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RESEARCH ARTICLE

Using turf transplants to reintroduce native forest understory plants into smelter-disturbed forests

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This study investigated factors affecting transplantation success of native forest understory vegetation on metal-contaminated soils. One year after transplantation along a gradient of historical Cu–Ni smelter pollution in Sudbury, Canada, community-level characteristics of the transplanted plots and short-term indicators expressing the performance of selected species were assessed. Thirty 16-m^2 plots were studied, each established with 45 transplanted 0.56 × 0.64–m turfs 10 cm thick, extracted from mixed-hardwood forests slated for development. Species richness, diversity, and evenness were not affected by environmental conditions but short-term responses of root growth and sexual reproduction of selected species to environmental variables indicate a need for long-term monitoring. Root growth of *Clintonia borealis* (Aiton) Raf. and *Gaultheria procumbens* L. was positively related to soil temperature. Root growth of *G. procumbens* correlated negatively with soil Ni availability, but in all plots, root growth was comparable with the literature values from unaffected forests. Flowering frequency of *G. procumbens* correlated negatively with soil pH and positively with tree cover, corresponding to ecological requirements of this species. Soil SO_4^{-2} had a negative effect on sexual reproduction of *C. borealis*. Unexpectedly, fruiting of *C. borealis* responded positively to Ni, and fruiting of *Maianthemum canadense* Desf. positively to As, possibly due to interdependencies among soil variables. The results are encouraging with respect to transplant success, as effects of smelter-related variables were relatively minor, but species-specific responses of the selected species to environmental factors indicate that species performance is dependent on site-specific conditions, potentially influencing long-term success of the transplants.

Key words: heavy metals, reproduction, root growth, smelter damage, soil temperature, transplantation success

Implications for Practice

- Transplanting turfs from areas slated for future development, with help of field crews, is a feasible method to accelerate the usually slow recovery of understory vegetation in restored forests after historical large-scale industrial damage.
- Good initial establishment of the understory plants even on metal-contaminated soils, with minimal losses compared with original vegetation, can be achieved by transplanting sections of 10-cm thick turf (diameter > 0.5 m) to even larger plots (16 m^2).
- As the success of restoration efforts using transplants can only be judged over longer-time periods, short-term measurements of plant performance (e.g. root growth and reproduction) can be used as potential indicators of the long-term prospects allowing for practitioners to adapt planting strategies and improve chances of success establishment.

Introduction

Metal-smelting activities have historically had large impacts on natural landscapes. Recovery of the vegetation in such areas is usually slow due to soil toxicity as well as poor water and nutrient availability and extreme microclimates resulting from associated environmental disturbances such as fire and erosion (Kozlov & Zvereva 2007). The area of focus in this investigation, the fragmented urban forests of Sudbury, Ontario, Canada, is an example of the severe negative effects past logging, fire, and prolonged Cu–Ni smelting can have on forest ecosystems (Winterhalder 1995). By the 1970s, 890 km^2 were left with only scattered stunted trees or with no trees at all and subjected to severe soil erosion (Courtin 1994). Revegetation of formerly forested lands in this area started in the late 1970s following improvements in air quality and reductions in aerial metal deposition (Watson et al. 2012). Revegetation efforts consisted of

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liming, seeding with an agricultural grass–legume mixture, and tree planting (Lautenbach et al. 1995). Understory species were expected to recolonize these areas naturally, but this succession appears to be very slow (Braun 2007). There is no information on seed banks in Sudbury soils prior to restoration, but based on studies elsewhere (Jiao et al. 2009), the intense soil erosion over several decades had likely led to a loss of the seed bank of native understory species. The slow recovery of understory herbs in disturbed habitats can be attributed to their poor dispersal ability, which plays an important role particularly in habitats that are fragmented or with the low nutrient availability of these soils (Mackenzie & Naeth 2010; Brunet et al. 2011). This is a problem for ecosystem recovery, as understory species make up as much as 80% of species richness in temperate forests and provide key ecosystem services (Gilliam 2007).

