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Ecological Solutions and Evidence

PRACTICE INSIGHTS

Species and microsite selection shape *Sphagnum* transplant success in a metal-contaminated peatland in Sudbury, Ontario

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Abstract

1. Peatlands can be degraded by mining and smelter emissions, with severe impacts on *Sphagnum* mosses, the key peat-forming species in many bogs and poor fens. While restoration of horticulturally extracted peatlands is common, less is known about restoring smelter-impacted peatlands, such as those in Sudbury, Ontario.
2. In 2019, 30 10×10×10 cm *Sphagnum* moss–peat plugs representing five species were transplanted into a denuded, smelter-impacted peatland. Transplant survival and plug dimensions were recorded from 2019 to 2024. After 2 years, one designated destructive plot was sampled for exploratory chemical and microbial analyses.
3. Transplant responses varied strongly among species. *Sphagnum fuscum* and *S. fallax* showed the strongest establishment, with *S. fuscum* plugs reaching mean dimensions of 25.5×25.3 cm by Year 5 and *S. fallax* colonizing patches outside the original plugs. *Sphagnum medium* survived but persisted at reduced size, while *S. cuspidatum* and *S. palustre* failed to establish.
4. Exploratory chemical and microbial data suggested that transplanted moss–peat plugs accumulated metals after placement in the host peatland, while retaining some donor-associated microbial signal after 2 years. Because destructive sampling was limited to one plot, these patterns are interpreted as descriptive context rather than formal tests of transplant effects.
5. *Practical implication.* This trial provides encouraging evidence that *Sphagnum* transplantation can contribute to restoration of smelter-impacted peatlands, but establishment depended on species identity and microsite position. Future restoration should prioritize species–microsite matching, with *S. fuscum* and *S. fallax* as promising initial candidates, rather than applying donor material uniformly across damaged peat surfaces.

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KEYWORDS
microbial ecology, peatlands, restoration, smelter pollution, *Sphagnum* mosses

1 | INTRODUCTION

Canadian peatlands are major carbon stores and important regulators of freshwater networks (Harris et al., 2022; Turetsky et al., 2015). Much of this function depends on *Sphagnum* mosses, which acidify their surroundings, slow microbial decomposition and contribute to long-term peat accumulation (Mäkilä et al., 2018; Marcisz et al., 2020; Moore & Bellamy, 1974; Piatkowski & Shaw, 2019; Rippy & Nelson, 2007). When *Sphagnum* is severely reduced or locally extirpated, peatland structure and recovery potential can be strongly altered. In Sudbury, Ontario, historical *Sphagnum* loss was likely driven largely by sulphur dioxide (SO_2) emissions and acidification, while elevated metals remain important legacy contaminants for peatland recovery and restoration (Barrett & Watmough, 2015; Gignac & Beckett, 1986).

Sudbury, Ontario, was formerly one of the world's largest point sources of SO_2 as well as nickel (Ni) and copper (Cu) particulate emissions from mining and smelting (Gunn et al., 1995). Gignac and Beckett (1986) reported that many peatlands within 12 km of Sudbury smelters had lost all *Sphagnum* species. Although emissions have declined since the 1970s, and *Sphagnum* has recently been reported in some peatlands as close as 4 km from active or former smelters (Seward et al., 2023), active restoration may still be needed in severely damaged peatlands that show little evidence of natural revegetation.

Restoration methods such as the moss layer transfer technique (MLTT) are widely used on horticulturally extracted peatlands (González & Rochefort, 2014; Gorham & Rochefort, 2003), but these methods may not translate directly to metal-contaminated peatlands with exposed contaminated surfaces and variable water-table positions. McCarter et al. (2023) modelled a peat-block restoration technique, in which intact blocks of living *Sphagnum* shoots and associated underlying peat are transferred together to help isolate introduced moss from contaminated surface peat, but emphasized the need for field experimentation. Here, we tested whether small intact living *Sphagnum* moss–peat plugs from an uncontaminated donor peatland could establish in a small, denuded, smelter-impacted Sudbury peatland. This small-scale trial evaluates how species identity and microsite placement influence *Sphagnum* establishment and provides guidance for future pilot restoration work in contaminated peatlands.

