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Substrate and Topsoil Impact on Soil Water and Soil Temperature in Arctic Diamond Mine Reclamation

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Abstract: Soil properties in the Arctic are insufficiently explored and documented, particularly extensive monitoring of soil water and soil temperature over a period of time. Soil water and soil temperature are critical for understanding land surface and atmosphere interactions and are considered key factors for revegetation during mine reclamation. This study assessed how substrate and topsoil influenced soil temperature and soil water content at a reclaimed diamond mine in the Northwest Territories of Canada. Three substrates (crushed rock, processed kimberlite, and lake sediment) with and without topsoil were used. Mean air temperature changed little from year to year, although summer temperature showed a slightly increasing trend. Both annual and summer precipitation sharply declined over time. Soil water was influenced more by substrate than by placing 10 cm of topsoil on it. Processed kimberlite had greater water retention characteristics and water content than lake sediment and crushed rock substrates (significantly). Surface soil water content was lower with than without topsoil, suggesting that 10 cm of topsoil was not enough to influence it. Soil temperatures were not influenced by either substrate or topsoil. This study suggests processed kimberlite could be used as a substrate component for water and temperature management during reclamation of this extreme environment.

Keywords: Arctic ecosystem; crushed rock; lake sediment; processed kimberlite; soil amendment

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1. Introduction

Arctic ecosystems are characterized by extremely low air and soil temperatures, low water content on elevated surfaces, shallow depth to thaw, nutrient deficiencies, and short growing seasons [1–4]. Low temperatures inhibit chemical weathering and biological decomposition, and with poor aeration, reduce nutrient release rates from soil organic matter and minimize nitrogen fixation rates. Nutrient inputs from precipitation are an order of magnitude lower in the Arctic than in temperate systems because low temperatures limit the quantity of precipitation and nutrients therein [5,6]. Large-scale disturbances such as diamond mining and gravel extraction can result in altered thermal, hydrologic, and/or nutrient regimes [7–9]. Land reclamation under such harsh environmental conditions and terrain is further challenged, as mining activities alter the shallow topsoil and subsoil, increase soil compaction by heavy equipment, and change other soil properties [10–12].

After the discovery of the first diamond mine in 1991, Canada became the world's third-largest diamond-producing country in 2011 [13,14]. Since then, overall mining exploration has intensified and increased almost 90%, mostly in the Arctic zone of Canada [14]. Intensive mining activities cause long-lasting changes in tundra landscapes [11] and have direct impacts on wildlife, human health, and the environment [8,13]. Diamond mine reclamation involves landform construction and re-establishment of soil processes and expected plant communities on gravel roads and pads, waste rock and lake sediment stockpiles, and processed kimberlite containment ponds [8]. Availability of topsoil for reclamation in the Arctic zone is a challenge due to the thin layer of natural topsoil [15] that is not always salvaged. Although waste materials from mining processes can be used as cover soils, they are sparse, often low in organic matter and nutrients, and are coarse textured, which directly influences soil water and soil temperature [8].

Soil water and soil temperature are critical for understanding land surface and atmosphere interactions. Water is an important component of the soil, as it helps determine the proportions of rainfall partitioned into runoffs, surface storage, and infiltration [16–18]. Soil water content exhibits tremendous heterogeneity in space and time [19]; thus, its spatial and temporal variations have always been critical issues in revegetation and water resource management, especially in semi-arid, arid, and Arctic ecosystems [9,16,20]. Surface soil temperature is another key variable in determining the land surface heat and water balance. Surface soil temperature determines the fluxes of outgoing longwave, sensible, and ground heat, and the magnitude of these fluxes determines latent heat flux (evapotranspiration by the energy balance principle) [21]. Therefore, changes in surface soil temperature can affect soil water and vice versa, which has a direct influence on reclamation outcomes. The role of soil water and soil temperature on soil biogeochemical processes and vegetation establishment [16,21] make them key components to address in land reclamation, which could be vital in extreme Arctic conditions.

Research on Canadian Arctic diamond mine reclamation has mainly focused on vegetation responses to substrates, topsoil types, and nutrients in the field and greenhouse [8,9,13,15,18,22–24]. Further research is needed to better understand how substrates develop and what they provide for the evolving plant community. Thus, the objectives of this study were (1) to assess how substrates with and without topsoil influenced soil temperature and soil water content at diamond reclamation sites in the Northwest Territories and (2) to ascertain how the substrates might contribute to greater reclamation success.

2. Materials and Methods

2.1. Site Description

Two study sites were located at Diavik Diamond Mine (64°24′46″ N, 110°16′24″ W), approximately 320 km northeast of Yellowknife, Northwest Territories, Canada, in the sub-Arctic tundra on the Precambrian Shield (Figure 1). The area is characterized by short and cool summers, long and cold winters, and continuous permafrost. The mean annual temperature is −9.3 °C, with the coldest in January at −27.2 °C and warmest in July at 13.2 °C. Permafrost ranges from 1 m in wet areas to 5 m in bedrock. Mean annual precipitation is 305.8 mm, with 169.5 mm snow and 136.3 mm rain. The study area consists mainly of massive Archean rocks that form outcrops and glacial deposits of boulders, till, and eskers. The landscape of the site is characterized by steep-sided bedrock outcrops, undulating to strongly rolling morainal deposits, ridged and hummocky glaciofluvial deposits, and level to depressional glaciolacustrine and organic deposits [25]. Soils in the area are typically classified as turbic and static cryosols. The area is a transition between taiga forest and Arctic tundra vegetation. Vegetation in upland areas is dominated by dwarf shrubs and is generally sparse and stunted. Sedges and mosses dominate in low-lying wet tundra.

