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Research Article

Anthropogenically-modified soil increases the performance of non-native plants in a subarctic ecosystem

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Abstract

Waste dumps contain human-modified soils that differ substantially from soils in natural areas. Such soils can create a suitable environment for weedy non-native species, so that waste dumps can act as epicentres for further dispersal. In the subarctic town of Churchill, Manitoba, Canada, multiple sites have been anthropogenically disturbed by the input of manure, agricultural waste and garden waste. Large populations of non-native plants often dominate these anthropogenically-altered sites, while nearby undisturbed areas with natural soil remain free of non-native species. When soil from these dumps is moved to other areas for construction, road repair or other purposes, these non-natives can travel with it and potentially establish new populations. In this study, we conducted soil addition experiments to investigate whether human-modified soil provide an ameliorated environment for non-native species when they are moved together into native-dominated subarctic ecosystems. We found that non-native species were able to germinate and survive in soils translocated from dumpsites into previously uninvaded areas in tundra or boreal forest. In addition, we found that deeper translocated soil tended to further increase the growth of non-native species. These results indicate that transported dumpsite soil creates an improved environment for non-native plants temporarily. However, survival decreased over time, suggesting that the ameliorated below-ground associated conditions were not sufficient to allow persistence in natural environments. As the climate continues to warm, anthropogenic soil movement may increase future risk of spread into currently inhospitable habitats.

Key words: Anthropogenic change, human-modified soil, non-native species, plant invasions, subarctic, waste dumps

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Introduction

Soils of human-disturbed sites can substantially differ from soils of undisturbed areas. In particular, refuse and waste collection areas, hereafter “dumps”, can provide a uniquely suitable environment for non-native plant species to invade and persist (Pyšek et al. 2003; Mokotjomela et al. 2022). Additionally, seeds and plant fragments of non-native species may be deposited into dumps, either as garden waste (Reichard and White 2001; Rusterholz et al. 2012) or as agricultural contaminants (Ikeda et al. 2022). Dumps are consequently a source of non-native plant species that can escape into the adjacent habitat (Ødegaard and Tømmerås 2000; Plaza et al. 2018).

The effect of human-disturbed soil on non-native species conflates several anthropogenic factors. The physical disturbance of such an area can remove competing native species, resulting in more available resources for non-natives (Davis et al.

2000). Human activity also tends to result in increases in soil nutrients (Pauchard et al. 2009), which may disproportionately benefit non-native species (Dukes and Mooney 1999; Liu et al. 2017). The association and proximity of dumps to settlements and other human activity can result in repeated inputs of non-native propagule pressure from multiple sources. Disentangling these factors can be difficult; here, we aim to investigate the overall effect of translocated dump soil on non-native species, instead of partitioning this effect into causal factors.

Dumps may especially increase the invasion risk of non-native species in otherwise unsuitable sites, such as at the edge of their ranges. For instance, tundra and other high latitude ecosystems are typified by nutrient-poor soils, low invertebrate and fungal diversity and harsh growing conditions (Robinson et al. 2003; Barry et al. 2013). As a result, non-native plants that are common in temperate regions still are relatively scarce at higher latitudes (Walther et al. 2009; Smith et al. 2012; Bartlett et al. 2021). Dumps, however, can create microsites of more suitable habitat, alleviating some of these stresses and providing large volumes of hospitable soils for weedy non-native species to colonise. Subsequent persistence of non-native species in these habitats may be due to growth via rhizomes and plant fragments or via germination of the soil seed bank that may form due to repeated inputs and seed storage from the plants that flower on these sites (Chesson 2000; Gioria and Pyšek 2016).

An ideal place to study the importance of dumpsite soil for non-native species is Churchill, Manitoba, Canada (58.5°N). A railway has linked a wharf and grain elevator in Churchill to southern agricultural areas since 1931 (Brandson 2011), bringing shipments of grain, but also seeds and other material from non-native species. These contaminants were cleaned from the grain before export and disposed of in several dumps close to town (Kent et al. 2018). Several of these areas also have been used for the disposal of manure from local livestock and potentially for household and garden waste and some are now dominated by persistent non-native plant species (Kent et al. 2018). Soil in these areas is regularly moved around for purposes including the construction and maintenance of roads, power lines and gardens (Syed et al. 2023). Seeds and other propagules in these contaminated soils can germinate to establish new satellite populations, though it is unclear how long such populations usually persist (Kent et al. 2018).

