EC may first limit growth of some plants. However, the properties of FC depend on the manufacturing process of the paper (raw material either mechanical mass, chemical pulp or recycled papermass from de-inking sludge) and thus various products and their long-term effects should be studied case by case.

Effect of Bc on plant germination and growth varied between the plant species but no improvement occurred when Bc was mixed with mere Ti (Exp. 1). Instead, when mixed to both Co and Ti (Exp. 2), the addition of Bc enhanced the shoot mass and root volume class of red fescue; the higher Bc concentration (0–60%) the higher was the growth. Also previously it has been found that the low vegetation growth caused by nutrient deficiency in Bc can be avoided by adding compost or manure to the Bc medium (Beesley et al. 2011). Both Bc types (50% rate) inhibited here remarkably germination of maiden pink compared to seeds sown in pure Co or Ti soil. Instead, red fescue and red clover grew better in soils with Bc or Co added either separately or mixed. In Exp. 1, Bc1 showed better plant growth than Bc2 but in Exp. 2 the effect was opposite. As the particle size distribution of Bc was the only difference between the batches, the main reason for growth variation was probably the coarser structure of Bc2 in Exp. 1 and Bc1 in Exp. 2, which lead to faster drying. This was also shown in their water retention characteristics as Bc2 (in Exp. 1) contained no plant available water between the matric potentials − 9.8 and − 98.1 kPa compared to Bc1. Nevertheless, both Bc1 (birch) and Bc2 (spruce) were relatively coarse and dry materials, which had to be irrigated frequently during the growing experiments. On the other hand, Bc tended to disintegrate and compact somewhat during the growing. Overall, the irrigation need varied a lot among the different growth media.

Differences in the concentrations of the PAH compound of Bc1 and Bc2 were high. In the case of Bc2, the sum of PAHs exceeded the recommendations for good quality biochar for land use (6 mg kg^{-1}) (EBC 2020) and can thus not be recommended to be used in tailings covers. Even though high PAH concentration had no effect on plant growth in our study, the long-term effects and bioaccumulation cannot be excluded. The reason for a high PAH content remains unresolved but together with tars observed in BET analysis it may indicate incomplete pyrolysis processes.

Fig. 3 Mean shoot mass of plant species in different growth media ▶ after Exp. 1. Above bars, the same letter denotes non-significant difference ($p > 0.05$ in LSD test) between media clones. On willow, LSD test is for the combined mass of both clones (K2183 and E6778) in pots



In general, the growth and vigour of the plant species grown in the studied growth media decreased in the order, pine, willow, red clover, red fescue and maiden pink. From the tested plant species, pine container seedlings, willow cuttings and sown red clover are presumably the most feasible to be grown on boreal tailings covers. The short duration of the growing experiments (one growing season) cannot, however, predict how the plants can grow later on. It may be, for instance, that pine and willow grew well in the first season using their photosynthate reserves but may grow less in the next season with reduced reserves. Furthermore, red clover possesses a high biological N fixing ability which could not be seen in growth in the first season, but may later enhance growth. On the other hand, red clover and red fescue yielded dense root systems in the first season, which may accomplish better nutrient and water availability in the next seasons and thus increased growth.

In addition to the plant species studied here, also response of other boreal plant species and forest floor communities to biochar and compost containing growth media may be worth for further examination. According to the review of Dhar et al. (2018), the studies conducted in boreal ecosystems of northern Alberta (Canada) showed that the use of forest floor mineral mix in oil sands reclamation results in greater overall plant cover, richness of native species, and lower non-native species cover relative for example to peat–mineral soil mix. Also in the synthesis paper of Mcdonald et al. (2015), the use of natural regeneration and direct placement of forest floor material combined with seedings of native species is recommend gaining the rapid forest re-establishment of mining sites. As our results are based only on one preliminary experiment with growing media from one or two batches only, they can provide only general indications. Repeated studies with varying materials from several production batches should be examined in the future before valid formula recommendations can be drawn.