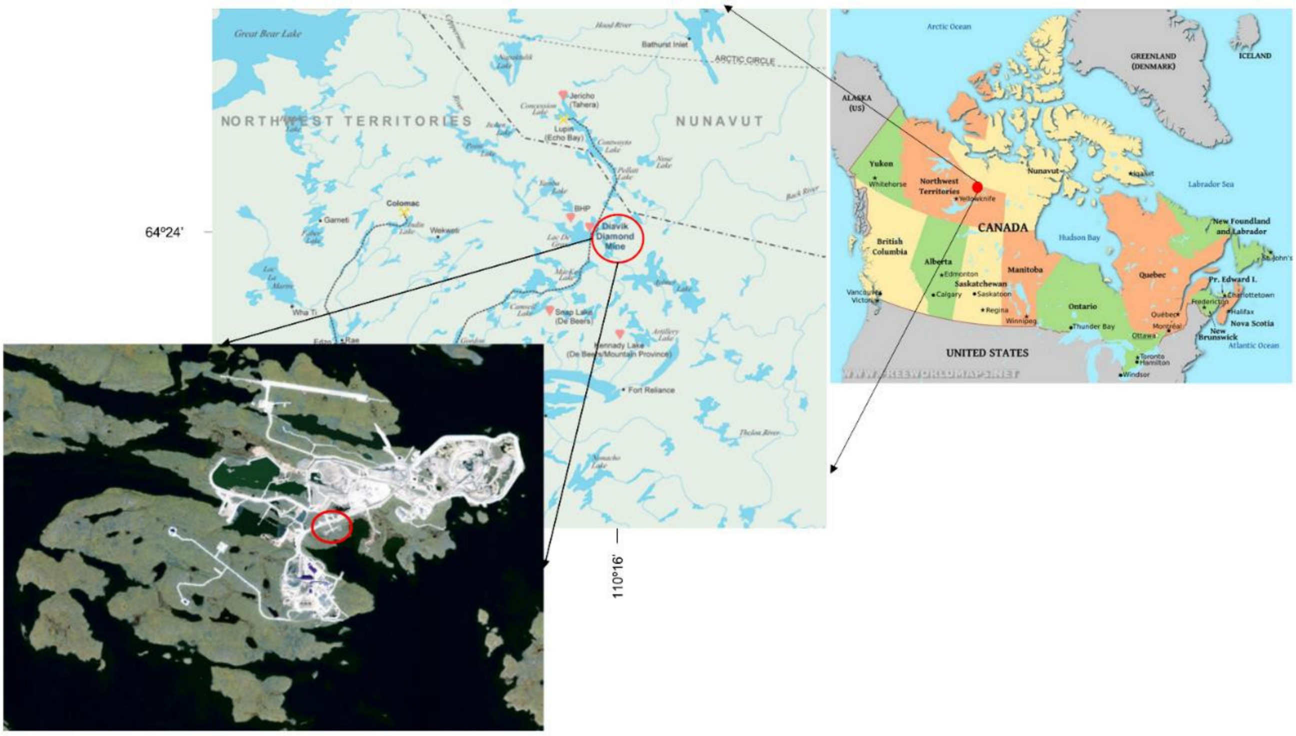


Figure 1. Location of research sites. The red circle shows the actual research site [25].

2.2. Reclamation Treatments and Experimental Design

Site A was established in September 2004 on a raised gravel pad previously used for ammonium nitrate storage and consisted of a layer of boulders over tundra, followed by a layer of small to mid-sized rocks, topped with 50 cm of gravel. Site B was established in June 2013 on a blasting pad at the former magazine storage facility. Three substrates were crushed rock, processed kimberlite (PK), and lake sediment, all with and without topsoil. Crushed rock was removed as waste material during pit excavation and crushed for onsite use. It consists of granite, containing <0.04 wt% sulphur, generally <20 mm in size, with 76.4% sand, 19.7% silt, and 3.9% clay. Fine-processed kimberlite materials, <1 mm in size, were collected from the containment facility, where they were placed as slurry, to dry a year earlier. They are predominantly composed of silicon, magnesium, and iron, with nickel, chromium, cobalt, strontium, and zinc the most abundant trace elements [26], and consist of 79.6% sand, 15.3% silt, and 5.1% clay. Lake sediment was removed from the pits after diking, and the water was pumped out. It comprises 62.6% sand, 29.9% silt, and 7.5% clay [26]. The organic matter content is 0.19 wt% in crushed rock, 0.11 wt% in processed kimberlite, and 0.10 wt% in lake sediment [26]. Substrates were applied at a depth of 50 cm over the gravel pad with a front-end loader. Topsoil from a wet tundra environment was stripped (O, A, B horizons); it is 80.9% sand, 15.4% silt, and 3.7% clay, and applied at an average thickness of 10 cm [26]. Topsoil consists of 1.02 wt% organic matter and 28.9% coarse fragments.

The experimental design for both sites was a randomized block with three replications. Each of the replicates was treated as a block, and three substrates with and without topsoil were applied to each of the three blocks. Three substrate plots, with areas of 150 to 300 m^2, were randomly established in each of the three blocks. Each substrate plot was divided into two equal halves for topsoil and no topsoil.

2.3. Data Collection

Soil water and soil temperature were measured using HOBO Smart SensorsTM, with 18 HOBO sensors per site installed (3 substrates × 2 topsoil treatments × 3 replicates). In total, 36 HOBO were installed in both sites and measured in three-year periods after installation. Each HOBO was equipped with four sensors; two soil water content sensors (soil moisture sensor) and two temperature sensors (12-bit temperature sensor), to record temperature and water content. Sensors were installed 5 to 10 cm below the soil surface in May or June (beginning of summer months in which soil was sufficiently thawed to allow installation). HOBOs were mounted on wooden stakes approximately 30 cm above the ground surface to prevent flooding and snow cover. Hourly measurements and mean weekly data for years and for summer months (June to August) were programmed for each site. Due to HOBO malfunction, data from September to December in site B were missing in the last measurement; thus, only summer months (June to August) data for both sites were used. Three years and four summer months of data were used for data interpretation and statistical analyses. Daily air temperature and precipitation data were collected by the Diavik diamond mine environment monitoring department.