Based on these findings, active reintroduction of the forest understory species seems to be necessary. Corresponding with known principles of island phytogeography, transplants create islands with a higher species richness promoting dispersal within the region (van Diggelen et al. 2012). Few studies have investigated the constraints of such reintroductions in contaminated areas, particularly in metal-stressed soils. A review by Koch (2007) on techniques used to restore understory vegetation in a dry sclerophyllous forest after mining for bauxite in Western Australia found that understory richness could be largely restored through direct topsoil transfer, seed application, and vegetative multiplication. However, introduction by seed can be hampered by years of unfavorable climatic conditions, repeated introductions being necessary in such cases (Wilson 2015). In another review of plant reintroductions, Godefroid et al. (2011) found that greater success has frequently been achieved by reintroducing mature plants rather than seedlings or seeds. Older plants are less susceptible to harsh environmental conditions than seedlings and transplanting mature plants bypasses hazards associated with germination of seeds in the field (Davy 2002). At a coal mine reclamation site, spreading topsoil with propagules and plant fragments from a donor site has been shown to aid in forest understory recovery (Macdonald et al. 2015). In the Sudbury region, local seed of understory species is not commercially available, so the existing research has focused on other methods to transplant the understory species. Winterhalder (2004) found in an 8-year study on forested mine tailings that a small number of understory plants performed well when introduced using plugs of individual plants, or in topsoil heaps, but the majority of the species did not survive. Braun (2007) found better rates of establishment after 3 years for plants reintroduced as transplanted turfs into forests disturbed by Cu–Ni-smelting activities, compared with introductions by imported topsoil or transplanted plugs of single individuals. The introduction of transplanted single individuals of perennial herbs has also been shown to have low long-term success rate in Massachusetts forests, despite high initial survival (Drayton & Primack 2012). Poor understanding of site characteristics required for the successful establishment of understory species additionally hampers the attempts to restore forest ecosystems (Mottl et al. 2006; Drayton & Primack 2012), and a mismatch between habitat characteristics and species requirements is a frequent reason for a failure of species reintroductions (Godefroid et al. 2011). Success of species establishment depends on soil characteristics such as moisture, organic matter content (OMC), and light conditions as influenced by the degree of canopy cover (Mackenzie & Naeth 2010; Trusty & Ober 2011). The effect of the environmental conditions will likely depend on species-specific adaptations.

The aim of this study was to investigate the feasibility of the large-scale restoration of regional forest biodiversity by introducing understory species as transplanted turfs and to determine the effects of environmental variables on the establishment of understory vegetation in a landscape strongly influenced by past Cu–Ni smelter emissions. A relatively large size of turfs was used to minimize damage on transplants and to reduce the harshness of microclimatic conditions. The study area has a markedly improved air quality, but soil concentrations of metals such as Ni and Cu around the sites of historical smelter emissions remain high (Spiers et al. 2012). To explore the effect of environmental conditions on understory transplant success, the turfs were transplanted on sites with a range of soil metal contamination in the smelter-disturbed landscape of Sudbury, Canada. Our approach was to assess performance of select species in the transplanted turfs a year after transplantation to give an indication of the future performance of the introduced species under a range of environmental conditions. Root growth and sexual reproduction were measured for three understory species common to all of the transplanted plots. These traits are known to respond to metals and other external environmental conditions (Loehle 1987; Salemaa & Monni 2003; Ryser & Sauder 2006), and the ability of transplants to flower and set fruit has been considered as a key quantitative measure of reintroductions (Godefroid et al. 2011). Root growth also plays an important role in early stages of ecosystem development after restoration (Boldt-Burisch et al. 2015). We also measured vegetative spread of individual plants out of the 16-m^2 plots. For a community-level description of the transplanted vegetation, we calculated for each of the plots Shannon–Wiener diversity index, species richness, and evenness. Given the higher concentrations of plant-available metals that remain in soils closer to smelters, we hypothesized that the performance of three selected transplanted species would be negatively affected by plant-available soil contaminants and the proximity to the smelters. We also hypothesized that the establishment would depend on environmental factors not directly related to smelter effects, such as soil temperature, soil nutrients, and canopy cover.