2 | METHODS

2.1 | Site descriptions and experiment design

Sphagnum mosses were collected from a donor peatland ('Dinner Bog'; 45°27′ N, 80°09′ W) approximately 165 km south of Sudbury, Ontario, within the Nibi (Water) Observatory for Boreal Ecohydrological Landscapes approximately 17 km north of Parry Sound, Ontario (Figure 1). The donor site was selected as it was outside the smelter-impact area of Greater Sudbury. The host peatland ('SUD103'; 46°27′ N, 80°58′ W) is within the Laurentian University Greenspace, approximately 7 km from the Copper Cliff smelter and lacks native *Sphagnum* cover (Figure 1). It contains exposed blackened, humified peat and resembles highly smelter-impacted peatlands described by Gignac and Beckett (1986). Open peatland area was estimated from Google Earth imagery as approximately 18.8 ha at the donor site and 0.55 ha surrounding the host transplant transect.

Hydrological context was described using 2020 water-table measurements from wells, field observations during transplant monitoring and regional weather records (Table S1). These data describe general site conditions but were not collected as continuous plot-level records. Regional May–September weather for 2019–2024 was summarized from daily Environment and Climate Change Canada (2026) records from the Sudbury Climate station and is provided in Table S1.

Vegetation at donor and host peatlands was surveyed along two randomly placed 30 m transects extending from the peatland margin towards the centre. Surveys were conducted every metre using 1 m^2 quadrats. Percent cover was estimated separately for the vascular plant layer and moss/peat surface layer, and results were pooled by site (Table S2).

In late spring 2019, five species of living *Sphagnum* and associated peat plugs, approximately 10 × 10 × 10 cm, were transplanted into six 1 × 1 m plots along the host transect. Two plots were placed at the peatland margin, two at 15 m from the margin and two at 30 m from the margin (Figure 2). Each plot received one plug of *S. fallax*, *S. palustre*, *S. fuscum*, *S. medium* and *S. cuspidatum*, giving 30 transplanted plugs in total. Plugs were placed in microsites resembling each species' typical habitat, such as raised hummocks for *S. fuscum* and wetter hollows for *S. cuspidatum* (Table S3).

2.2 | Data handling

Survival was assessed during annual field visits from 2019 to 2024. Field photographs were taken each summer, and the length and width of surviving transplants were measured with a ruler in the initial year, Year 3 and Year 5. In summer 2021 (Year 2), one sample per surviving *Sphagnum* transplant and its associated transplanted peat was collected from one designated destructive plot, Plot 5, for chemical and microbial analysis (Figure 2). Botanical data were summarized using importance values, calculated as percent cover plus percent frequency, with a possible maximum of 200 (Halls & Phillips, 1960). Microbial beta diversity was visualized using NMDS of Bray–Curtis dissimilarity.



FIGURE 1 Donor site (Nobel, Parry Sound, Ontario) (top) photographs show vegetation survey transects (left), overhead view of peatland (middle) and healthy *Sphagnum* moss (right). Host peatland (Sudbury, Ontario) (bottom) photographs show vegetation survey transect (left), boardwalk of transplant plots (middle) and highly humified and disturbed peat (right). Photographs were taken 2 years after transplantation (2021).