As Bc is yet not a standardized product, its properties and also application targets may differ greatly depending on the used feedstock material and production conditions (Youn et al. 2019). Even though the pyrolysis conditions of Bc1 and Bc2 were exactly the same, their chemical and physical characteristics varied depending on feedstock material. Effects of Bc on soil depend on the properties of the Bc and the soil (Nelissen et al. 2014; Burrel et al. 2016; Hagner et al. 2016; Hansen et al. 2016; Lim et al. 2016; Liu et al. 2017; Kaudal et al. 2018). In general, Bc has shown to be a potential growth medium component for agri- and

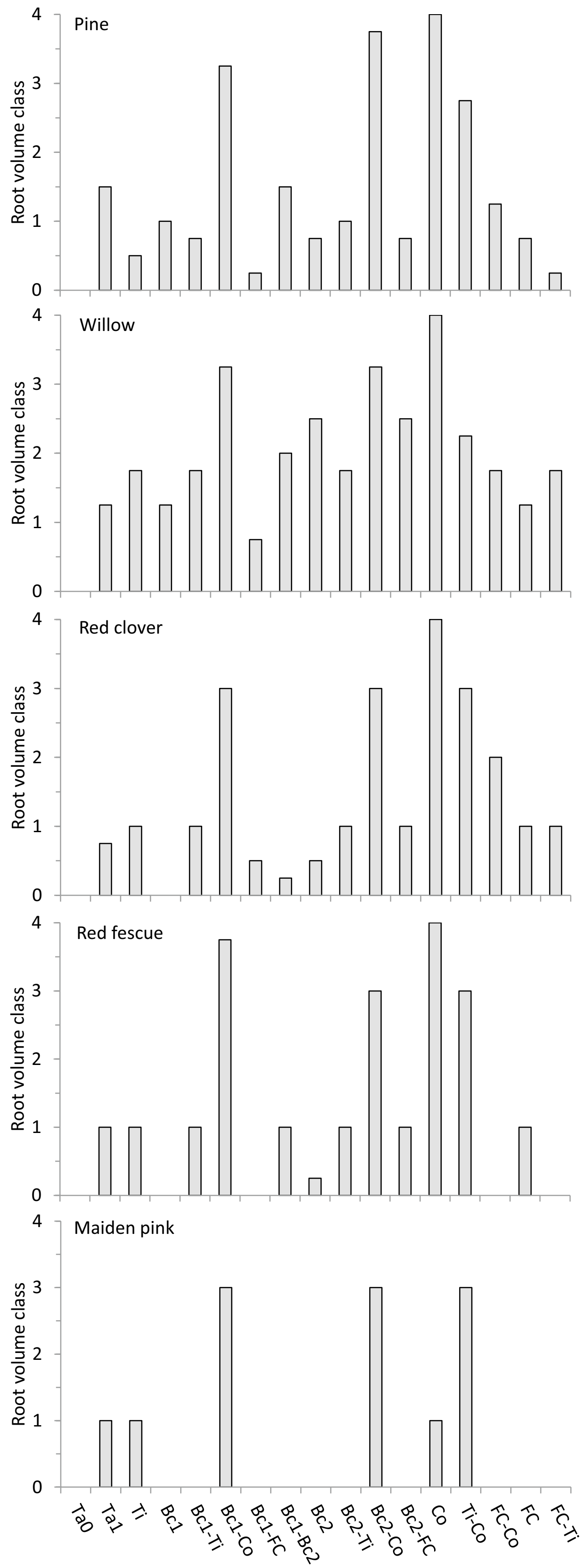


Fig. 4 Mean root volume class (0–4) in different growth media after Exp. 1. On pine, the root volume was estimated from roots grown out from the container (root plug). No LSD test is provided as there were not observations in all the category and medium combinations

Table 8 One-way analysis of variance for the effect of growth medium on shoot dry mass of red fescue in Exp. 2

Source	SS	df	MS	F	*p*
Corrected model	6,123	16	0.383	61.08	< 0.0005
Intercept	4.507	1	4.507	719.31	< 0.0005
Medium	6.123	16	0.383	61.08	< 0.0005
Error	0.320	51	0.006		
Total	10.950	68			
Corrected total	6.443	67			

