Distributed temperature observations reveal the scale of spatial variability in unsaturated soil covers

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ABSTRACT: Unsaturated reclamation soil covers are designed under the assumption of homogeneous, one-dimensional behaviour across the entire spatial extent. This assumption is rarely, if ever, tested. The costs associated with measuring water content often preclude intensive monitoring to verify soil cover homogeneity. Distributed Temperature Sensing (DTS) is an emerging technology that uses fibre optic cables and a laser reader to measure temperature every metre at ranges up to thousands of metres. Applying this technology to monitoring of reclamation soil covers allows for an investigation of the spatial and temporal scales of variation. Cover systems at uranium and oil sands mines were instrumented with a DTS system. An investigation of temperature variability using geostatistical techniques revealed that cover physical properties had a strong influence on the scales of variation.

1 INTRODUCTION

Mining companies are required to reconstruct functioning landscapes that reproduce the associated functions of natural watersheds as a precondition for operation (Carey, 2008). The industry has extensively used engineered soil covers to achieve this condition (Nicholson et al., 1989; Yanful, 1993). Current soil cover design methods attempt to optimize key vadose zone processes such as maximizing evapotranspiration and minimizing net percolation in a subsection of designs known as Unsaturated, Evapotranspirative (ET) or Store and Release covers. (McGuire, et al., 2009; Blight and Fourie, 2005; Albright, et al., 2004; Hauser, et al., 2001; Khire, et al., 1997). The dynamics of these cover systems is governed by the physical properties of the cover material and the coupled heat and mass transfer within the cover itself and between the cover and the atmosphere (Kelln et al., 2008).

The current state of practice for cover design involves the construction of small test covers with localized soil profile monitoring of suction, water content, and temperature. Performance monitoring centers on reducing the net annual percolation below the cover into the waste to an acceptably small percentage of precipitation input (Scanlon et al., 2006). Monitoring data are interpreted using one-dimensional numerical models to simulate field water and energy dynamics. One-dimensional analyses have been found to be inadequate in predicting percolation and runoff when they are extrapolated to the field scale (Ogorzalek et al. 2008; Bohnhoff et al. 2009; McGuire et al. 2009). Furthermore, in the soil science discipline it has long been accepted that a full characterization of the spatial variability of certain soil parameters will lead to a more complete understanding of the system (Oliver, 1987). A well-characterized system optimizes what is known as the scale triplet of spacing, extent, and support (Blöschl and Grayson, 2000). By optimizing the triplet a balance is struck between capturing small-scale variability, covering large spatial extents, and sampling a volume that is not so large as to artificially smooth the data (Blöschl and Grayson, 2000). Despite the recognition that spatially distributed measurements of various performance parameters is important, there remains a paucity of data on the subject, especially with regards to unsaturated soil covers.

Distributed temperature sensing (DTS) is a system that precisely measures temperatures at high spatial and temporal resolutions (Tyler et al., 2009). A DTS system uses a high-powered laser to interrogate a fiber-optic cable. The backscattering of the light pulse is partitioned into a wavelength of the incident light, and wavelengths that are slightly above and below the incident wavelength. The latter two wavelengths are known as the Stokes and Anti-Stokes wavelengths, and the ratio of the two are temperature sensitive. The utility of a DTS system lies in the optimization of the scale triplet. Spatial resolutions are as high as 1 m while extending up to 5000 m. Temporal resolution can be as high as every 30 seconds, depending on the integration time of the signal. In this way, a cover system can be instrumented with a fiber-optic cable and can be monitored for temperature every meter for thousands of meters every 30 seconds.

Soil temperature is an important variable of interest in mine reclamation, albeit one that is most often overlooked in favor of soil water content. Soil temperature is a key state variable in the surface energy balance and is linked to the soil water balance through the latent energy term. Fluctuations in soil temperatures are governed by soil physical and thermal properties, the partitioning of radiation at the surface, and the volume of water in the subsurface (Hillel, 1998). Given the ease with which temperature is measured with a DTS system, the spatial distribution of temperatures in covers systems warrants further investigation.