A greenhouse experiment was conducted to determine water retention for the substrates and topsoil. We used 7 cm tall and 8 cm diameter round pots, with four replicates of each material. The weight of the filled pots was determined, and then, they were placed in a tray of water for 24 h. Pots were weighed upon removal from the tray, representing saturation weight. Pots were weighed approximately twice a day for the first two days, then daily until constant weight. Water retention was determined by subtracting pre-watering weight from the weight at each assessment and calculating the % water by weight. Three time periods were assessed to estimate soil water potential: 0 h for approximating saturation, 48 h for field capacity, and 77.2 h for near dry.

2.4. Statistical Analyses

We examined the effect of substrate, topsoil, and time since reclamation on soil water and temperature using linear mixed-effects modelling with the nlme package v. 3.1. The fixed effects were treatment (substrate and topsoil), and year and their interactions, while the random effects were block and site. Repeated measures of plots over the years were modelled using a continuous autoregressive correlation matrix. Tukey HSD post hoc comparisons were conducted using the package multicomp package v. 1.3-2 when treatment or treatment–year interaction (Trt × Yr) was significant in the overall model, and treatment also had a significant effect in a reduced model for an individual year. Normality and homogeneity of variances were tested by examining the residuals versus the fitted plots and the normal q–q plots of the models. Water retention data (saturation, field capacity, near dry) were analyzed using ANOVA for continuous data. All statistical analyses were conducted using R version 4.0.3 [27] with a significance level $\alpha = 0.05$.

3. Results

Mean air temperature changed little from year to year, with the highest recorded in 2006 and the lowest in 2008 (Figure 2a). Summer temperatures from June to August increased from 2005 to 2016, with the highest in 2006 and lowest in 2009. Mean annual and summer precipitation declined from 2005 to 2016, with the highest in 2008 and lowest in 2016 (Figure 2b).

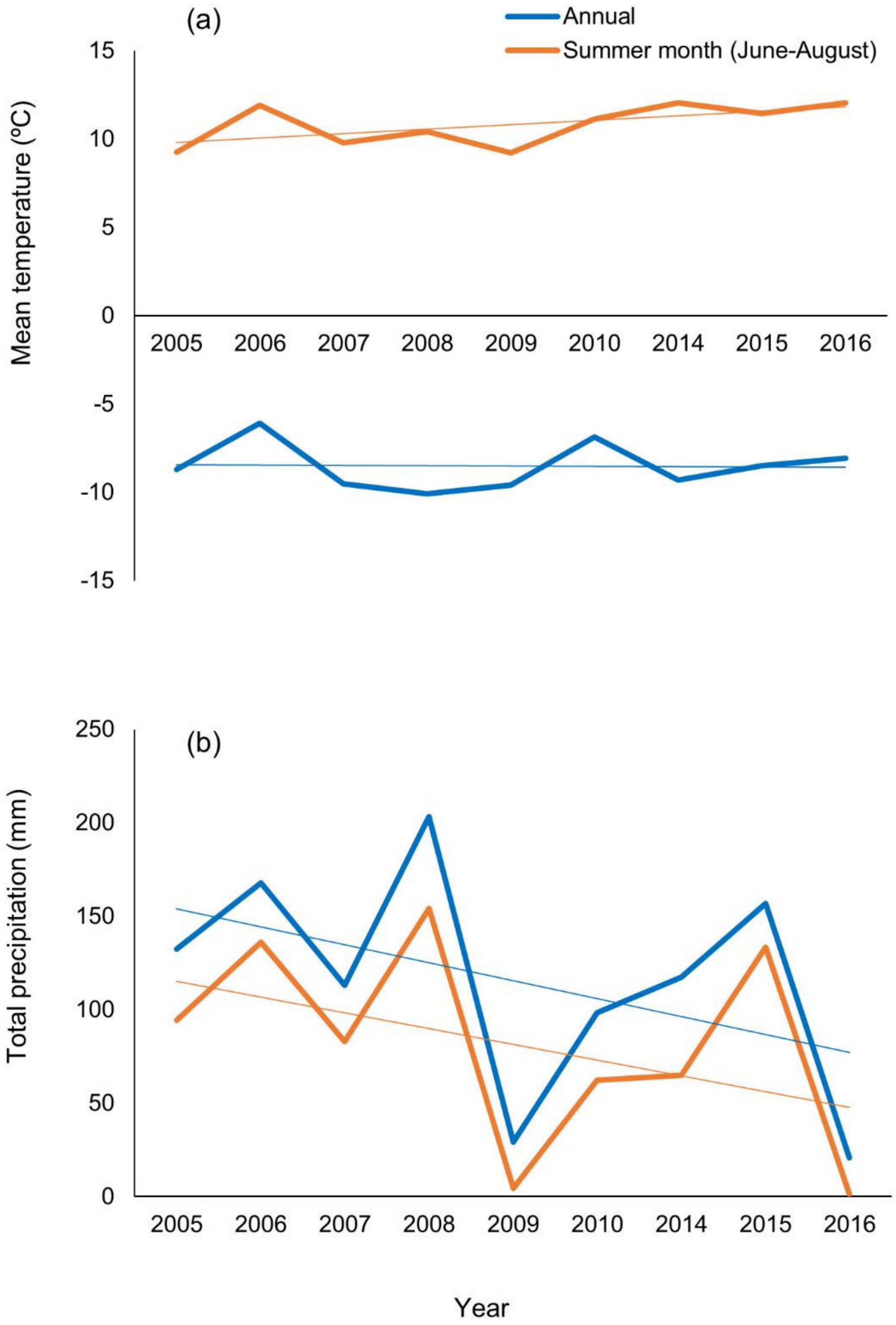


Figure 2. Annual and summer (June–August) (**a**) ambient temperature and (**b**) precipitation from 2005–2016 at the research sites.