Although natural, undisturbed areas in the subarctic, such as the tundra and boreal forest, currently are inhospitable for most non-native species (Anisimov et al. 2007; Alsos et al. 2015), germinating and growing in soils originating from dumpsites may help non-natives to overcome these barriers to invasion. In a greenhouse study, we previously have shown that soils from invaded sites in the Churchill area frequently contain viable seeds of both native and non-native weedy species (Syed et al. 2023). Here, we investigate whether such soil is simply a vehicle for the movement of non-native species to new sites or whether it also provides a hospitable environment for them in otherwise invasion-resistant habitats. To accomplish this, we established two field experiments in uninvaded areas. The first was a spatially-replicated Common Garden experiment, in which we compared the growth and survival of fragments of non-native plants in soil collected from invaded dumpsites versus naturally-occurring soils. The second was a Cross-Biome experiment, in which we compared survival and growth of transplanted fragments of non-native plants in two different depths of dumpsite soil along roadsides in the tundra and boreal forest.

Materials and methods

Study species

In both experiments, we used locally-collected transplants of three weedy non-native perennials: *Plantago major* L. (common plantain), *Linaria vulgaris* Mill. (common toadflax) and *Taraxacum officinale* F.H. Wiggers (common dandelion). All three species are introduced from and widely distributed in Europe, but have occurred in the Churchill area for over 60 years (Beckett 1959) . All produce seeds; however, seeds of locally-occurring *L. vulgaris* are rarely viable (Staniforth and Scott 1991) and this species consequently may, instead, rely on rhizome fragments for spread (Nadeau et al. 1992; Syed et al. 2023). All non-native plants and dump soil were removed upon the completion of each experiment.

Soil collection sites

Soil used in these experiments was collected from four dumpsites in the Churchill area (Suppl. material 1: fig. S1). All of these sites are extensively invaded by non-native species, including *L. vulgaris*, *P. major* and *T. officinale*. Soil collected from these areas were visibly darker, suggesting previous nutrient enrichment and greater organic content (see Kent et al. (2018); Syed et al. (2023) for further analyses of invaded soils) and possibly higher temperatures due to heat absorption. Field-collected soil was homogenised prior to transplant. Soil collection sites were at least 10 km away from the study sites.

Common garden experiment

This experiment was established in August 2021, near the end of the growing season, to determine if the presence of translocated dumpsite soil is sufficient to support the growth of invaders. In a previously disturbed, currently revegetated treeline area near the Churchill Northern Studies Centre (CNSC: https://churchillscience.ca/), approximately 20 km east of the town of Churchill, a common garden with thirty 25 cm × 25 cm plots was established (Suppl. material 1: fig. S2). This site was chosen because past disturbance associated with construction and proximity to the road network make it representative of the kind of site vulnerable to soil dumping. Soils were stony marine sediments; vegetation was sparse, but typical of nearby tundra sites, with species such as *Rhododendron lapponicum* (L.) Wahlenb. (Lapland rosebay), *Salix* spp (willows), *Arctostaphylos* spp (bearberry), *Vaccinium uliginosum* L. (blueberry), *Dryas integrifolia* Vahl (arctic avens) etc. Plots were randomly divided into two treatments: half of these plots were disturbed and raked to a depth of 5 cm, but original soil was kept in the plot ("tundra" soil); in the remaining plots, original soil was removed to a depth of 5 cm and replaced by homogenised field-collected soil from the three dumpsites located at the Port of Churchill (Cape Merry Roads, Granary Ponds and Port Roads), at the north edge of the town (Suppl. material 1: fig. S1). Layers of dumped soil this thin have been observed to support non-native plants in the field (*pers. obs.*). One individual of each species was transplanted into each plot: for *L. vulgaris*, we planted the shoot and 5 cm of the rhizome and for *P. major* and *T. officinale*, we planted the complete rosette and roots. Prior to planting, initial condition was recorded: height was measured for *L. vulgaris* and the length of the longest leaf for both *P. major* and *T. officinale*.