$R^2=0.950$, adjusted $R^2=0.935$

horticulture and for vegetation restoration as well as for C sequestration (e.g. Steiner and Harttung 2014; Nemati et al. 2015; Thomas and Gale 2015). Bc addition to coarse or compact soil tend to increase soil crumb structure, porosity and water retention capacity and decrease bulk density (Beesley et al. 2011; Nelson et al. 2011; Basso et al. 2013; Heiskanen et al. 2013; Peltz and Harley 2016; Tuomisto et al. 2016; Aller et al. 2017). Bc usually increases also soil pH, CEC and concentrations of C, P and K, but it provides no actual liming effect (Robertson et al. 2012; Tuomisto et al. 2016; Li et al. 2018).

In forest soil, Bc addition can increase N net mineralization and NH_4 concentration during two growing seasons as found in Northern Sweden (Gundale et al. 2016). According to Palviainen et al. (2018), Bc addition of 5–10 t ha^{-1} to mid-Finnish Scots pine forest soils may increase N mineralization slightly in 2 years. Bc can also alter soil microbe structure and greenhouse gas emissions (usually reduces N_2O emission and increases CH_4 sink and has mixed effect on CO_2 emission) (Li et al. 2018). Adding Bc to soils is usually found unharmful for forest tree seedlings or may enhance their growth prerequisites (Heiskanen et al. 2013; Robertson et al. 2012; Pluchon et al. 2014; Thomas and Gale 2015). Bc is a potential growth media for tree seedlings especially when pH, irrigation and fertilization are adjusted to the properties of the Bc media (Heiskanen et al. 2013; Dumroese et al. 2018; Lange and Allaire 2018; Sarauer and Coleman 2018). Addition of Bc into a highly weathered acidic soil has been found to increase seed germination, plant growth, vegetation cover, as well as N and P use efficiency (Zhu et al. 2014; Anawar et al. 2015). According to Pluchon et al. (2014), Bc with high P concentration and CEC increase growth of tree seedlings in Northern Sweden, but deciduous tree seedlings (Silver birch and European aspen) seem to be more sensitive to Bc additions than coniferous seedlings

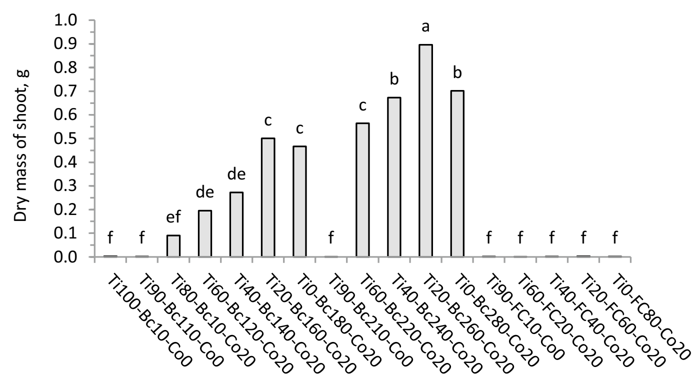


Fig. 5 Mean shoot mass of red fescue in different growth media after Exp. 2. Above bars, the same letter denotes non-significant difference ($p>0.05$ in LSD test) between media

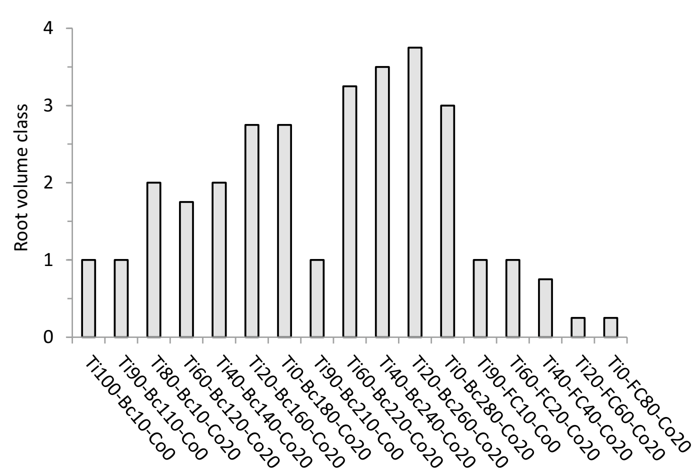


Fig. 6 Mean root volume class (0–4) of red fescue in different growth media after Exp. 2. No LSD test is provided as there were not observations in all the category and medium combinations

(Scots pine and Norway spruce). However, in this study, no differences were found in pine and willow shoot and root growth, and vigour class. This discrepancy is most probably due to the differences in the used Bc types and high Bc application dose (50%) as well as to the fact that the pine seedlings were containerized in this study.