Water retention differed by substrate, with processed kimberlite holding significantly more water than lakebed sediment and crushed rock at saturation (Figure 3). At field capacity and near dry, lakebed sediment and processed kimberlite did not significantly differ, although processed kimberlite held slightly greater water. Lakebed sediment and processed kimberlite each held more water than crushed rock at all three potentials (Figure 3). Considering the topsoil amendment with substrates, again processed kimberlite had slightly greater water content than lakebed sediment and crushed rock, but none differed significantly.

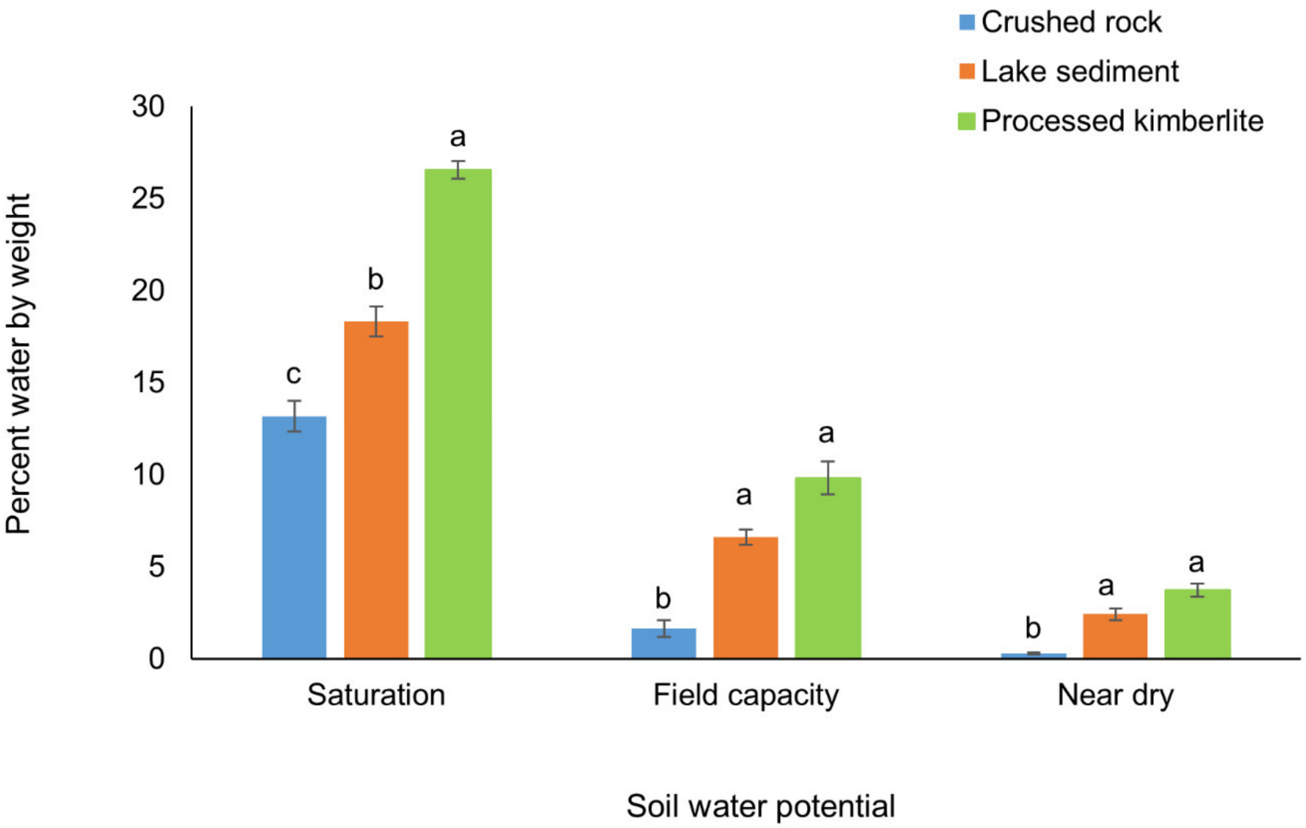
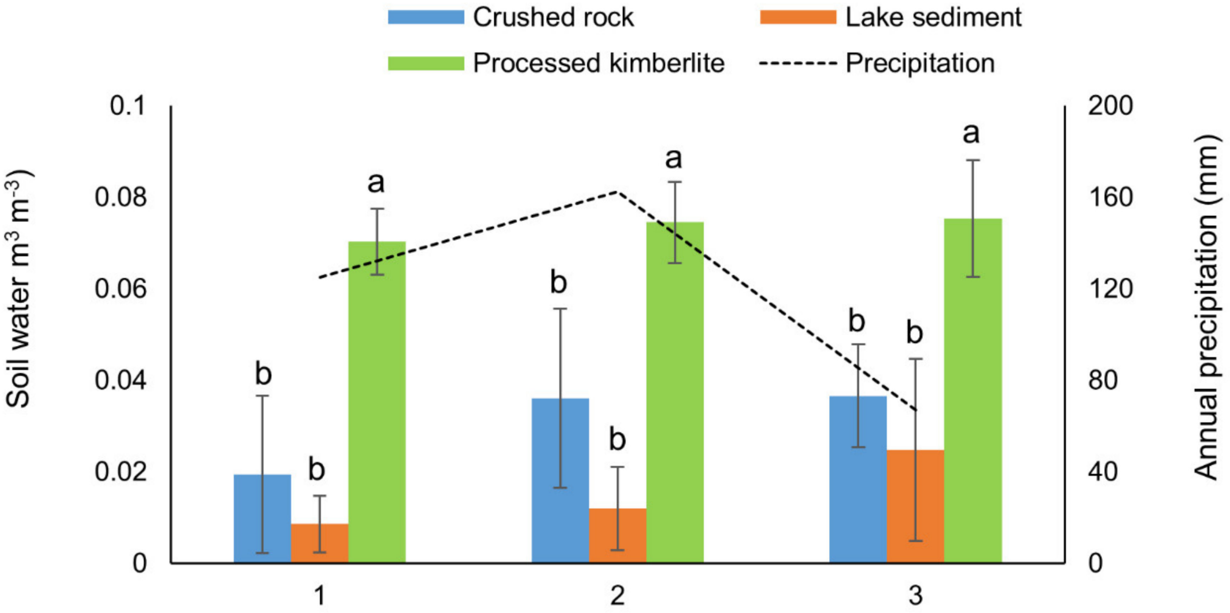