Methods

Study Area

This study was conducted within the City of Greater Sudbury, Ontario, Canada (46°21′N, 80°59′W), on the southern edge of the Canadian Shield. The area is characterized by glacial deposits of sand and gravel and by thin discontinuous glacial till (Rousell et al. 2002). Soils of the study sites are podzolic or thin eroded soil layers (<10 cm) overlaying the bedrock (Gillespie et al. 1983). Average temperature in January is -13.5°C and 19°C in July, and the total annual precipitation is 899 mm, 47% of which occurs from May to September (Environment Canada 2012). The average frost-free growing season ranges between 125 and 145 days (OMAFRA 2013). Forests around Sudbury belong to Great Lakes-St. Lawrence forest region (Rowe 1972), and have been severely affected by logging, mining, and the smelting of the sulfide-rich Cu–Ni ore, beginning in the late 1800s (Winterhalder 1995). Over 100 million tonnes of SO_2 and tens of thousands of tonnes of Cu, Ni, and Fe have been released into the atmosphere as a result of over a century of mining and smelting activities within this region (Potvin & Negusanti 1995). These emissions have lowered soil pH and increased the amount of available metals in the soil and in plant tissue (Wren et al. 2012). Loss of tree canopy and a closed ground cover due to these combined industrial activities and associated environmental consequences resulted in extensive soil erosion (Courtin 1994).

Since 1972, enhanced smelter technology and increased government-regulated air pollution controls have reduced the amount of industrial emissions and have allowed Sudbury's landscape to slowly recover (Watson et al. 2012). This recovery has been augmented through municipal and industrial reclamation initiatives, which included application of limestone and fertilizer, seeding with agronomic grass–legume mixture (including species such as *Poa pratensis* L., *Festuca rubra* L., and *Lotus corniculatus* L.), and planting of trees and shrubs (Lautenbach et al. 1995). These efforts have allowed a partial recovery of forests dominated by trees such as *Betula papyrifera* Marshall, *Pinus resinosa* Aiton, *P. banksiana* Lamb., *Populus tremuloides* Michx., *P. grandidentata* Michx., and *Quercus rubra* L. (Sinclair 1996). Despite the great strides in ecological recovery, terrestrial plant communities within this area continue to be affected by elevated levels of soil metals, mainly Ni, Cu, and Co, low soil pH, low nutrient availability, and lack of soil organic matter (Wren et al. 2012). They also have low diversity of understory plants (Braun 2007).

Between April and September 2010, turfs of mainly herbaceous forest floor vegetation were salvaged from an area 50 km south of Sudbury slated for a highway expansion, hereafter referred to as the donor site (46°10′N, 80°43′W). This area was not affected by past smelter emissions due to the distance and location with respect to prevailing winds (Winterhalder 1995). Transplants contained herbs, shrubs, tree seedlings, ferns, lichens, and mosses. The most common herbaceous species introduced were *Aralia nudicaulis* L., *Clintonia borealis* (Aiton) Raf., *Cornus canadensis* L., *Maianthemum canadense* Desf., *Gaultheria procumbens* L., and *Trientalis borealis* Raf. Vegetation was removed with shovels in turfs roughly 64 × 56 cm and 10 cm thick, and transported in trays to Sudbury where they were stored and watered. One to three days following collection, the material was transplanted into sites located within the Sudbury region, hereafter referred to as receptor sites. The most commonly found species within these locations prior to receiving transplanted turfs included *Avenella flexuosa* (L.) Drejer, *Rumex acetosella* L., *Pteridium aquilinum* (L.) Kuhn, the mosses *Polytrichum* sp. Hedw., and *Pohlia nutans* (Hedw.) Lindb., and lichens of *Cladonia* sp. Hill ex P. Browne.

The turfs were planted into 16 m^2 units (4 × 4 m), hereafter referred to as plots. These plots were created by placing approximately 45 transplanted 0.64 × 0.56 m turf fragments adjacent to each other. The large size of the turfs should reduce hazards associated with establishment, such as root system damage and microclimatic effects. Woody debris and the existing vegetation were first removed from the receptor sites prior to transplantation. The underlying substrate was loosened with a garden fork to a depth of approximately 10 cm. To minimize desiccation and erosion, the turfs were placed flush with one another, and forest floor litter was raked up along the edges. The plots were not watered or fertilized after transplantation. Temperatures during the months of May to September 2010 were close to historical averages. Total annual precipitation was 660 mm, 27% below the historical average. Sixty-one percent of total annual precipitation in 2010 fell between the months of May and September (Environment Canada 2012).