Distributed temperature sensing has recently been used in the earth sciences, particularly in the area of stream hydrology (Selker et al., 2006a,b). The method has also been applied as a means of estimating water content through thermal diffusivity (Steele-Dunne et al., 2010; Rutten et al., 2010; Krzeminska et al., 2011). While inferring soil water content by passively monitoring thermal diffusivity has showed initial promise, the technique suffers from a non-unique relationship between diffusivity and water content (Steele-Dunne et al., 2010). The uncertainty involved in inferring soil water content from thermal properties may make the technique unsuited to examining the spatial variability of cover systems.

Spatial variations in soil temperature have been investigated previously. Vauclin et al. (1982) examined the spatial structure of soil temperature and found it to be well correlated with soil water content. Mohanty et al. (1995) found that spatial correlations will change based on soil physical properties. Interestingly, it was found by Mohanty et al. (1998) that soil temperature will vary temporally in hysteretic loops with minimum temperature variances occurring at the point of daily temperature minimum. Soil temperature demonstrates spatial and temporal structure and can be used to examine the scales of variability in reclamation cover systems.

The implicit assumption in the design of unsaturated soil covers is that disturbance of the cover materials in cover construction will serve to homogenize the cover, thus obviating the need for investigating spatial variability of cover soil parameters. However, this assumption has never been tested. Given the lack of data existing for the mining industry, further investigation into the spatial scales of cover system variability is warranted. The objective of this study was to i) investigate the utility of intensive temperature monitoring in unsaturated soil covers using a DTS system; and ii) to provide a preliminary assessment of the spatial variability of temperature as it relates to physical parameters in unsaturated soil systems.

2 MATERIALS AND METHODS

2.1 *Study Area*

A field experiment was conducted at a uranium mine in northern Saskatchewan, Canada, from August 20 to 28, 2011. The study area was a waste rock dump on which a cover system had been constructed two months prior to commencing the field study. The cover system consisted of a 1 ha plateau and a 0.5 ha slope. The plateau area had a 2% south facing slope and the slope faced north at 25%. The cover system was constructed to a nominal thickness of 1 m using fine sand salvaged from a local drumlin. Average sand, silt, and clay content were 94, 5, and 1%, respectively, with an average bulk density of 1.55 g cm^{-3}.

2.2 *Climate*

Climate at the site was classified as continental. Thirty year climate normals indicated mean January and July air temperatures of -23 and +16 °C, respectively. Thirty year mean annual precipitation was 481 mm (Carey et al., 2005).

2.3 *DTS System*

An Oryx DTS-SR (Sensornet, UK) was used for the field experiment. The Oryx was field deployable and had a measurement range up to 5000 m with a 1 m measurement resolution. Temperature resolution was 0.05 °C with a 60 s integration time. Measurements were calibrated by reserving a 50 length of cable to be kept in an ice bath. The temperature along that 50 m portion was calibrated against a pair of PT-100 platinum thermistors. The DTS system was powered by deep cycle batteries that were charged with a solar panel array.

The fiber-optic cable installed at the site was the Sensornet DamSense cable (Sensornet, UK). The DamSense cable was 5.5 mm in diameter and was rated for accurate temperature measurements from -55 to +85 °C.

2.4 *Cable Installation*

A 500 m fiber-optic cable was installed in a linear transect that was excavated into the existing cover system. The transect extended for 65 m on the plateau and 35 m down the slope. Cable was installed at 90, 50, 10, and 0 cm. Note that the 0 cm cable was laid on the surface and was only covered with enough material so as to not be directly exposed to the atmosphere.

The installation process proceeded as follows: a trench was excavated with an excavator. Once the proper depth was reached, the cable was laid out by hand and protected with a layer of cover sand. The trench was then backfilled until the next depth was reached, at which point the process repeated. In this way, the cable was extended in one continuous length and wrapped back on itself to proceed to the next depth.

2.5 *Data Collection*

Spatially distributed temperature measurements were taken with the DTS system every 20 minutes with a 60 s integration time for the duration of the field experiment. Soil temperature data were complimented by climatic data from an automated meteorological station 20 m from the transect. The meteorological station collected data on air temperature and humidity, wind speed and direction, and all-component radiation.