Bc addition has shown potential for revegetating mine tailings and decreasing the bioavailability of organic and inorganic pollutants in heavy-metal-concentrated soils (Beesley and Marmiroli 2011; Fellet et al. 2011, 2014; Peltz and Harley 2016; Ali et al. 2017; Yuan et al. 2019). In the actual boreal mining reclamation sites, the possible long-term effects, such as alterations in fertility and phytotoxicity of the growth medium layer on tailings soil and flux of metals to cover plants, remain to be assessed by later studies. At the moment, the main hindrance to practical application of Bc is its high production costs. To minimize transportation costs, Bc pyrolysis should be performed close to local raw material reserves and be mixed with other materials (e.g. composts, manures) for synergic effects (Petz and Harley 2016). Also initially nutrient-rich Bc (e.g. derived from sewage sludge and animal manures) might provide long-term fertility for plant growth.

Conclusions

Studies investigating the feasibility of recyclable waste materials as a growth medium layer for the cover systems of mine tailings and their effects on vegetation restoration are scarce especially in the boreal climate. In this study, the potential of various recyclable by-product amendments (biochar, composted sewage sludge and fibre clay) in improving the success of boreal plant species on reclaimed mine tailings was investigated in two well-controlled greenhouse experiments. Our results showed marked differences in the properties among the growth media mixtures as well as in plant growth. Used fibre clay was too coarse and a dry material and showed only poor plant growth. All media without compost additive showed relatively poor growth which indicates the lack of nitrogen. From tested plant species, pine container seedlings, willow cuttings and sown red showed the best growth.

The results suggest that forest till soil is biologically and economically the most suitable growth media for the cover systems of boreal mine tailings when added with compost or another N source. However, when considering also the possible life-cycle costs and longer term effects on soil fertility, plant growth and C sequestration, biochar with N addition may be better medium for tailings covers if its production costs can be reduced. The long-term effects of nutrients and metals on fertility and phytotoxicity of the media and on plant growth as well as the life-cycle costs of media components and their effects for C sequestration on mine reclamation sites remain to be assessed by further studies.

Funding Open access funding provided by Natural Resources Institute Finland (LUKE).

References

Anawar HM, Akter F, Solaiman ZM, Strezov V (2015) Biochar: An emerging panacea for remediation of soil contaminants from mining, industry and sewage wastes. Pedosphere 25:654–665

Ali A, Guo D, Zhang Y, Sun X, Jiang S, Guo Z, Huang H, Liang W, Li R, Zhang Z (2017) Using bamboo biochar with compost for the stabilization and phytotoxicity reduction of heavy metals in mine-contaminated soils of China. Sci Rep 7:2690

Allaire S, Lange SF (2018) Substrates containing biochar for white spruce production (*Picea glauca* sp.) in nursery: Plant growth, economics, and carbon sequestration. Technical report CRMR-2018-SA-2-EN. Centre de Recherche sur les Matériaux Renouvelables, Université Laval and GECA Environnement, Quebec, Qc, Canada, p 32

Aller D, Rathke S, Laird D, Cruse R, Hatfield J (2017) Impacts of fresh and aged biochars on plant available water and water use efficiency. Geoderma 307:114–121

Arif M, Ilyas M, Riaz M, Ali K, Shah K, Ul Haq I, Fahad S (2017) Biochar improves phosphorus use efficiency of organic-inorganic fertilizers, maize-wheat productivity and soil quality in a low fertility alkaline soil. Field Crop Res 214:25–37