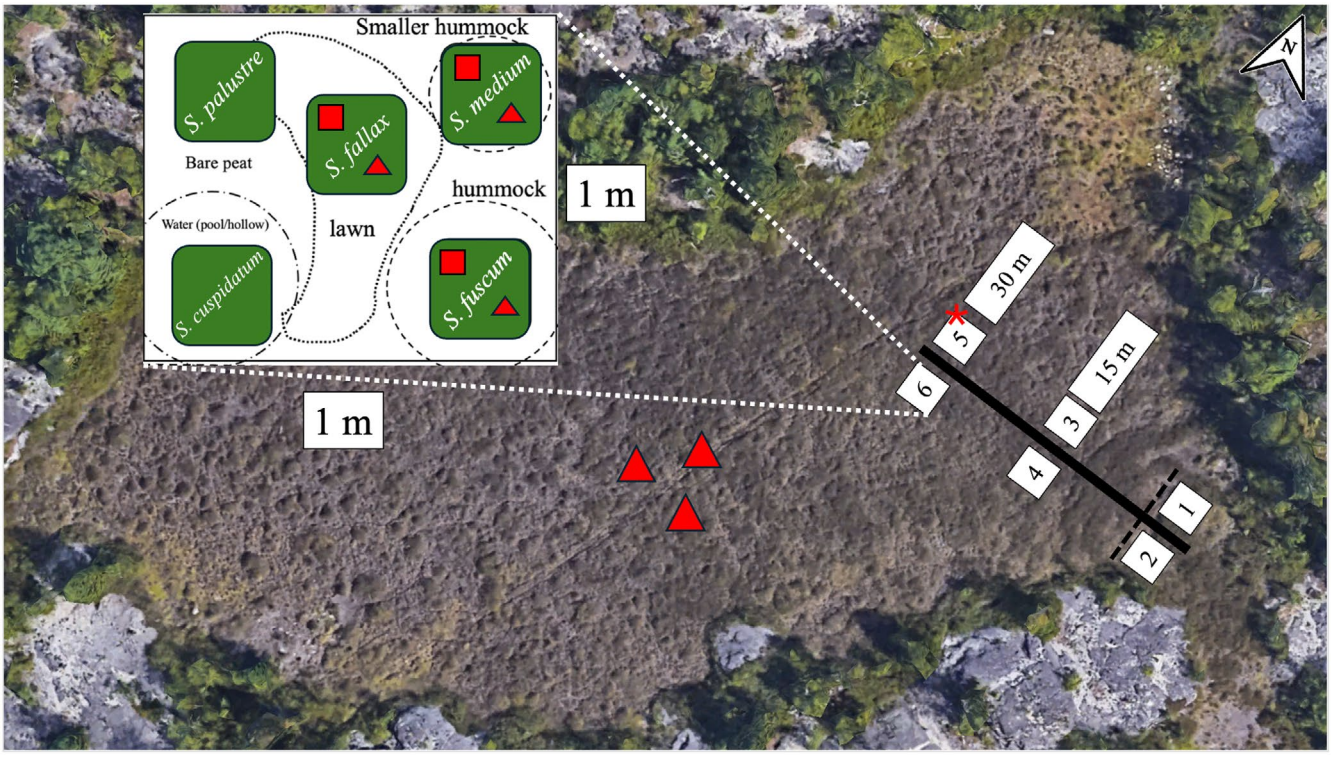


FIGURE 2 Blueprint of host peatland site SUD103 (Sudbury, Ontario, Canada) depicting peat transplant locations. The red * indicates the designated destructive sampling 10plot (number 5). Red squares indicate where transplanted moss samples were taken. Red triangles indicate approximate areas where peat samples were taken from host peatland and from the destructive plot from underneath the sampled transplanted mosses. Plots 1 and 2 (below the dashed line) are considered the 'margin plots'. Image of host peatland was acquired from Google Earth.

Because chemical and microbial sampling was limited to one designated destructive plot, these data are treated as descriptive observations and not as formal tests of transplant effects. Additional methods and interpretations (Appendix S1), as well as supporting data, including vegetation summaries (Table S2), chemistry and pH values (Tables S4 and S5; Figure S1), regional weather summaries (Table S1), microbial alpha-diversity results (Table S6), taxonomic community summaries (Figures S2 and S3) and additional photographs (Photos S1 and S2) are provided in Supporting Information.

3 | RESULTS

3.1 | Transplanted *Sphagnum* moss success

The donor peatland had near-continuous *Sphagnum* cover, including *S. fallax*, *S. medium* (formerly *Sphagnum magellanicum* complex), *S. cuspidatum*, *S. fuscum*, *S.* rubellum and *S. palustre* (Table S2). In contrast, the host peatland had no native *Sphagnum* during the study and was dominated by *Chamaedaphne calyculata*, *Juncus brevicaudatus* and *Eriophorum virginicum* (Table S2). Bare peat was exposed during dry months and partially flooded after snowmelt or heavy rain.

Of the 30 transplanted *Sphagnum* moss–peat plugs, 12 survived after 2 years, giving an observed survival rate of 40% (Table 1). Survival was limited to the four interior plots, where *S. fallax*, *S. fuscum* and *S. medium* survived, whereas no species survived in the two margin plots. *Sphagnum palustre* and *S. cuspidatum* failed in all plots.

Surviving species showed different establishment patterns. *Sphagnum fuscum* expanded from the initial 10 × 10 cm plug size to mean dimensions of 19 × 19.3 cm by Year 3 and 25.5 × 25.3 cm by Year 5 (Table 1; Figure 3; Photo S1). *Sphagnum fallax* initially showed blackened and dried material but later grew away from the original plug locations, colonizing nearby hollows and lawns and reaching up to 23 cm from the initial transplant location by Year 5 (Table 1; Figure 3). *Sphagnum medium* persisted at reduced size and did not show clear lateral colonization beyond the original transplant area (Table 1; Figure 3; Photo S2).