These plots were monitored throughout the summer growing season from 2022 until 2024. Transplants were surveyed for survival by recording emergence and survival aboveground. If transplants emerged, but died in the same summer, the individual was recorded as dead for the respective year. Performance metrics were recorded individually for each species: plant height and the number of ramets was recorded for *L. vulgaris* and length of the longest leaf and number of leaves were recorded for both *P. major* and *T. officinale*. In 2024, all surviving transplants were harvested, dried at 60 °C for 48 hours and weighed to determine above- and belowground biomass.

Cross-biome experiment

In August 2023, a second experiment was established to test the effect of the depth of transported soil on non-native species introduced as ramets or in the soil seed bank across two habitats. Along the edges of roadsides near the CNSC, 16 experimental sites were established (Suppl. material 1: fig. S2). Eight sites were located along Palsa Road surrounded by lichen-heath tundra, dominated by plants including *Arctostaphylos* spp. (bearberry) and other species of Ericaceae, *Dryas integrifolia* (arctic avens) and *Salix reticulata* L. (snow willow). Another eight sites were along Twin Lakes Road, surrounded by boreal forest dominated by *Picea glauca* (Moench) Voss (white spruce), mosses and lichens. In both habitats, the plots were established adjacent to the roadway on roadsides consisting largely of exposed sand and gravel, with a few pioneer species, notably *Dryas* and acrocarpous mosses, such as *Dicranum* spp. Sites were separated by 500 to 1000 m by road to capture spatial variation across along each roadside. Roadsides like this are vulnerable to dumping and have occasionally been observed to support non-native plants (usually *P. major* and *T. officinale*), but typically are within a few metres of natural tundra or boreal forest.

Dump soil was collected again, this time from Cape Merry Road and the entrance to the currently operational city dump (Suppl. material 1: fig. S1). At each roadside site, three 25 cm × 25 cm plots were established, separated by approximately 25 cm from each other. In two randomly-selected plots, the original soil was removed and the human-modified dump soil was added to two depths: 5 cm (“shallow”) and 20 cm (“deep”). The third plot at each site was disturbed to a depth of 5 cm, but the original tundra/boreal forest soil was not replaced, acting as a control. One individual of *L. vulgaris*, *P. major* and *T. officinale* was transplanted into each of these 16 experimental sites. Similar to the Common Garden experiment, we measured initial condition prior to planting, which included also measuring the length of rhizomes of *L vulgaris*.

We returned to all plots in August of 2024 to record survival data of transplants and performance at the end of the growing season, using height and number of ramets for *L. vulgaris* and the length of the longest leaf and number of leaves for both *P. major* and *T. officinale* (the same metrics as the Common Garden experiment). All surviving transplants were then removed, dried in 60 °C for 48 hours and weighed to determine above- and below-ground biomass. Natural emergence of the seed bank was recorded for non-native species identity and total number of seedlings in August. We did not assess the number of ungerminated seeds.

Statistical analysis

All statistical analyses were conducted in R (Version 4.1.1; R Core Team (2021)). For all tests, we initially created fully crossed mixed effects models with the blocking effect of plot/site using the `lme4` package (Version 1.1-30; Bates et al. (2015)) and created additional models by removing fixed and random effects using the `stats` package (Version 4.1.1). We performed model comparison using Akaike's Information Criterion corrected for small samples (AICc; Johnson and Omland (2004)) and we present results ($\alpha = 0.05$) using Type 3 analysis-of-variance from the `car` package (Version 3.1-2; Fox and Weisberg (2019)) for the models that performed equally or better during model selection (See Suppl. material 1: table S9 for a summary of all models used). We conducted post-hoc tests by computing estimated marginal means (EMMs) using the `emmeans` package (Lenth et al. 2021).