A total of 250 plots of transplanted vegetation were created by the City of Greater Sudbury in the summer 2010. Sites for the plots were chosen to reflect the environmental variation in the area. Due to proximity to urbanized areas, minimizing tampering by the public was a priority, no attempts were made to randomize the site selection. Thirty of the transplanted plots were chosen for this study in 2011 (Fig. 1) and were selected to reflect gradients of historical smelter pollution and current tree canopy cover. Tree cover over the transplanted plots ranged from about 65% to a complete closure. In addition, six 16-m^2 plots of untransplanted vegetation were marked off in an undisturbed area of the donor site to serve as a comparison for the development of species composition of the transplanted plots. These donor site plots were only used as a comparison of species composition at the undisturbed donor site and were not included in tests of environmental effects.

Data Collection

Root growth of transplanted turfs into the receptor site soil was assessed for two common transplant species, *C. borealis* (Aiton) Raf. (blue-bead lily) and *G. procumbens* L. (wintergreen). These species are occasionally found throughout the Sudbury region, which indicates that they are able to tolerate the elevated metal levels to some extent. This makes them suitable species for this assessment, as a potential negative effect of the polluted conditions would not be fatal, as it could be for more vulnerable species. Root growth, expressed as root mass density, was assessed using the ingrowth core method as it is well suited for estimating the potential of annual fine root production between different sites and provides dependable and comparable results (Makkonen & Helmisaari 1999; Brunner et al. 2013). There was one core for each of the two study species per plot. The ingrowth cores were filled with 1-cm-sieved receptor site soil, collected within 1 m from the transplanted plot from the top 5-cm layer of soil where the metal contaminants in Sudbury soils mostly occur (Spiers et al. 2012). Ingrowth cores were installed in each transplanted plot between 19 May, 2011 and 21 June,