2.6 *Data Analysis*

The spatial structure of soil temperature data along the transect was analyzed using semivariograms (Isaaks & Srivastava, 1989). Temperature data were aggregated across all days to form a single minimum and maximum temperature dataset for each individual depth. Aggregated semivariograms were calculated using (Si et al., 2007):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{k=1}^{N(h)} [T(x_k) - T(x_h + h)]^2 \tag{1}$$

where N is the number of pairs at lag distance, h, $T(x_k)$ is the measured soil temperature at location x_k, and $T(x_k+h)$, the soil temperature at location x_k increased by h lags. Semivariograms were then fit with a spherical model (Si et al., 2007):

$$\gamma(h) = c_0 + 1.5\frac{h}{\alpha} - 0.5\left(\frac{h}{\alpha}\right)^3 \tag{2}$$

where c_0 is the nugget, or the extrapolated semivariance at lag = 0, and α is the range, or the lag at which the semivariance reaches a plateau and becomes constant. The semivariance at which the range is reached is known as the sill. A spherical model can be combined to form nested models in the case of a semivariogram that displays more than one obvious structure.

Spatial dependence provides an indication of the distance at which any particular measurement remains similar to another measurement. For example, in a field that exhibits high spatial dependence, the degree of similarity between two points depends greatly on how proximal they are to each other. At low spatial dependencies, two measurements can be located large distances apart and still be similar. Spatial dependence describes how much two points being similar depends on the distance between those points. Spatial dependence is calculated as the ratio of the nugget to the sill. Spatial dependence <25% is considered strong, values between 25 and 75% are considered moderate, and spatial dependencies > 75% are indicative of little to no structure (Si et al., 2007).

3 RESULTS

3.1 *Preliminary Data Analysis*

The field experiment was conducted in late August as air and soil temperatures were beginning to decline from their summer maxima (Fig. 1). Average air temperature was 15.6 °C and average soil temperatures were 13.9, 13.9, 15.7 and 14.6 °C at the 0, 10, 50, and 90 cm depths, respectively. The highest average soil temperature at 50 cm depth was indicative of the lag in temperature propagation with depth. Preliminary indications of spatial variability of soil temperature, as denoted by the coefficient of variation (CV = standard deviation / mean) demonstrated that variability decreased with depth. Soil temperature CVs were 29, 19, 5, and 2% at the 0, 10, 50, and 90 cm depths, respectively.