In the Common Garden experiment, a binomial generalised linear model was used to test for an effect on survival, blocked by plot, resulting in the formula: `~ soil origin + year + (1|plot)`. A linear mixed effects model was used to analyse the effect on plant growth using with plot used as a random effect: `~ soil origin + year + (1|plot). Although we measured initial plant size (height for *L. vulgaris* and leaf length of both *P. major* and *T. officinale*), models with initial plant size as a covariate did not perform as well (higher AICc by over 2 units) as a model without initial size, so we dropped this variable to prevent overfitting. We natural log-transformed the height measurements for *L. vulgaris*, but did not transform any other measurements of growth, to meet the assumption of normality of residuals. We compared growth between soil origin treatments and over time from 2022–2024 (or over time from 2022 to 2023 for *T. officinale*, as there were no more surviving transplants in 2024), but did not compare transplant sizes to the initial pre-transplant size measured in 2021. Only three transplants survived by 2024 (one *P. major* in dump soil, one *P. major* in the control and one *L. vulgaris* in dump soil) and only two individuals of *L. vulgaris* flowered in 2022 in dump soil, with no successful flowering in subsequent years (Suppl. material 1: table S1); thus, no analyses were performed on biomass or flowering measurements.

In the Cross-Biome experiment, a binomial generalised linear model was used to test for an effect on survival: `~ habitat + soil depth`; a Poisson generalised linear model was used to test for an effect on germination from the soil seed bank by species: `~ habitat + soil depth + species`. A linear mixed effects model was used to analyse the effect on plant size and biomass with initial transplant size as a covariate only for *L. vulgaris* and *T. officinale*: `~ habitat + soil depth + initial size`; models fitted for *P. major* growth with initial plant size (leaf length) did not perform as well, so we dropped them, resulting in the model: `~ habitat + soil depth`. We natural log-transformed all measurements of growth and biomass for all three species to meet the assumption of normality of residuals. We again compared transplant growth across soil depth treatments, but did not compare transplant size against the initial pre-transplant size.

Results

Common garden experiment

In the Common Garden experiment, there was no effect of the soil origin on the survival of any of the three non-native transplants, but survival significantly declined over time for all three species (Fig. 1, Suppl. material 1: tables S1, S2); for *L. vulgaris* and *T. officinale*, no control plants survived past 2022, restricting the number of comparisons possible for measurements of performance. There was no effect of soil origin on the physical size of *L. vulgaris* (plant height or number of ramets; Fig. 2A). For *T. officinale*, dump soil improved performance (Fig. 2C, Suppl. material 1: table S3). Leaves of *T. officinale* were longer in dump soil one year post-transplant in 2022 ($F_{(1,15)} = 16.69$, $p = 0.001$), with an average leaf length of 7.6 cm in dump soil compared to 4.9 cm in control soil. Over time, transplant sizes decreased: the average number of leaves of *T. officinale* decreased over time from 8.7 in dump soil and 7.0 in control soil in 2022, to 5.0 in dump soil in 2023 ($F_{(1,3)} = 15.56$, $p = 0.03$). The size and number of leaves of *P. major* declined over time (Fig. 2B, Suppl. material 1: table S3): transplants had on average 6.5 leaves in dump soil and 6.4 leaves in control soil in 2022, but leaf number decreased to 3.0 in dump soil and 4.0 in control soil in 2024 ($F_{(1,15)} = 34.33$, $p = 0.002$);

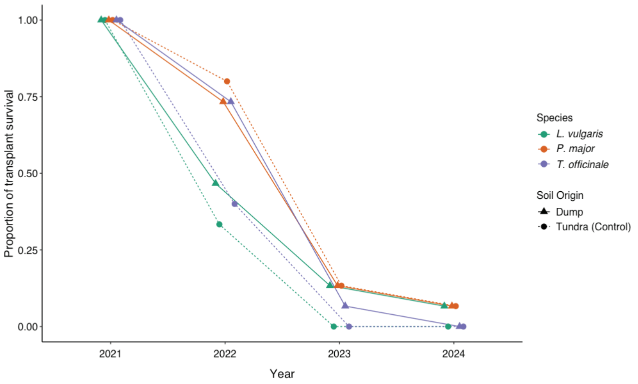

Figure 1. Proportion of surviving non-native transplants at the end of the summer in dump soil (triangles, solid line) or tundra soil (circles, dotted line), coloured by the non-native species in the Common Garden experiment. There is no significant difference in survival between soil origins for any of the three non-native species, but there was a significant negative effect of year for *L. vulgaris* ($p = 0.01$), *P. major* ($p < 0.001$) and *T. officinale* ($p < 0.001$).