Basso AS, Miguez FE, Laird DA, Horton R, Westgate M (2013) Assessing potential of biochar for increasing water-holding capacity of sandy soils. GCB Bioenergy 5:132–143

Beesley L, Moreno-Jiménez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T (2011) A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. Environ Pollut 159:3269–3282

Beesley L, Marmiroli M (2011) The immobilization and retention of soluble arsenic, cadmium and zinc by biochar. Environ Pollut 159:474–480

Bouazza A, Rahman F (2007) Oxygen diffusion through partially hydrated geosynthetic clay liners. Géotechnique 57:767–772

Brunauer G, Emmett PH, Teller E (1938) Adsorption of gases in multimolecular layers. J Amer Chem Soc 60:309–319

Bunt AC 1988. Media and Mixes for Container-Grown Plants. 2nd ed. Unwin Hyman Ltd., London, UK, p 309

Burrell LD, Zehetner F, Rampazzo N, Wimmer B, Soja G (2016) Long-term effects of biochar on soil physical properties. Geoderma 282:96–102

Chong C, Lumis GP (2000) Mixtures of paper mill sludge, wood chips, bark, and peat in substrates for pot-in-pot shade tree production. Can J Plant Sci 80:669–675

Dere AL, Stehouwer RC, McDonald KE (2011) Nutrient leaching and switchgrass growth in mine soil columns amended with poultry manure. Soil Sci 176:84–90

Dhar A, Comeau PG, Karst J, Pinno BD, Chang SX, Naeth AM, Vassov R, Bampfylde C (2018) Plant community development following reclamation of oil sands mine sites in the boreal forest: a review. Environ Rev 26:286–298

Dietrich ST, MacKenzie MD, Battigelli JP, Enterina JR (2017) Building a better soil for upland surface mine reclamation in northern Alberta: Admixing peat, subsoil, and peat biochar in a greenhouse study with aspen. Can J Soil Sci 97:592–605

Drozdowski BL, Naeth MA, 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 92:77–88

Dumroese KR, Heiskanen J, Tervahauta A, Englund K (2011) Pelleted biochar: chemical and physical properties show potential use as a substrate in container nurseries. Biomass Bioenergy 35:2018–2027

Dumroese RK, Pinto JR, Heiskanen J, Tervahauta A, McBurney KG, Page-Dumroese DS, Englund K (2018) Biochar can be a suitable replacement for Sphagnum peat in nursery production of *Pinus ponderosa* seedlings. Forests 9:1–21

EBC (2012) European Biochar Certificate -Guidelines for a Sustainable Production of Biochar. European Biochar Foundation (EBC), Arbaz, Switzerland. (http:European-biochar.org). Version 9.0E of 1st June 2020

Fagernäs L, Kuoppala E, Arpiainen V (2015) Composition, utilization and economic assessment of torrefaction condensates. Energy Fuels 29:3134–3142

Fellet G, Marchiol L, Delle Vedove D, Peressotti A (2011) Application of biochar on mine tailings: Effects and perspectives for land reclamation. Chemosphere 83:1262–1267

Fellet G, Marmiroli M, Marchiol L (2014) Elements uptake by metal accumulator species grown on mine tailings amended with three types of biochar. Sci Total Environ 468–469:598–608

Finncao Oy (2001). Finncao-kuitusavet pintarakenteiden tiivistekerroksissa. Suunnittelu- ja mitoitusohje. Finncao Oy. www.metsatissue.com/en/AboutUs/Operations-in-Finland/Suomi/tuotannon-sivutuotteet/Documents/Suunnittelu- ja mitoitusohje pintarakenteiden tiiviskerrokset.pdf. [in Finnish] Accessed 5 August 2019

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. Biol Fert Soils 35:219–230

Gundale MJ, Nilsson M-C, Pluchon N, Wardle DA (2016) The effect of biochar management on soil and plant community properties in a boreal forest. GCB Bioenergy 8:777–789

Gwenzi W, Chaukura N, Mukome FND, Machado S, Nyamasoka B (2015) Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. J Environ Manage 150:250–261