3.2 | Descriptive chemical and microbial observations

Destructive sampling from one interior plot in 2021 provided exploratory chemical and microbial context. Transplanted *Sphagnum* mosses contained higher concentrations of Ni, Fe, Cu and Al, but lower concentrations of P and Mn than donor mosses (Table S5; Figure S1). pH was also higher in transplanted mosses (Table S4). Among peat samples, transplanted peat had the highest mean Ni, Fe and Cu concentrations, while host peat had the highest mean P concentration (Table S5; Figure S1).

Microbial community composition differed among donor, transplanted and host materials (Figure 4). Transplanted peat samples were positioned between donor and host peat, suggesting that transplanted peat microbial communities shifted away from the donor condition but did not fully converge with host peat after 2 years. Donor and transplanted *Sphagnum* microbiomes also differed within the same moss species (Figure 4). Because these data came from a single plot, they are interpreted descriptively.

4 | DISCUSSION

Sphagnum fuscum, *S. fallax* and *S. medium* survived in the interior plots, whereas *S. palustre* and *S. cuspidatum* failed to establish after 1 year, and no species survived at the peatland margin. These patterns suggest that restoration of smelter-impacted peatlands

TABLE 1 Survival location and growth of transplanted *Sphagnum* moss–peat plugs from 2019 to 2024.

Species	Target microsite	Margin plots 1–2	15 m plots 3–4	30 m plots 5–6	Total survival	Growth measurements and outcomes
S. medium	Around vascular plant stems/ protected hummocks	0/2	2/2	2/2	4/6 (66.7%)	Initial: 10 × 10 cm; year 3: 4 × 4 cm; year 5: 5.5 × 5 cm. Persisted around vascular plants
S. fallax	Moist lawns and hollows	0/2	2/2	2/2	4/6 (66.7%)	Initial: 10 × 10 cm; year 3: 20.3 × 8.5 cm; year 5: 23 × 9 cm. Spread into nearby hollows/lawns
S. fuscum	Raised *Chamaedaphne* hummocks	0/2	2/2	2/2	4/6 (66.7%)	Initial: 10 × 10 cm; year 3: 19 × 19.3 cm; year 5: 25.5 × 25.3 cm. Expanded strongly
S. palustre	Shaded lawn or margin microsites	0/2	0/2	0/2	0/6 (0%)	Initial: 10 × 10 cm; no living material observed by year 2
S. cuspidatum	Wet hollows or pools	0/2	0/2	0/2	0/6 (0%)	Initial: 10 × 10 cm; no living material observed by year 2
Total	—	0/10	6/10	6/10	12/30 (40%)	—

Note: Each of six plots received one plug of each species. Values under transect position show the number of surviving plugs divided by the number transplanted at that position. Plots 1–2 were located at the peatland margin, Plots 3–4 were 15 m from the margin and Plots 5–6 were 30 m from the margin. Growth measurements are mean length × width of living transplants in successful plots.