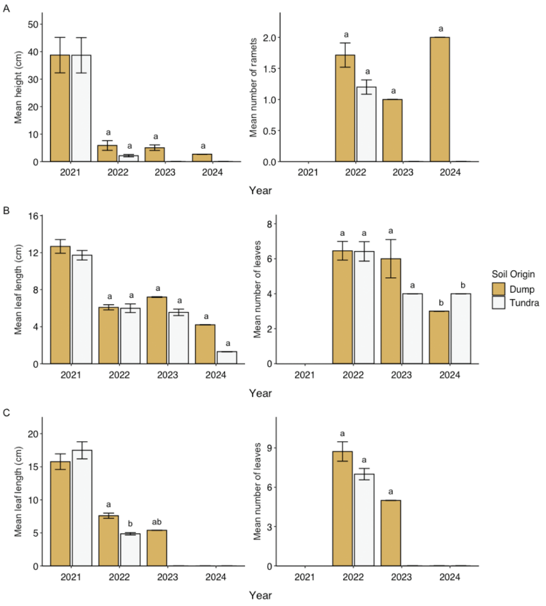

Figure 2. Growth (± standard error) of transplants in dump (yellow) and control tundra (white) plots over time, including initial size in 2021, in the Common Garden experiment. Bars sharing letters do not differ significantly ($p > 0.05$). **A.** There was no effect of soil origin or year on *L. vulgaris* height (cm) and number of ramets; **B.** There was no effect of soil origin on leaf length (cm) and number of leaves of *P. major*, but transplants had smaller ($p = 0.07$) and fewer leaves ($p = 0.002$) over time; **C.** Transplants of *T. officinale* in dump soil had a longer leaf length (cm) ($p = 0.001$) and transplants had smaller ($p = 0.06$) and fewer leaves ($p = 0.03$) over time.

transplant leaves also trended towards shorter lengths, from 6.1 cm in dump soil and 6.0 cm in control soil in 2022, to 4.2 cm in dump soil and 1.3 cm in control soil by 2024, but the effect was marginally non-significant ($F_{(1,21)} = 3.09$, $p = 0.07$).

Cross-biome experiment

In the Cross-Biome experiment, there was no significant effect of soil depth treatment or habitat on survival of *L. vulgaris* or *P. major* (Fig. 3, Suppl. material 1: tables S4, S5), whereas survival was higher in the boreal forest for *T. officinale* transplants ($p = 0.03$). We observed seeds of five different non-native species germinating from the soil seed bank (Table 1), but no significant differences between soil treatments ($\chi^2 = 2.85$, $p = 0.09$) or habitats ($\chi^2 = 2.89$, $p = 0.09$, Suppl. material 1: table S6).

When experimental effects on plant growth were detected, post-hoc tests found that plants were significantly larger on the 20 cm deep dump soils compared to the 0 cm control and there was a general trend towards greater growth with deeper soil, but there was no detected difference between transplants in the tundra and boreal