Hagner M, Kemppainen R, Jauhiainen L, Tiilikkala K, Setälä H (2016) The effects of birch (*Betula* spp.) biochar and pyrolysis temperature on soil properties and plant growth. Soil Tillage Res 163:224–234

Hansen V, Hauggaard-Nielsen H, Petersen CT, Mikkelsen NT, Müller-Stövera D (2016) Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types. Soil Tillage Res 161:1–9

Heiskanen J (2013) Effects of compost additive in sphagnum peat growing medium on Norway spruce container seedlings. New For 44:101–118

Heiskanen J, Tammeorg P, Dumroese K (2013) Growth of Norway spruce seedlings after transplanting into silty soil amended with biochar: a bioassay in a growth chamber. J For Sci 59:125–129

Hernández-Apaolaza L, Gascó AM, Gascó JM, Guerrero F (2005) Reuse of waste materials as growing media for ornamental plants. Bioresour Technol 96:125–131

INAP (2009) The Global Acid Rock Drainage Guide. The International Network for Acid Prevention (INAP). www.gardguide.com. Accessed 5 August 2019

ISO 10694 (1995) Soil quality - Determination of organic and total carbon after dry combustion. Finnish Standard Association, Helsinki

ISO 11260 (2018) Soil quality - Determination of effective cation exchange capacity and base saturation level using barium chloride solution. Finnish Standard Association, Helsinki

ISO 13878 (1998) Soil quality - Determination of total nitrogen content after dry combustion. Finnish Standard Association, Helsinki

ISO 16703 (2004) Soil quality - Determination of content of hydrocarbon in the range C10 to C40 by gas chromatography. Finnish Standard Association, Helsinki

Järvinen V, Vänni T (1998) Sadeveden pitoisuus- ja laskeuma-arvot Suomessa vuonna 1996. Suomen ympäristökeskuksen moniste 120. Suomen ympäristökeskus, Helsinki, p 67 [in Finnish]

Kalra YP, Maynard DG (1991) Methods manual for forest soil and plant analysis. Information Report NOR-X-319E. Forestry Canada, Northwest Region, Northern Forestry Centre, Edmonton, Alberta, p 116

Kaudal BB, Aponte C, Brodie G (2018) Biochar from biosolids microwaved-pyrolysis: Characteristics and potential for use as growing media amendment. J Anal Appl Pyrol 130:181–189

Kauppila P, Räisänen ML, Myllyoja S (2013) Best Environmental Practices in Metal Ore Mining. The Finnish Environment 29en/2011. Finnish Environment Institute, Helsinki, p 219

Kern J, Tammeorg P, Shanskiy M, Sakrabani R, Knicker H, Kammann C, Tuhkanen E-M, Smidt G, Prasad M, Tiilikkala K, Sohi S, Gasco G, Steiner C, Glaser B (2017) Synergistic use of peat and charred material in growing media – an option to reduce the pressure on peatlands? J Environ Eng Landsc Manag 25:160–174

Klute A (1986) *Methods of soil analysis. Part 1. Physical and mineralogical methods.* 2nd ed. Agronomy 9. American Society of Agronomy, Soil Science Society of America. Madison, Wisconsin, p 1188

Kotilainen J (2015) Environmental Disasters as the Drivers for Policy Change – Case Study: Talvivaara Mine. Master thesis. University of Eastern Finland, p 101

Kukkonen S, Tammikari M, Tuomola P (2011) Decreasing phosphorus leaching and compaction of peat based growing media with clay, fiber clay and dark peat. Acta Hort 891:149–158

Kuokkanen T, Nurmesniemi H, Pöykiö R, Kujala K, Kaakinen J, Kuokkanen M (2008) Chemical and leaching properties of paper mill sludge. Chem Spec Bioavailb 20:111–122

Lange K, Rowe RK, Jamieson H (2010) The potential role of geosynthetic clay liners in mine water treatment systems. Geotext Geomembranes 28:199–205

Larchevêque M, Desrochers A, Bussière B, Cimon D (2014) Planting trees in soils above non-acid-generating wastes of a boreal gold mine. Écoscience 21:217–231