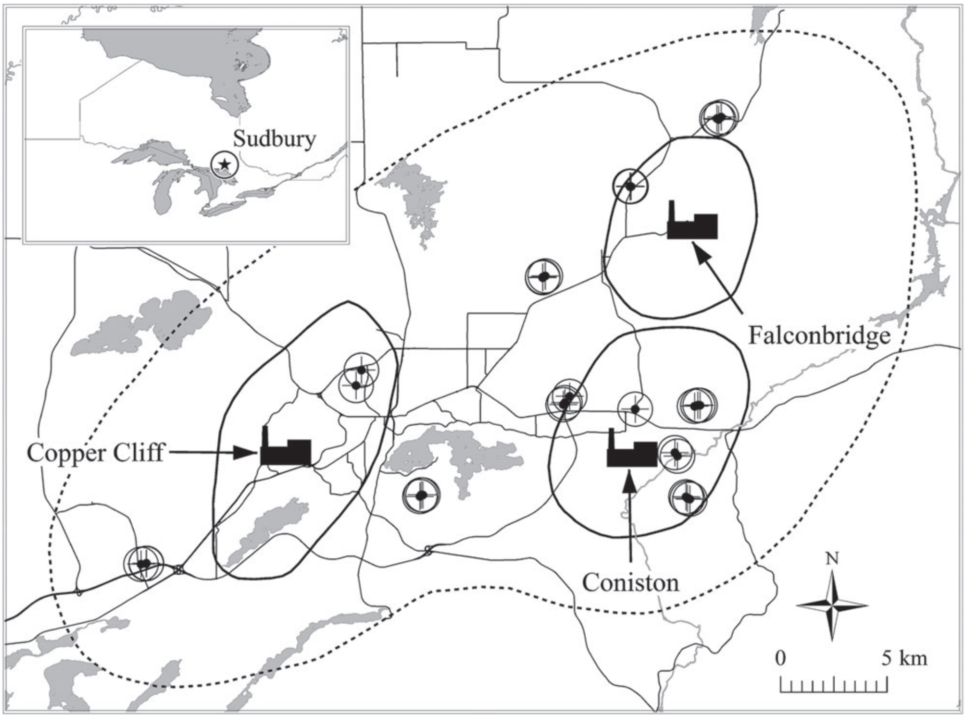

Figure 1. Map of the sites of plots investigated in this study (target signs) in relation to the degree of environmental damage at its height in 1973 in Sudbury region (Winterhalder 1995). Zones severely damaged by past smelter emissions are indicated with solid lines, the intermediately damaged zone with a hatched line. Smelter locations are indicated with factory signs. The Coniston smelter ceased operation in 1972, the other two have strongly reduced their output of air pollutants since the 1970s.

2011, each between two individuals of a study species, which were approximately 10 cm apart. Each core, a sock made of 5-mm nylon mesh with 5 cm diameter and 20 cm depth (less for shallow soils), was filled with the sieved soil. To achieve a similar bulk density within each core, the soil was added in 2-cm layers packing each layer lightly with a wooden dowel. The ingrowth cores were collected after 11 weeks in August and September, staggered in time in a similar manner as their installation. The cores were stored at 5°C for up to 5 days after which the roots were washed from the soil, dried at 75°C for at least 48 hours, and weighed. It was not possible to identify roots of the individual species. Root mass density was calculated as root dry mass divided by the core volume.

Sexual reproduction within each plot was quantified by counting the number of fruit-bearing individuals of *C. borealis* and another common transplant species, *M. canadense* Desf. (Canada mayflower), and by determining the flowering frequency of *G. procumbens* in early July 2011. Vegetative spread was described by the total number of individual plants producing runners beyond the edges of the 4 × 4−m plots in mid-July 2011.

The cover of all understory species in the 16-m^2 plots was determined between 25 June, 2011 and 11 July, 2011 using a modified Braun-Blanquet cover scale (Elzinga et al. 1998). Occasionally occurring weeds within the plots included *Hieracium aurantiacum* L., *H. caespitosum* Dumort., *L. corniculatus* L., *Fallopia cilinodis* (Michx.) Holub, *R. acetosella* L., *Taraxacum officinale* F.H. Wigg., and *Solidago* sp. L., and are referred to in this experiment as non-target species.

Tree canopy cover above the transplanted plots was measured between 30 June, 2011 and 7 July, 2011 using one spherical densiometer reading taken at the center of the plot (Lemmon 1956). Soil growing degree days (soil GDDs) were calculated for each transplanted plot based on measurements with iButton temperature data loggers (DS1921G-F5# Maxim Integrated, San Jose, CA, U.S.A.), placed in the center of each plot 4 cm below the soil surface in a waterproof PVC container (3.6 × 3.0−cm), with a measurement every 4.25 hours. Soil GDDs for the period between 1 January, 2011 and 27 June, 2012 were calculated using a base temperature of 5°C, commonly used in context of understory herbs (Anderson & Loucks 1973; De Frenne et al. 2011). Distance from the nearest of the three smelter locations (Fig. 1) was measured using topographic maps (Department of Energy, Mines and Resources, Canada).

In May 2012, 18 soil samples were collected around each transplanted plot 1 m from the edge and from the top 5-cm layer, and pooled into one sample. Soil samples were collected using a stainless steel corer with 5 cm diameter (Nelson GM Ltd., Sudbury, Ontario, Canada). Plant-available chemicals of concern (Cu, Ni, Co, Pb, As, and Se) were extracted with ammonium acetate (Baker et al. 1994) and analyzed with inductively coupled plasma mass spectrometry (ICP-MS) (Testmark Laboratories, Sudbury, Ontario, Canada). To measure pH, SMP buffer solution (Shoemaker, McLean and Pratt method) was used (Agri-Food Laboratories, Guelph, Ontario, Canada). Plant-available P, K, Ca, and Mg, total organic C, SO_4, NO_3^-, and NH_4^+, and cation exchange capacity (CEC) was analyzed at Agri-Food Laboratories using provincially accredited protocols.