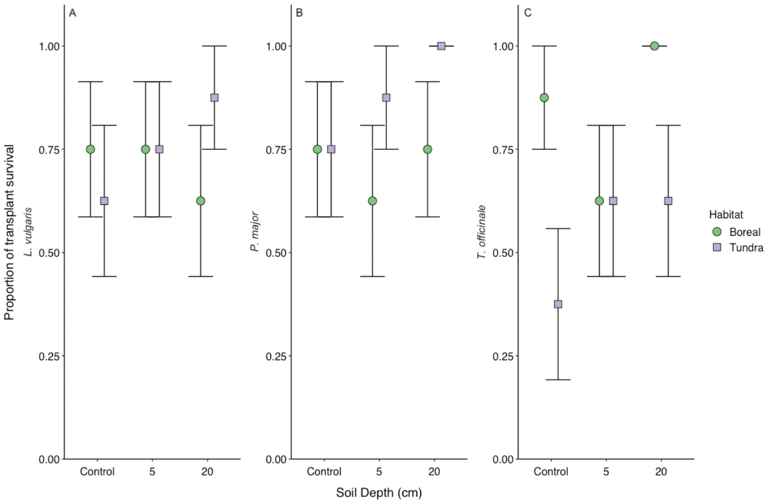

Figure 3. Average survival (± standard error) of transplants (**A.** *L. vulgaris*; **B.** *P. major*; **C.** *T. officinale*) in different depths of anthropogenically-modified soils (5 cm and 20 cm) and original soil (control) in boreal forest (green circles) and tundra (purple squares) roadside plots one year post-transplant in the Cross-Biome experiment. There was no effect of soil treatment or habitat on survival of any species with the exception of *T. officinale*, which had higher survival in the boreal forest ($p = 0.03$).

Table 1. Total observed number of germinated seeds in different depths of anthropogenically-modified soil (5 cm, 20 cm) translocated in boreal forest and tundra roadside plots in the Cross-Biome experiment.

Species	Habitat	5 cm	20 cm
Capsella bursa-pastoris	Tundra	0	0
	Boreal Forest	0	3
Galeopsis tetrahit	Tundra	1	20
	Boreal Forest	1	0
Plantago major	Tundra	0	1
	Boreal Forest	0	0
Taraxacum officinale	Tundra	1	0
	Boreal Forest	0	1
Thlaspi arvense	Tundra	36	44
	Boreal Forest	26	47

forest habitats. There was a significant effect of soil treatment on the height and number of ramets of *L. vulgaris* and on the leaf length of *P. major* and *T. officinale* (Fig. 4, Suppl. material 1: table S7). Transplants of *L. vulgaris* were tallest on average in deepest soil ($F_{(2,30)} = 19.47$, $p < 0.001$): transplants were 19.2 cm in 20 cm deep soil and 3.1 cm in the control in the boreal forest and 16.2 cm in 20 cm deep soil and 4.1 cm in the control in the tundra (Fig. 4A). Transplants of *L. vulgaris* also had more ramets in the deepest dump soils ($F_{(2,30)} = 5.49$, $p = 0.009$), with an average of 9.1 ramets in the tundra and 7.8 ramets in the boreal forest in 20 cm deep soil and 2.8 ramets in the tundra and 4.7 ramets in the boreal forest in controls. Dump soils also increased the length of the longest leaf of *P. major* transplants ($F_{(2,34)} = 9.23$, $p < 0.001$), especially in boreal habitats ($F_{(1,34)} = 3.51$, $p = 0.07$): leaves of transplants were 7.3 cm in 20 cm deep dump soil compared to 5.2 cm in the control treatment in the tundra and leaves were 11.5 cm in 20 cm deep dump soil compared to 4.6 cm in the control treatment in the boreal forest (Fig. 4B). Leaf length was significantly larger for *T. officinale* in dump soils ($F_{(2,28)} = 5.84$, $p = 0.008$), with leaves at 6.9 cm in the tundra and 8.7 cm in the boreal forest in 20 cm soils, compared to 3.8 cm in the tundra and 5.1 cm in the boreal forest in the control treatment (Fig. 4C). Transplants of *T. officinale* also had a higher number of leaves in dump soil ($F_{(2,28)} = 4.77$, $p = 0.02$), with an average of 6.0 leaves in the tundra and an average of 7.9 leaves in the boreal forest when in 20 cm deep dump soil, while there was an average of 4.7 leaves in the