Lehmann J, de Silva JP, Steiner C, Nehls T, Zech W, Glaser B (2003) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249:343–357

Leppänen JJ, Weckström J, Korhola A (2017) Multiple mining impacts induce widespread changes in ecosystem dynamics in a boreal lake. Sci Rep 7:10581

Li Y, Hu S, Chen J, Müller K, Li Y, Fu W, Lin Z, Wang H (2018) Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J Soil Sediment 18:546–563

Lim TJ, Spokas KA, Feyereisen G, Novak JM (2016) Predicting the impact of biochar additions on soil hydraulic properties. Chemosphere 142:136–144

Liu Z, Dugan B, Masiello CA, Gonnermann HM (2017) Biochar particle size, shape, and porosity act together to influence soil water properties. PLoS ONE 12:e0179079

Lottermoser BG (2007) Mine wastes - Characterization, Treatment, Environmental Impacts, 2nd edn. Springer, Heidelberg, New York, p 304

Lutter R, Tullus T, Tullus A, Kanal A, Tullus H (2017) Forest ecosystem recovery in 15-year-old hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) plantations on a reclaimed oil shale quarry. Oil Shale 34:368–389

Martins GC, Penido ES, Alvarenga IFS, Teodoro JC, Bianchi ML, Guilherme LRG (2018) Amending potential of organic and industrial by-products applied to heavy metal-rich mining soils. Ecotoxicol Environ Saf 162:581–590

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 For 46:703–732

MEND 2012. Cold Regions Cover Systems Design Technical Guidance Document. The Mine Environment Neutral Drainage program (MEND). MEND Report 1.61.5c. mend-nedem.org/wp-content/uploads/2013/01/1.61.5c.pdf. Accessed 5 August 2019

Méndez A, Paz-Ferreiro J, Gil E, Gascó G (2015) The effect of paper sludge and biochar addition on brown peat and coir based growing media properties. Sci Hortic 193:225–230

Miller VS, Naeth MA (2017) Amendments and substrates to develop anthroposols for northern mine reclamation. Can J Soil Sci 97:266–277

Nelissen V, Ruysschaert G, Müller-Stöver D, Bodé S, Cook J, Ronsse F, Shackley S, Boeckx P, Hauggaard-Nielsen H (2014) Short-term effect of feedstock and pyrolysis temperature on biochar characteristics, soil and crop response in temperate soils. Agronomy 4:52–73

Nelson NO, Agudelo SC, Yuan W, Gan J (2011) Nitrogen and phosphorus availability in biochar-amended soils. Soil Sci 176:218–226

Nemati M, Simard F, Fortin J-P, Beaudoin J (2015) Potential use of biochar in growing media. Vadose Zone J 14:1–8

Niutanen V, Korhonen J (2002) Management of old landfills by utilizing forest and energy industry waste flows. J Environ Manage 65:39–47

Nurmesniemi H, Pöykiö R (2006) Sequential leaching of heavy metals in fibre clay from a chemical wastewater treatment plant at a paper mill. J Residuals Sci Tech 3:25–33

Nurmesniemi H, Pöykiö R, Keiski RL (2007) A case study of waste management at the Northern Finnish pulp and paper mill complex of Stora Enso Veitsiluoto Mills. Waste Manage 27:1939–1948

O'Kane M, Wels C (2003) Mine Waste Cover System Design - Linking Predicted Performance to Groundwater and Surface Water Impacts. In: Proceedings of 6 th International Conference for Acid Rock Drainage. Cairns, Qld., Australia, , July 2003. Carlton South, Vic: AusIMM, pp 341–349

Palviainen M, Berninger F, Bruckman VJ, Köster K, Moreira R, de Assumpção C, Aaltonen H, Makita N, Mishra A, Kulmala L, Adamczyk B, Zhou X, Heinonsalo J, Köster E, Pumpanen J (2018) Effects of biochar on carbon and nitrogen fluxes in boreal forest soil. Plant Soil 425:71–85

Peltz C and Harley C (2016) Biochar application for abandoned mine land reclamation. In: Guo M, He Z and Uchimiya SM (eds) Agricultural and Environmental Applications of Biochar: Advances and Barriers. Special Publication 63. Soil Science Society of America, Madison, pp 325–339