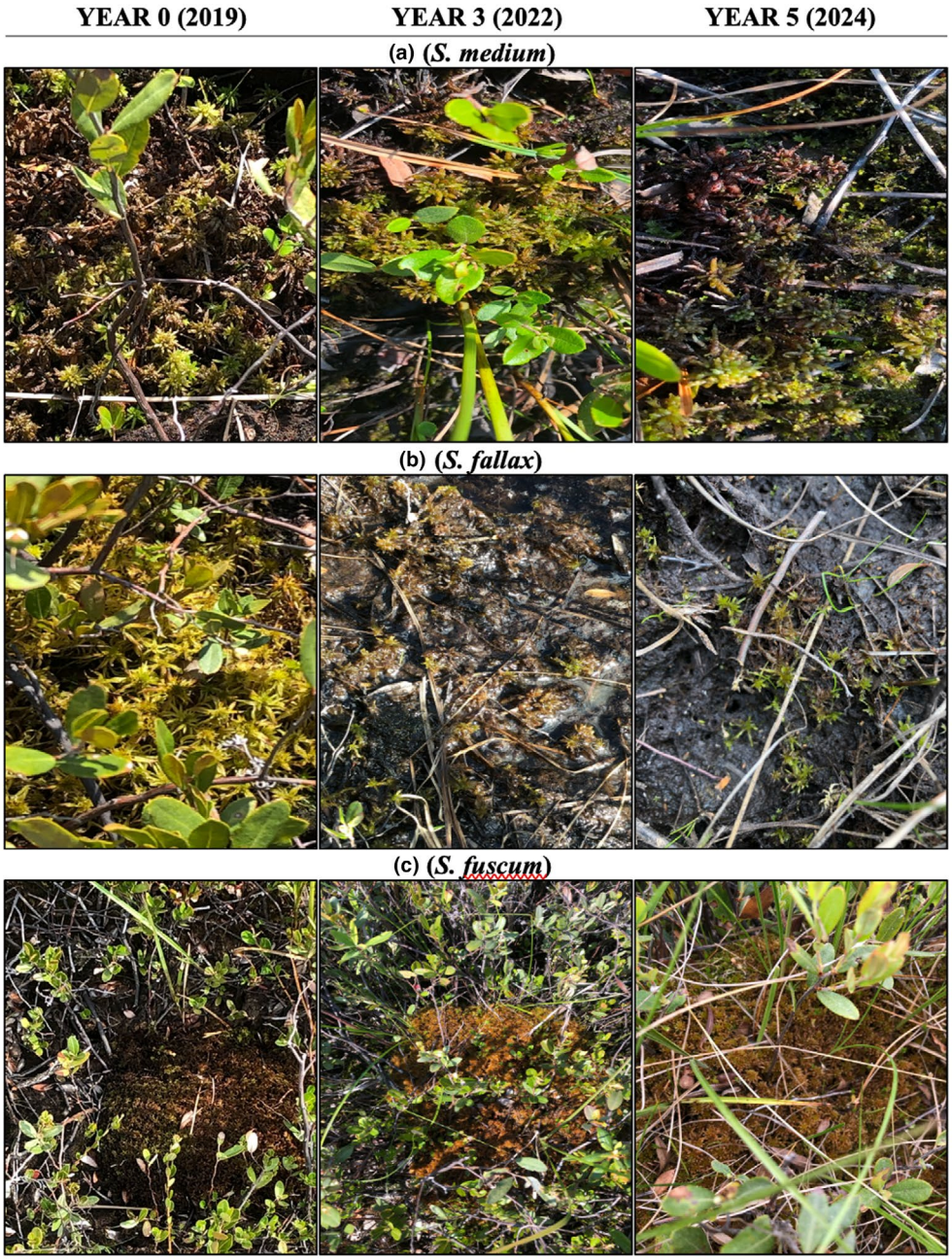


FIGURE 3 Field photographs of transplanted *Sphagnum medium* (a), *fallax* (b) and *fuscum* (c) mosses from initial year of transplantation, Year 0 (2019), Year 3 (2022) and Year 5 (2024).

should not rely on uniform *Sphagnum* application across damaged peat surfaces. Instead, species should be selected carefully and matched to microsites that provide appropriate hydrological position.

Sphagnum fuscum showed the clearest plug expansion. This species forms compact hummocks composed of tightly packed shoots, a growth form that may help maintain moisture during dry periods. Hummock-forming *Sphagnum* species, including *S. fuscum*, can persist above the water-table by retaining water within the moss structure and moving water upward through capillary rise and pore spaces (McCarter & Price, 2014). In this study, raised placement may also have created small ombrotrophic-like microsites, reducing direct contact between living moss and contaminated host peat and porewater. This is consistent with reports of *S. fuscum* occurring on high, probably ombrotrophic hummocks even within rich fen systems (Bengtsson et al., 2020).

Unlike *S. fuscum*, *S. fallax* appeared to establish by spreading from the original transplant into nearby hollows and lawns rather than expanding as a compact plug. This apparent ability to grow directly on contaminated bare peat suggests greater tolerance of exposed host-peat conditions than the other surviving species. This interpretation is consistent with previous work showing that *S. fallax*/*S. recurvum* can be relatively tolerant of sulphur-related pollution and can establish on bare peat surfaces