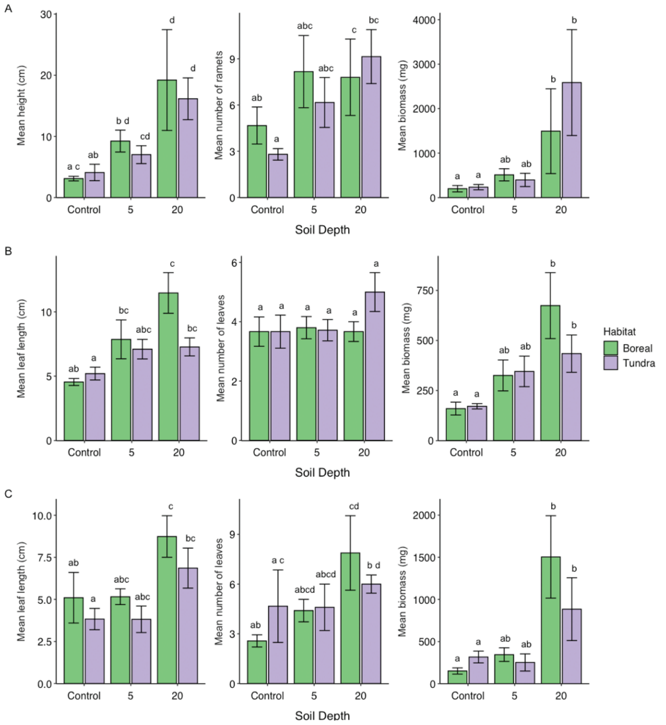

Figure 4. Growth (± standard error) of transplants in different anthropogenically-modified soil depths (5 cm, 20 cm) and original soil (control) in boreal forest (green) and tundra (purple) roadside plots in the Cross-Biome experiment. Bars that do not share letters differed significantly ($p < 0.05$). **A.** Transplants of *L. vulgaris* had larger height (cm, $p < 0.001$), more ramets ($p = 0.009$) and greater biomass ($p < 0.001$) in 20 cm dump soil compared to the control; **B.** Transplants of *P. major* had longer leaf length (cm, $p < 0.001$) and greater biomass ($p < 0.001$) in 20 cm dump soil, but there was no effect on the number of leaves. Transplants of *P. major* also had slightly longer leaves in the boreal forest (cm, $p = 0.070$); **C.** Transplants of *T. officinale* increased leaf length (cm, $p = 0.008$), a higher number of leaves ($p = 0.02$) and greater biomass ($p < 0.001$) in 20 cm dump soil.

tundra and 2.6 leaves in the boreal forest when in the control treatment. No analyses were performed on the number of flowering individuals (Suppl. material 1: table S4), as flowers of these species are likely preformed from the previous growing season, so that differences may not reflect effects of soil treatment or depth.

In both habitats, dump soil at 20 cm depth had a significant effect on the dry biomass of all three species compared to the control and there was again a trend that deeper soil tended to result in greater biomass production (Fig. 4, Suppl. material 1: table S8). Dry biomass of *L. vulgaris* transplants in 20 cm deep dump soil was on average 2586 mg in the tundra and 1494 mg in the boreal forest, while in control plots, dry plant biomass was, on average, 235 mg in the tundra and 200 mg in the boreal forest (Fig. 4A, $F_{(2,30)} = 9.67$, $p < 0.001$). Similarly, average dry plant biomass of *P. major* transplants were 434 mg in the tundra and 578 mg in the boreal forest in 20 cm deep dump soils, compared to 172 mg in the tundra and 137 mg in the boreal forest in the control plots (Fig. 4B, $F_{(2,34)} = 12.44$, $p < 0.001$). Finally, soil treatment significantly affected the dry plant biomass of *T. officinale* ($F_{(2,26)} = 16.26$, $p < 0.001$), where transplants averaged 884 mg in the tundra and 1504 mg in the boreal forest in the 20 cm depth and 317 mg in the tundra and 151 mg in the boreal forest in the control treatment (Fig. 4C). Effects of habitat on biomass were inconsistent and non-significant for all species; in the deepest soils, *L. vulgaris* tended to have the greatest biomass in the tundra, but the other species tended to have greater biomass in the boreal forest.

Discussion

Although invasive species have been previously reported in dumpsite soils (Plaza et al. 2018), including at high latitudes (Alsos et al. 2015), this is one of the first studies to experimentally investigate the potential role of soil dumps in plant invasions in northern ecosystems. Dumps can act as a source of seeds and other propagules for the surrounding area (Plaza et al. 2018; Syed et al. 2023). Here, we found that, as well as assisting plant dispersal, soil movement can increase the growth of non-native species once they arrive in natural subarctic habitats.