Figure 3. Mean percent water by weight at saturation, field capacity, and near dry for different substrates. Different letters indicate significant differences at $p = 0.05$ in Tukey HSD post hoc comparisons.

Substrates did not show any significant treatment × year (interaction) effect for mean annual water content, although a significant treatment (substrate) (annual mean $p < 0.001$) effect was observed. Processed kimberlite had significantly greater water content than crushed rock and lake sediment (Figure 4a). June-to-August water content showed similar trends, i.e., it was over twice as high in processed kimberlite than in lake sediment and crushed rock, with an increasing trend over time (Figure 4b). Mean annual temperature did not significantly differ among substrates, with the highest values in crushed rock, followed by lake sediment and processed kimberlite (Figure 5a). Unlike mean annual temperature, summer temperatures slightly differed among substrates, with its highest in processed kimberlite in most seasons, followed by lake sediment and crushed rock (Figure 5b). Soil water content in different substrates was not influenced by precipitation, whereas soil temperature showed some level of relationship with mean annual air temperature (Figures 4 and 5).

(a) Annual



(b) Summer month (June-August)

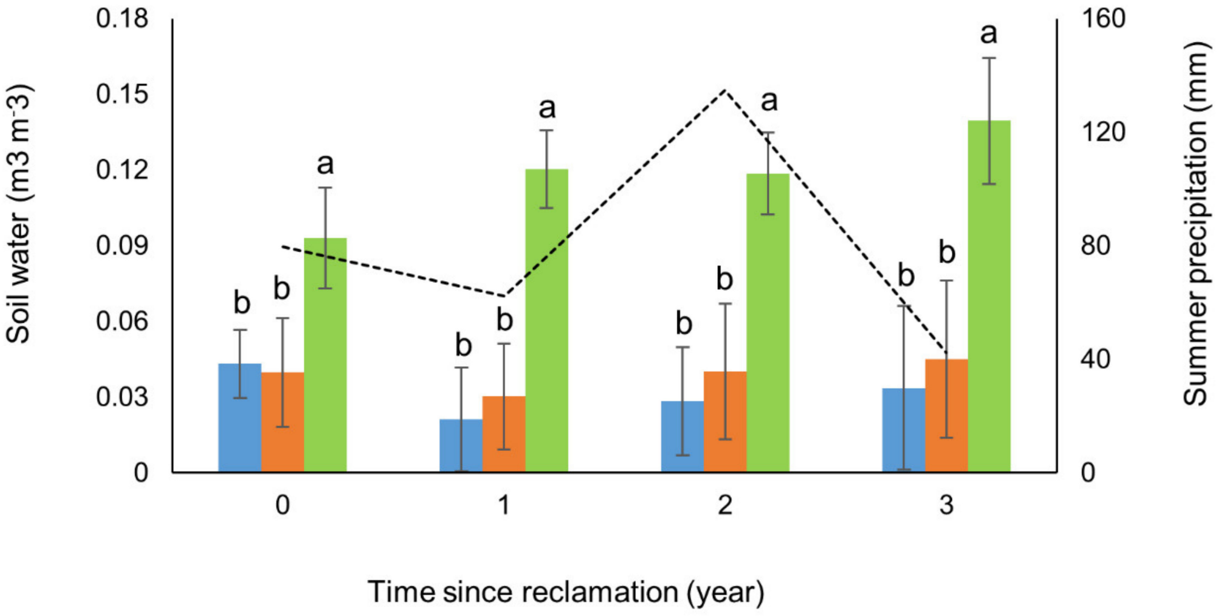
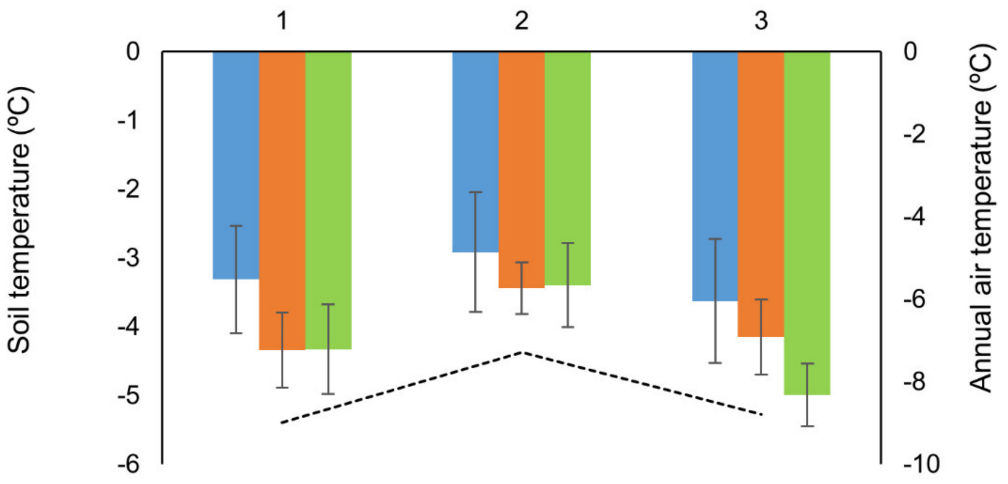


Figure 4. Mean (**a**) annual and (**b**) summer month water content by substrate type and precipitation at the research sites. Different letters indicate significant differences at $p = 0.05$ in Tukey HSD post hoc comparisons.