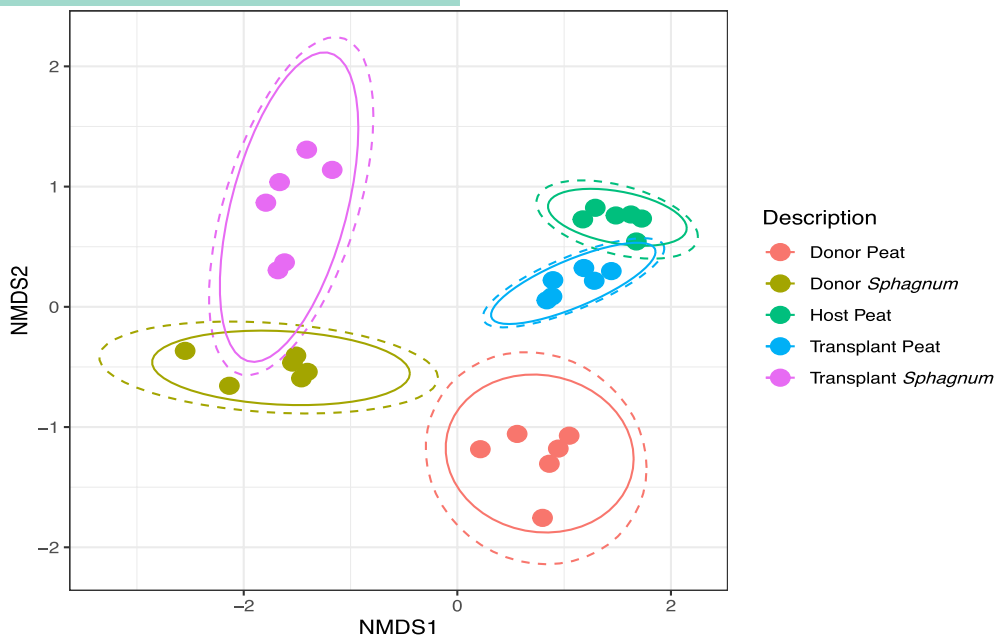


FIGURE 4 Non-metric multidimensional scaling (NMDS) plot of bacterial/archaeal communities in peat and *Sphagnum* moss in donor, host and transplants. Ordination was based on Bray–Curtis dissimilarity values. The solid-line ellipse assumes a multivariate t-distribution, whereas the dashed-line ellipse assumes a multivariate normal distribution. Sampling and sequencing were performed 2 years after transplantation (2021).

(Buttler et al., 1998; Ferguson et al., 1978; Ferguson & Lee, 1983). Together, these patterns suggest that *S. fallax* may be useful as an early colonizing species in contaminated peatlands where wetter microsites remain available.

Sphagnum medium survived but remained reduced in size and concentrated around *Chamaedaphne* or other vascular plant stems, suggesting persistence in protected microsites but limited short-term expansion. Its 5-year survival indicates that it should not be dismissed as unsuitable for contaminated peatlands, but it may require sheltered microsites and may be less useful as an early colonizing species than *S. fallax* or *S. fuscum*.

The failure of *S. cuspidatum* and *S. palustre* likely reflected unsuitable early establishment conditions. *Sphagnum cuspidatum* is typically associated with wet hollows and pools and may have suffered during dry periods in 2019 and 2020. *Sphagnum palustre* is often associated with shaded wet woodlands, forested peatlands and some peatland margins, but the exposed margin plots in this study did not appear to provide suitable habitat. Drying and metal stress may both have contributed, as the water-table was approximately 10 cm below the plugs during one field visit and Baker (1992) found that elevated Cu and Zn inhibited growth of *S. palustre* and *S. cuspidatum* in aqueous culture.

The chemistry and microbial data help interpret the trial, but they are limited by sampling from one destructive plot. Higher metal concentrations in transplanted mosses than in donor mosses suggest that plugs accumulated metals after placement in the host peatland. Even with this limitation, the NMDS ordination suggests a promising pattern for transplant establishment, as transplanted peat microbial communities fell between donor and host-peat communities after 2 years. Rather than becoming indistinguishable from the contaminated host peat, the plugs retained some donor-associated microbial signal while also responding to the host environment. Although exploratory, this pattern suggests that intact moss–peat plugs may provide both plant material and donor-associated microbial communities that could support recolonization.

4.1 | Practical implications and next steps

This trial provides evidence that *Sphagnum* transplantation can contribute to restoration of smelter-impacted peatlands, but donor material should not be applied uniformly across damaged peat surfaces. At this site, survival was highest in interior microsites with existing vascular plant structure, while no transplants survived in exposed margin plots. This suggests that microsite screening should precede larger restoration work, with *S. fuscum* and *S. fallax* prioritized as initial candidates.