Pluchon N, Gundale MJ, Nilsson M-C, Kardol P, Wardle DA (2014) Stimulation of boreal tree seedling growth by wood-derived charcoal: effects of charcoal properties, seedling species and soil fertility. Funct Ecol 28:766–775

Pöykiö R, Nurmesniemi H, Keiski RL (2007) Environmental risk assessment of heavy metal extractability in a biosludge from the biological wastewater treatment plant of a pulp and paper mill. Environm Monit Assess 128:153–164

Raivio A-J (2013) Kuitusaven jatkokäsittelyvaihtoehdot. Insinöörityö, Kymenlaakson ammattikorkeakoulu. urn.fi/URN:NBN:fi:amk-2013121321142. [in Finnish] Accessed 5 August 2019

Redente EF, Mclendon T, Agnew W (1997) Influence of topsoil depth on plant community dynamics of a seeded site in northwest Colorado. Arid Soil Res Rehab 11:139–149

Robertson SJ, Rutherford PM, López-Gutiérrez JC, Massicotte HB (2012) Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. Can J Soil Sci 92:329–340

Sarauer J, Coleman MD (2018) Biochar as a growing media component for containerized production of Douglas-fir. Can J For Res 48:581–588

SFS-ISO 11466 (2007) Soil quality - Extraction of trace elements soluble in aqua regia. Helsinki Finland: Finnish Standard Association. Finnish Standard Association, Helsinki

Steiner C, Harttung T (2014) Biochar as growing media additive and peat substitute. Solid Earth Discuss 6:1023–1035

Sydnor WME, Redente EF (2002) Reclamation of high-elevation, acidic mine waste with organic amendments and topsoil. J Environ Qual 31:1528–1537

Thomas SC, Gale N (2015) Biochar and forest restoration: a review and meta-analysis of tree growth responses. New For 46:931–946

Tordoff GM, Baker AJM, Willis AJ (2000) Current approaches to the revegetation and reclamation of metalliferous mine wastes. Chemosphere 41:219–228

Thorpe N (2010) Notes from the red planet - Hungary's Worst ever Chemical Disaster. Hungarian Review 1:30–35

Tuomisto J, Virtanen E, Sipilä A, Simojoki A, Karppinen A, Kuokkanen T, Kuokkanen M, Kuokkanen V (2016) Maan rakenne osana perunamaan tuottavuutta ja ympäristönhoitoa. Loppuraportti. Perunantutkimuslaitos. urn.fi/urn:nbn:fi-fe2017112755074 [in Finnish] Accessed 5 August 2019

Verheijen F, Jeffery S, Bastos AC, van der Velde M, Diafas I 2010. Biochar application to soils A critical scientific review of effects on soil properties, processes and functions. JRC Scientific and Technical Reports. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg, p 162

Vuorenmaa J, Järvinen O and Leinonen L (2001) Sadeveden laatu ja laskeuma Suomessa vuonna 1998. Suomen ympäristö 468. Suomen ympäristökeskus ja Ilmatieteen laitos, Helsinki, p 115 [in Finnish]

Vuorinen J, Mäkitie O (1955) The method of soil testing in use in Finland. Agrogeological Publications 63:1–44

Yuan P, Wang J, Pan Y, Shen B, Wu C (2019) Review of biochar for the management of contaminated soil: Preparation, application and prospect. Sci Tot Environ 659:473–490

Zhu QH, Peng XH, Huang TQ, Xie ZB, Holden NM (2014) Effect of biochar addition on maize growth and nitrogen use efficiency in acidic red soils. Pedosphere 24:699–708

Zipper CE, Burger JA, Barton CD, Skousen JG (2013) Rebuilding soils on mined land for native forests in Appalachia. Soil Sci Soc Am J 77:337–349

Zipper CE, Burger JA, McGrath JM, Rodrigue JA, Holtzman GI (2011) Forest restoration potentials of coal-mined lands in the Eastern United States. J Environ Qual 40:1567–1577