(a) Annual



(b) Summer month (June-August)

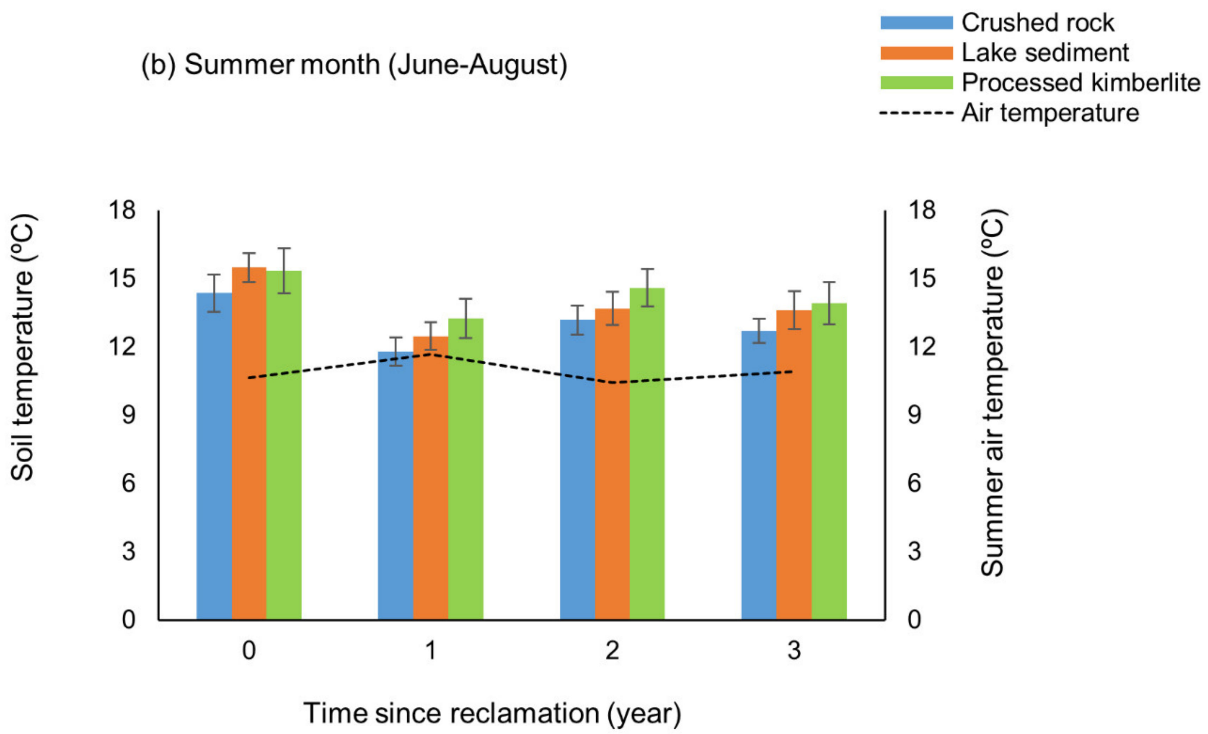


Figure 5. Mean (**a**) annual and (**b**) summer month soil temperature by substrate type and air temperature at the research sites.

In the absence of interaction effects (amendments × year), treatments and years were separately analyzed. Only water content differed significantly with and without topsoil (annual mean p = 0.010; summer month mean p = 0.004), with no significant differences found for temperature. Annual and summer month water contents were greater without topsoil than with it (Figure 6), with a slightly increasing trend with time; no such trends were observed for temperature (Figure 7). In most cases, processed kimberlite substrate had greater water content and lower temperature for both annual and summer months (Figures 6 and 7), whereas crushed rock substrate without topsoil had the lowest water content and temperature (Figures 6c,d, and 7c,d).