Future trials should use replicated pilot plots across hydrological, pH and metal-availability gradients, including reference-site transplant controls, to identify the factors governing establishment and separate transplant stress from host-site contamination. In highly degraded systems, transplantation may need to be paired with hydrological stabilization, surface protection, contaminant-risk assessment or other site-preparation measures before scaling up.

AUTHOR CONTRIBUTIONS

Lorna I. Harris, James M. Waddington, Peter Beckett, James Seward and Nathan Basiliko designed the project. Emily Smenderovac, Lorna I. Harris, Peter Beckett and James Seward conducted the

experiments. James Seward, Peter Beckett, Suzanna Bräuer, Pascale Roy-Léveillée, Ellie Goud, Shaun Watmough and Nate Basiliko contributed to data handling and interpretation. All authors contributed to writing and editing the manuscript. Nate Basiliko, Shaun Watmough, James M. Waddington, and Peter Beckett acquired funding and staffing support.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflicts of interest.

PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1002/2688-8319.70314.

DATA AVAILABILITY STATEMENT

The raw SSU rRNA gene amplicon sequence data generated in this study are publicly available in the NCBI Sequence Read Archive under BioProject accession PRJNA1269234 (Seward, 2025): https://www.ncbi.nlm.nih.gov/bioproject/PRJNA1269234.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Additional methods and descriptive context.

Table S1. Regional May–September weather summaries within 2019–2024 and 2020 well-based water-table measurements from the donor and host peatlands. Weather data are from the Environment and Climate Change Canada Sudbury Climate station and summarize May–September conditions for each year. These data provide regional climatic context and are not site-level

hydrological measurements. Water-table values are reported relative to the peat surface, with negative values indicating water below the surface and positive values indicating standing water above the surface.

Table S2. Flora of the donor and host peatlands. These data are represented as Importance Values (Halls & Phillips, 1960).

Table S3. *Sphagnum* species descriptions and habitat preferences for the five species used for this transplant experiment. Supportive literature provided.

Table S4. pH values for *Sphagnum* moss and peat samples (from triplicate samples, then average with standard deviation) from donor, host and transplant samples. These measurements were taken on fresh peat and living *Sphagnum* tissue in the 2nd year after transplantation (2021).

Table S5. Total elements from ICP-OES for peat and *Sphagnum* moss samples taken 2 years after initial transplantation. Values under the replicates (Rep. 1, 2, & 3) are expressed as mg/g. For the *Sphagnum* moss replicates, Rep. 1 is *S. fuscum*, Rep. 2 is *S. medium* and Rep. 3 is *S. fallax*. < LOD indicates below the limit of detection and N/A indicates not applicable due to a lack of required data. SD and SE are standard deviation and standard error, respectively. A 95% confidence interval is represented as CI 95%.

Table S6. Mean alpha-diversity values ($n = 6$), Shannon and inverse Simpson indices, of peat and *Sphagnum* mosses (all species combined) in donor and host peatlands, as well as transplant samples. SE is standard error, respectively. A 95% confidence interval is represented as CI 95%.

Figure S1. Box and whisker analysis for the 4 main elements of interest, total Ni, P, Al and Fe (Cu is excluded here but shows a similar trend seen for Ni) for peat samples (donor, transplant and host) as well as for donor and transplanted *Sphagnum* mosses. The red diamond indicates mean value. These samples were taken 2 years after initial transplantation during the summer. Peat samples were taken between 5 to 10 cm depths. *Sphagnum* samples consisted of living moss tissue. For the transplanted *Sphagnum*, samples were taken from either the original plugs (*S. fuscum* and *S. medium*) or from new colonizing individual mosses (*S. fallax*), all of which was pulled together for analysis. Data points with a red * indicates high variability within the sample replicates ($n = 3$ per sample set).

Figure S2. Relative abundance taxonomic bar plot at Phylum level for bacterial and archaea communities in *Sphagnum* mosses (all species combined) from donor peatland and transplants as well as donor, transplant and host peat samples. These values reflect the average of all replicates and sequencing duplicates ($n = 6$). Sample collection and sequencing was performed 2 years after transplantation (2021).

Figure S3. Heat map showing ASV lineages associated with selected microbe metabolic function in peat and *Sphagnum* moss using the FAPROTAX software. These values range from 0 to ~20,000 associated ASVs.

Photo S1. 2023 photograph of *S. fuscum* transplant from Plot 4 with ruler.

Photo S2. 2023 photograph of *S. medium* transplant from Plot 3 with ruler.

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