Data Analysis

Multiple linear stepwise regressions were conducted to identify environmental factors explaining plant traits related to transplant establishment. Due to the large number of environmental variables, the number of independent variables was reduced prior to the regressions to reduce collinearity within the models. To achieve this, six plant-available chemicals of concern (Cu, Ni, Co, Pb, As, and Se) were first reduced using a principal component analyses (PCA) with varimax rotation. The suitability of the data for the PCA was assessed using the Kaiser–Meyer–Olkin measure of sampling adequacy (>0.6) and Bartlett's test of sphericity ($p < 0.05$; Norman & Streiner 2008). Eigenvalues and scree plots were used to determine principal components. Plant-available chemicals of concern with the highest loading values from these rotated principal components were then retained for evaluation for collinearity. After this, for all remaining variables, Pearson product-moment correlations were conducted between all possible pairwise combinations, and in case of highly significant correlation ($p < 0.01$) between two variables, the a priori more important variable was retained (Table S1, Supporting Information). Dependent variables used for multiple regression analysis consisted of root mass density of *G. procumbens* and *C. borealis*; frequency of flowers produced by *G. procumbens*; number of fruiting individuals *M. canadense* and *C. borealis*; spread of individual plants from the plots; species richness; Shannon–Wiener diversity index; and evenness. Non-target species were not included in calculation of community characteristics. To attain normality, the number of fruiting individuals of *M. canadense*, distance from a smelter, and all soil chemical variables were log transformed prior to analyses. Root mass density of *G. procumbens* and *C. borealis* were square root transformed. In the multiple regression analyses, the best models were selected using the Akaike information criterion (AIC). All statistical analyses were performed using SPSS version 19 (Chicago, IL, U.S.A.).

Results

For the PCA used to reduce the number of chemicals of concern to be utilized as independent variables, As and Ni showed the highest correlations with the two first components (each $r > 0.9$), respectively, and were retained for the regressions. Among the remaining environmental variables, soil pH, CEC, and OMC strongly correlated with each other. Of these three variables, pH was retained due to its central role for soil chemistry, including metal toxicity. Consequently, the independent variables in the multiple linear regression included plant-available Ni, As, P, NO_3^-, and SO_4^2, soil pH, soil GDD, percent tree canopy cover, and distance from a smelter.

In stepwise liner regression between measured plant traits and environmental variables, root mass density of both *Gaultheria procumbens* L. and *Clintonia borealis* (Aiton) Raf. in the ingrowth cores related positively with soil GDD (Table 1). In addition, the root mass density of *G. procumbens* was negatively related to plant-available Ni. In contrast, root mass density of *C. borealis* was not affected by smelter-related variables (mean *C. borealis*: 0.63 g/cm^3, range: 0.16–1.37 g/cm^3; mean *G. procumbens*: 0.68 g/cm^3, range: 0.06–1.49 g/cm^3; Table S2).

Flowering frequency of *G. procumbens* in the transplanted plots ranged between 0 and 90% and was negatively related to pH and positively to percent canopy cover (Table 1). *Clintonia borealis* had between zero and six fruiting individuals per plot, the number being negatively related with soil SO_4^{-2}, but positively related with plant-available Ni (Table S2). The number of fruit-bearing individuals of *Maianthemum canadense* ranged between 0 and 14 per plot and was positively related to plant-available soil As and negatively to plant-available P (Table S2). Just over 60% of observed transplanted plots had at least one individual spreading from them with an average of 3.5 individuals and a maximum of 26 individuals. These variables were not significantly related to any of the environmental variables.

A total of 102 species (excluding non-target weedy species) were encountered in our transplanted plots, with an average of 24 species per 16-m^2 plot (Table S3), when compared with the donor site plots, with 17 species per plot. The transplanted plots were also more diverse with a Shannon–Wiener diversity index of 2.65 for transplanted plots and 2.40 for donor site plots. The range in species evenness within plots (between 0.67 and 0.96) was similar in range to that of the donor plots (between 0.72 and 0.93). Environmental site characteristics did not explain variation in target plant species richness, Shannon–Wiener diversity index, or evenness within the plots. Twenty-one plots had non-target species within them, mostly *Hieracium* sp. L. or *Rumex acetosella* L., on average 1.2 species per plots. Their number was not affected by the environmental variables.