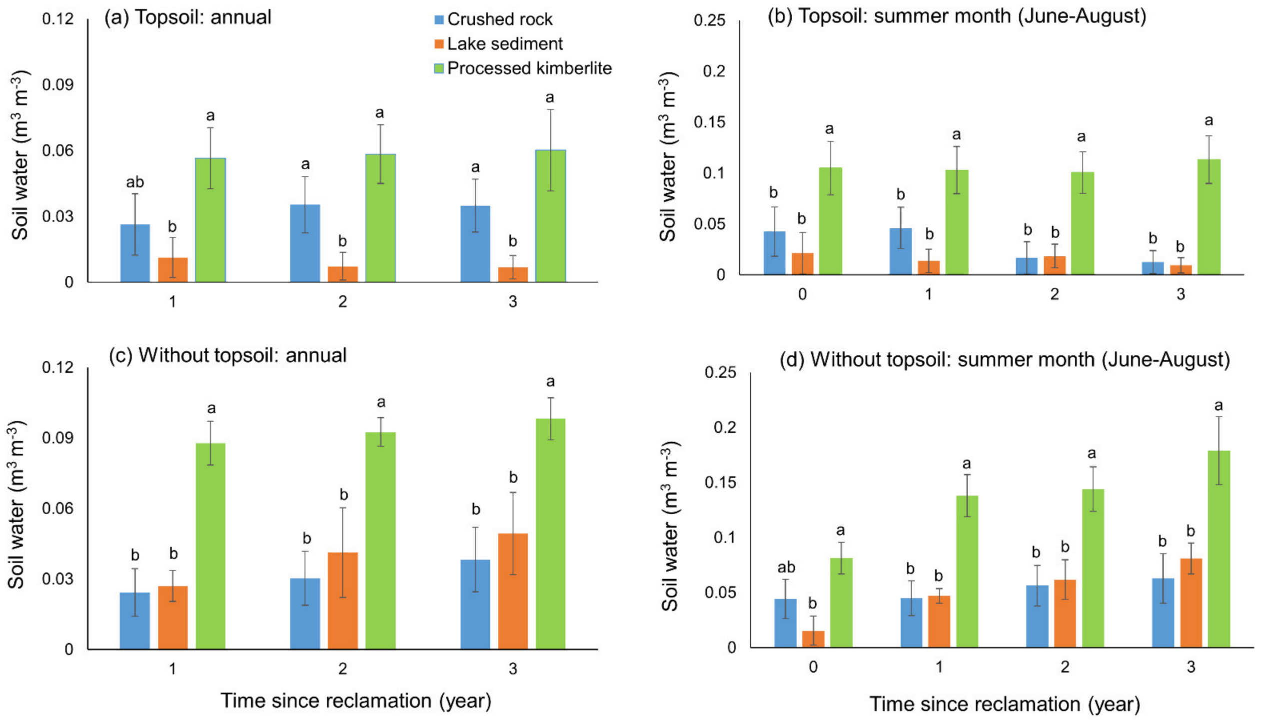


Figure 6. (**a**–**d**) Mean annual and summer month water content by topsoil treatments and substrate types at the research sites. Different letters indicate significant differences at $p = 0.05$ in Tukey HSD post hoc comparisons.

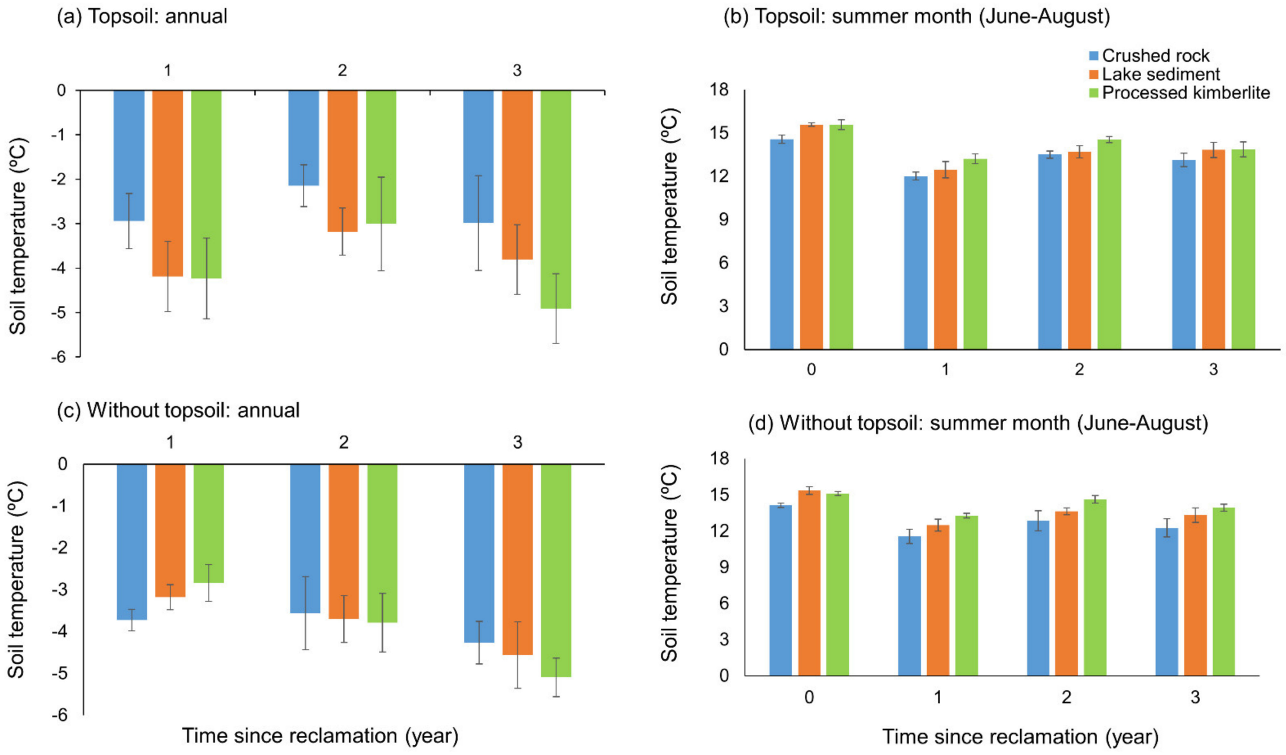


Figure 7. (**a**–**d**) Mean annual and summer month soil temperature by topsoil treatments and substrates at the research sites.