Waste materials originating from human-disturbed areas often contain seeds and fragments of non-native plants; in particular, garden or agricultural waste can contain a high number of non-native propagules in the form of plant fragments and seeds (Rusterholz et al. 2012; Tomše et al. 2025). Persisting populations of non-native species established in dumps can also contribute to a high density of seeds in the seed bank (Kim and Lee 2005). Previously, we have found evidence of a viable seed bank within human-modified soils in Churchill (Syed et al. 2023). Seeds of non-native plant species likely arrived in the area as contaminants in the grain via rail (Beckett 1959; Povoroznyuk et al. 2023) and spread into human-disturbed areas, including into rubbish dumps (Staniforth and Scott 1991). These non-native species consequently produce and add viable seeds into the soil seed bank and these non-native seeds can contribute to persisting populations of non-native species or may be able to persist below-ground over time, even if they are not found above-ground (Gioria et al. 2021; Dai et al. 2025).

We found that non-native species benefitted from growing in human-modified soils, especially with deeper soil depths, as individual transplants had increased growth in translocated dumpsite soils compared to transplants in control soils. This likely primarily reflects the nutrient-enriched nature of dumpsite soils: as Arctic environments typically are nutrient-poor, an increase in nutrients can modify the community (Henry et al. 1986; Lang et al. 2021), favouring non-native species (Lembrechts et al. 2016). Roadsides, such as those used in the Cross-Biome experiment, may be particularly vulnerable, as they are exposed to a higher frequency of disturbance and soil movement, altering the availability of nutrients, physical soil properties and microbial communities (Trombulak and Frissell 2000; Johnston and Johnston 2004; Clavel et al. 2025) and facilitating the spread of non-native species over long distances (Lippe and Kowarik 2007; Mortensen et al. 2009; Rauschert et al. 2017). However, this positive effect of disturbed soil on transplants was short-term, as survival of transplants steadily decreased despite growing in translocated dump soils. Even the ameliorated below-ground conditions associated with translocated soil was apparently not enough to reverse the invasion failure of non-native plants into tundra and treeline roadside habitats over time.

Although we observed non-native species germinating from our experimental dumpsite soil, there was no difference between soil depths in the number of seeds germinating. Instead, germination rate was highly dependent on species (Sonkoly et al. 2020). This lack of a difference in seed germination between soil depths likely occurred because, regardless of depth, most successful seed germination occurs at or near the soil surface; deeper layers may contain seeds, but their probability of emergence is low (Baskin and Baskin 1998; Fenner and Thompson 2005).

In our controlled experiments, moving dumpsite soil to new sites did result in the establishment of non-native species from both transplanted ramets and from seeds in the soil seed bank, but their persistence was only temporary. The transience of these new populations may, in part, be due to the limited sample size that we were able to transplant; however, this also suggests that the local environment remains too harsh to allow persistence, at least in the small volumes of soil moved. Larger soil movements likely represent proportionally greater invasion risks; we have observed multi-year persistence of non-native plants at sites where large amounts (i.e. truckloads) of soil have been dumped. As well, climate change may interact with local-scale anthropogenic disturbances and soil nutrient changes to increase the invasibility of a habitat (Bradley et al. 2010), especially at high latitudes, where the climate is warming at a much faster rate than the global average (Alsos et al. 2015; Rew et al. 2020; Rantanen et al. 2022). Warming may particularly benefit invasive species such as the ones included in this study, which presumably originated at temperate latitudes, but were transported to near their northern range limits; for example, Da Silva and Kotanen (2024) previously found that *T. officinale* in Churchill was more abundant in warmer microsites. Similarly, Zhang and Kotanen (2025) found evidence that warming improved the performance of non-native plants in northern ecosystems. As the climate continues to warm, movement of soil by humans due to land use and urbanisation risks significantly increasing both the dispersal and establishment of non-native species into currently uninvaded ecosystems.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Conceptualization: VMZ, PMK. Data curation: VMZ. Formal analysis: VMZ. Funding acquisition: PMK, VMZ. Investigation: VMZ. Methodology: PMK, VMZ. Supervision: PMK. Visualization: VMZ. Writing - original draft: VMZ. Writing - review and editing: VMZ, PMK.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplementary infotmation

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