Discussion

High metal concentrations, low pH, low nutrient availability, poor water-holding capacity in the soils and low canopy cover have been found to limit colonization of understory plants in close proximity to Cu–Ni smelters (Kozlov & Zvereva 2007). Loss of seed bank due to soil erosion, characteristic for smelter-damaged lands, is also a factor that can inhibit colonization (Jiao et al. 2009). Poor dispersal ability of understory herbs is also attributed to limited ability of understory herbs to recolonize disturbed sites (Mackenzie & Naeth 2010). Elevated concentrations of soil Cu and Ni are known to reduce root growth of herbs and shrubs (Salemaa & Monni 2003; Roiloa & Retuerto 2006), which could make transplanted vegetation on metal-contaminated soils more sensitive to desiccation, in addition to their increased vulnerability to xylem embolisms (Tanentzap & Ryser 2015). Transplantation itself also damages the roots. Also in this study, some smelter-related effects were found, the negative relationships being significant between

Table 1. Models which significantly explain variance of the investigated dependent variables. Independent variables retained in the analyses are Ni, plant-available soil nickel; soil growing degree days, sGDD; pH, buffering soil pH; Cover, percent tree canopy cover; SO_4^{2-}, plant-available sulfate; P, plant-available phosphorus; and As, plant-available soil arsenic.

Dependent Variable	*n*	*Best Fit Regressions*	r^2	*AIC*	*F*	*p*
Root growth *Gaultheria*	28	$y = -0.43\ \log(\text{Ni}) + 0.00094\ \text{sGDD} + 0.55$	0.48	−12.0	12.2	<0.001
Root growth *Clintonia*	30	$y = 0.00092\ \text{sGDD} + 0.24$	0.16	−5.6	5.1	0.033
Flowers *Gaultheria*	30	$y = -2.42\ \text{pH} + 0.11\ \text{Cover} + 8.36$	0.34	130.5	6.8	0.004
Fruits *Clintonia*	30	$y = -4.49\ \log(\text{SO}_4^-) + 2.31\ \log(\text{Ni}) + 6.19$	0.32	117.8	6.3	0.007
Fruits *Maianthemum*	30	$y = -0.44\ \log(\text{P}) + 0.40\ \log(\text{As}) + 1.42$	0.27	−24.5	4.8	0.015

fruiting of *Clintonia borealis* and soil SO_4^{-2}, and between root growth of *Gaultheria procumbens* and soil Ni concentration. Yet, these adverse effects of smelter-related factors on plants in the turfs 1 year after transplantation were not fatal, and contrary to our prediction, root growth within plots of the two observed species was not significantly explained by proximity of the plots to the smelters. The range of observed root growth in the ingrowth cores, when converted into area-based root mass density, is comparable with studies of root production in boreal forest herbs growing in undisturbed forests. Bauhus and Messier (1999) found in aspen- and conifer-dominated boreal forests root mass densities for herbs and unidentified plants of 6–22 g/m^2, compared with 31–273 g/m^2 for *C. borealis* and 8–284 g/m^2 for *G. procumbens* in this study. It is possible that some roots of other understory species within the plots grew into the ingrowth cores, but that does not influence the conclusion that root production on the sites was comparable with that in undisturbed forests.

The relationships between environmental conditions and sexual reproduction were different for the three investigated species, indicating that the probability of a successful long-term establishment along the gradient of smelter effects may differ among the species. The positive responses of fruit production of *Maianthemum canadense* and *C. borealis* to plant-available As and Ni, respectively, were surprising, as elevated concentrations of Cu, Ni, and As have been shown to decrease fruit yield (Barrachina et al. 1995), reduce investment into sexual reproduction (Saikkonen et al. 1998), or delay reproduction (Ryser & Sauder 2006). Nevertheless, in a similar manner, Zvereva and Kozlov (2005) found increasing seed production in *Vaccinium* sp. with increasing proximity to a Cu–Ni smelter, explaining it as stress-induced flowering (Loehle 1987). Low levels of arsenic have also been found to stimulate root growth in *Artemisia annua* (Rai et al. 2011). The positive responses may also have been coincidental, e.g. as availability increasing with the distance from a smelter, possibly due to changed soil sorption characteristics (Barry et al. 1995; Jones et al. 1997). The negative relationship between soil P and sexual reproduction of *M. canadense* might be a positive response to liming, which can reduce P availability (Schachtschabel et al. 1989).