4. Discussion

The highest water retention and contents in processed kimberlite substrate with or without topsoil support the results of other studies associated with diamond mine reclamation in the Arctic [18,23]. Other studies reported that processed kimberlite was less limited by low water content, as it retains more water than crushed rock and lake sediment due to its lack of coarse material [8,28]. This would be affected by the finer texture of processed kimberlite particles (under 2 mm), which can easily hold more water than coarser textured lake sediment and crushed rock. At saturation, processed kimberlite held ~27% water by weight, with the highest water retention of the three substrates. Fine-textured lakebed sediment, with likely greater pore space and surface area, had higher water retention than crushed rock [18]. Miller and Naeth [18] found greater water retention in processed kimberlite relative to crushed rock and lakebed sediment was due to its composition of particles under 2 mm. Soil texture can influence water retention, and predominantly coarse-textured soils typically have high infiltration rates and saturated hydraulic conductivity, and low water holding capacity [29]. Several other studies found coarse-textured mine wastes were characterized by lower soil water contents and nutrient retention capacities [11,15,23].

Differences in water content among the substrates could greatly influence vegetation establishment in an Arctic environment. In a field experiment at King Christian Island, Northwest Territories in Canada, Bell and Bliss [22] found seeds germinated and established best in microsites such as soil cracks, where soil water would likely be highest over the longest periods in summer. They stated that Arctic regions are barren of vegetation largely as a result of the lack of surface water in summer. Therefore, for any reclamation effort initiated in the Arctic, the soil water content of the substrate should be earnestly considered.

Adding topsoil can regulate soil water content and soil temperature in the Arctic. Although our findings were inconsistent, we suggest that adding topsoil cannot expedite water retention capacity in processed kimberlite substrate, which supports the findings of Naeth and Wilkinson [23] and Miller and Naeth [18] but contradict those of Bishop et al. [30], Kidd and Max [31], and Drozdowski et al. [8]. Drozdowski et al. [8] found topsoil increased water retention and temperature in processed kimberlite substrate, compared with lake sediment or crushed rock. Bishop et al. [30] and Kidd and Max [31] found topsoil significantly increased soil water, nutrient availability, vegetation cover, and plant productivity, compared with no topsoil. The difference in our study regarding water content with topsoil might be due to the source of topsoil used in the study. According to Miller and Naeth [18], limited increased water retention with topsoil may be due to its low organic carbon content, and a high proportion of sand (sand 74.4%, silt 20.7%, clay 4.9%). Therefore, soil amendment should be selected based on organic carbon content. Greater organic-carbon-containing amendments such as inorganic fertilizer, peat, biochar, and sewage sludge can be used in artic mine reclamation for enhancing nutrient availability, increasing soil water holding capacity, improving the soil microbial community, and/or ameliorating soil pH. This was evinced by Bishop et al. [32], who found soil water and plant cover were significantly higher in organic amendment treatments than in several other amendments.

The lack of overall mean soil temperature differences among substrates and slightly higher soil temperatures during the growing season in processed kimberlite were similar in other studies [8,23]. The higher temperature in processed kimberlite substrate would be due to soil colour, texture, and chemical properties. Generally, processed kimberlite substrate is dark in colour, similar to black sand, therefore absorbing more latent heat than light coloured soils [8,23,33]. Soil texture is another contributing factor, as gravel substrates have higher porosity, resulting in surface pores being filled with air rather than water; thus, soil temperature remains lower as air is a poor heat conductor.

Soil temperature can also depend upon mineral composition, organic matter, and volume of fractions of water and air [8,34,35]. According to Chambers et al. [34] and Chambers [35], other than environmental conditions, as well as soil physical and chemical properties, can influence soil temperature and nutrient regimes. However, the overall small difference among treatments throughout the year may not have a great implication for vegetation development, as most species in this Arctic environment use apomixis and vegetative reproduction [36,37], and only a few plant species produce dormant seeds that may require germination temperatures between 12 °C and 20 °C [22,38]. According to Billings et al. [37], small temperature differences would not impact apomixis and vegetative reproduction, including root growth, but this is not yet confirmed. High temperature demanding species might have better germination and establishment in processed kimberlite than crushed rock or lake sediment substrates.

Although processed kimberlite had more appropriate soil water content and soil temperature for plant growth, it may not be the best substrate until it can provide a better growth medium for plant growth. Some studies suggest processed kimberlite requires amendments to address its structural and nutritional limitations as they found unamended processed kimberlite had little plant cover [8,39,40]. Processed kimberlite amended with fertilizer or sludge had the lowest plant densities, richness, and cover 5 years after reclamation [41]. Plants grew in kimberlite but had small biomass with evidence of metal toxicity at Ekati Diamond Mine studies [31,42]. Some studies found good growth in processed kimberlite using high rates of amendments [39] or peat amendment [43]. In our study, adding 10 cm topsoil on substrate did not influence soil water content and temperature, which indicates the amount of topsoil we added was not enough to show any impact. Reclamation success was influenced by soil temperature and water, which improved soil respiration, microbial decomposition, organic matter storage, mineralization, and a variety of chemical reactions and pedogenic processes in the soils [44–48], and with the presence of microorganisms, organic matter, native propagules, and erosion. Although it would be interesting to conduct further studies using processed kimberlite substrate with variable topsoil depths to determine the appropriate depth that can influence successful reclamation at diamond mines and other disturbed sites, the lack of significant amounts of topsoil in these northern environments may make this impractical. Instead, studies addressing mixtures of topsoil and other amendments may prove more valuable from a reclamation perspective.

5. Conclusions

This study provided valuable insight into the role of substrate and topsoil on soil water and temperature management in Arctic diamond mine reclamation sites. The results suggest water content was influenced more by substrate than by placing 10 cm of topsoil on the substrate. Mean annual air temperature did not change much from year to year, although summer temperature showed an increasing trend. Both annual and summer precipitation showed a declining trend with time. Processed kimberlite substrate had greater water retention characteristics and water content than lake sediment and crushed rock (significantly), whereas soil temperature was not influenced by substrate or topsoil. Treatments with topsoil had lower water content than those without topsoil, suggesting that placing 10 cm of topsoil on the substrate was not enough to show any impact.

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