The response of flowering of *G. procumbens* to environmental variation in this study seems to reflect ecological requirements of this species. Its flowering was positively related to soil acidity and higher canopy cover, the species having a known affinity for such sites (Moola & Vasseur 2009).

General site quality played a role especially for root growth. Root mass density of both *G. procumbens* and *C. borealis* positively correlated with soil GDD, warm soils promoting root growth. It is not clear what is driving the observed variation in soil temperature, as soil GDD unexpectedly did not correlate with canopy cover. GDD could be influenced by several factors such as slope aspect and thermal properties of soils (Oke 1992). These findings suggest that warm sites are advantageous for transplant establishment, at least for our observed species.

Shannon–Wiener diversity index, evenness, and species richness of targeted species in the plots, as well as vegetative spreading out from the plots were not significantly influenced by the measured environmental variables. Diversity and richness along pollution gradients created by smelter emissions are all known to be reduced in the long term as a result of low pH, metal stress, and harsh microclimates associated with these areas (McLaughlin 1985), but in this study, no relation between these measures and environmental site conditions was detected 1 year after transplanting. This could be the result of a slow response of newly transplanted species, as found by Mottl et al. (2006), changes in species composition in response to environmental conditions happening only over longer time periods. Nevertheless, the few observed negative effects on performance of the selected species are in agreement with Saikkonen et al. (1998) who found negative effects of vicinity of a smelter on sexual and vegetative reproduction already after 37 days and may indicate possible negative long-term effects on sensitive species. The slightly higher values for species richness and Shannon diversity of targeted species in the plots compared with donor plots were possibly a result of a bias to select species-rich transplant material.

Disturbances can promote the establishment of ruderal and exotic species that can then subsequently prevent the regeneration of native species (Pyle 1995; Stylinski & Allen 1999). Invasion of such species can be an expensive problem to control in restored forests, and a careful monitoring should be implemented to avoid such issues from intensifying (Greipsson 2011). There were few weedy non-target species within the plots, including *Lotus corniculatus* L. of the restoration seeding mix comprised of agronomic grasses and legumes used in this region. This would suggest that non-target weedy species colonizing plots are not a present threat, but long-term monitoring should be continued to determine whether fast-growing non-target species could outcompete the transplanted species in the future.

As metal-contaminated soils are a widespread phenomenon associated with mining industry (Kozlov & Zvereva 2007), there is a need to test methods to enhance understory richness in temperate and boreal forests on metal-contaminated soils. Due to lack of commercially available seed and slow succession rates in the cool climate, transplantation of understory turfs seems to be a promising method. But as the use of transplanted turfs for reintroduction is costly and labor intensive and access to transplantable plant material is limited, a success has to be probable. Hence, to attain early indication of how transplanted species would respond to their new environment, we propose testing species that are common to transplant turfs by measuring traits related to plant's ability to become established on the site. Root growth and sexual reproduction are such traits, for example. Early signs of stress could allow restoration practitioners to adjust their planting strategies accordingly. In our study, smelter-related environmental factors did not affect diversity and species richness of the plots within a year, and despite differences along the gradient, the observed quantity of root growth is encouraging for the long-term prospects. The large size of transplants may have contributed to this, as turf fragments of at least 20–30 cm in diameter have been found to be more favorable for the transplantation or rhizomatous herbs and resulting in greater species richness in comparison with smaller turf fragments which favor grasses and mosses (Aradottir 2012). However, significant negative effects of smelter-related variables on aspects of performance of some of the species may indicate reduced longer-term transplant success under certain site conditions.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Pearson's product-moment *r* correlations between environmental predictors.

Table S2. Environmental variables and variables describing community characteristics and performance of the selected species in the 30 forest understory turf transplanted 16-m^2 plots of this study.

Table S3. List of species found in the 30 transplanted 16-m^2 plots and the percentage of plots each species occurred in.

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