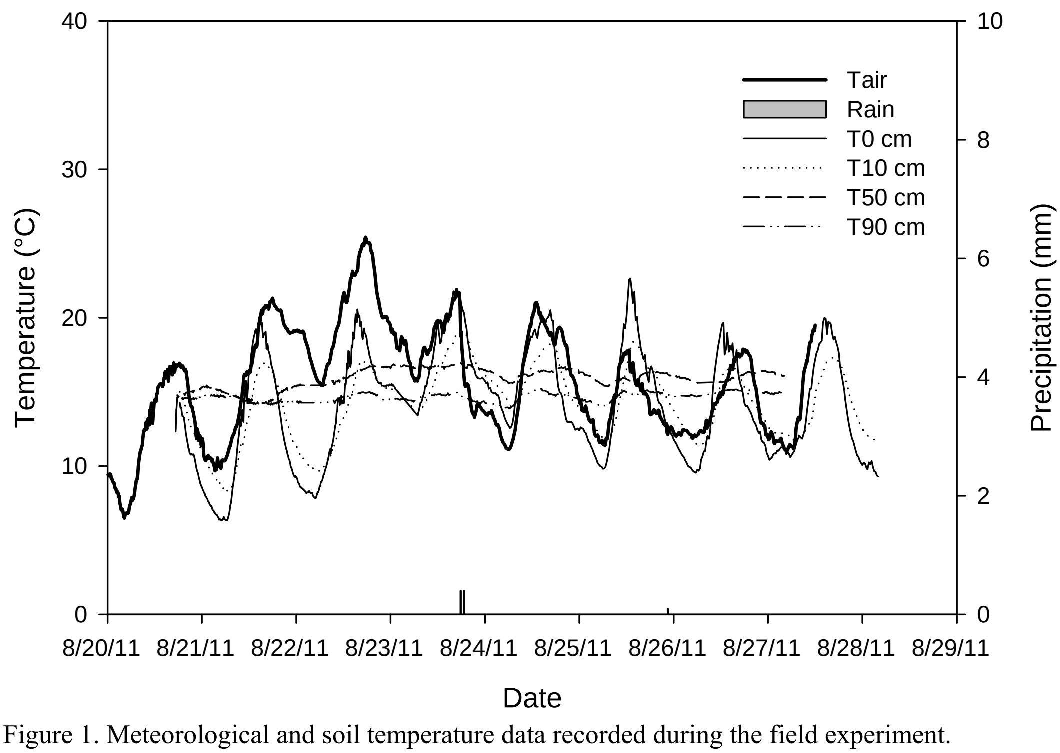

Figure 1. Meteorological and soil temperature data recorded during the field experiment.

Physical properties of the cover system were homogeneous across the entire transect (Fig. 2). Coefficients of variation for percent sand content and bulk density were 2.2 and 5.8%, respectively. The increased CV for bulk density was likely a result of the inherent difficulty in taking precise bulk density measurements in the field.

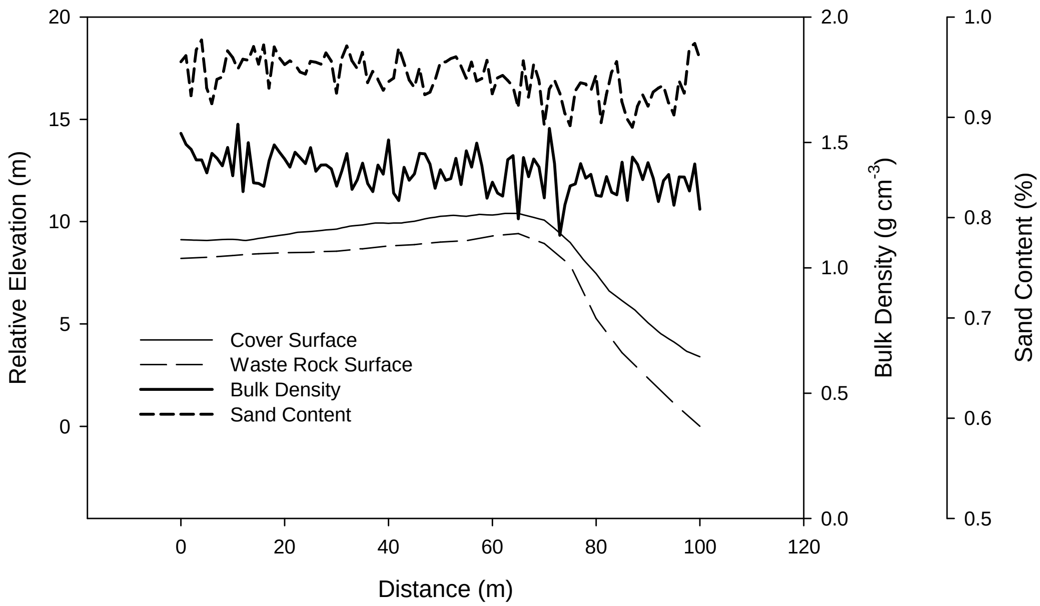

Figure 2. Spatial variation of bulk density, sand content, and relative elevation profile of the cover system experimental transect.

3.2 *Temperature Contours*

Cover system temperatures measured with a DTS system demonstrated homogeneity in both time and space (Fig.3). Cover system temperatures and qualitative indications of variability decreased between depths (Fig. 3 a, b, c, d). Within a given depth, the patterns of soil temperature did not show marked changes between days. Similar temperatures between days compared well with air temperature measurements, as no single day had substantially higher or lower air temperatures during the experiment. The majority of cover system temperature variation occurred within a given days as a function of transect distance. A zone of distinctly cooler temperatures consistently occurred from 65 to 100 m across each day during the experiment. This area corresponded to the slope area with a northern aspect.

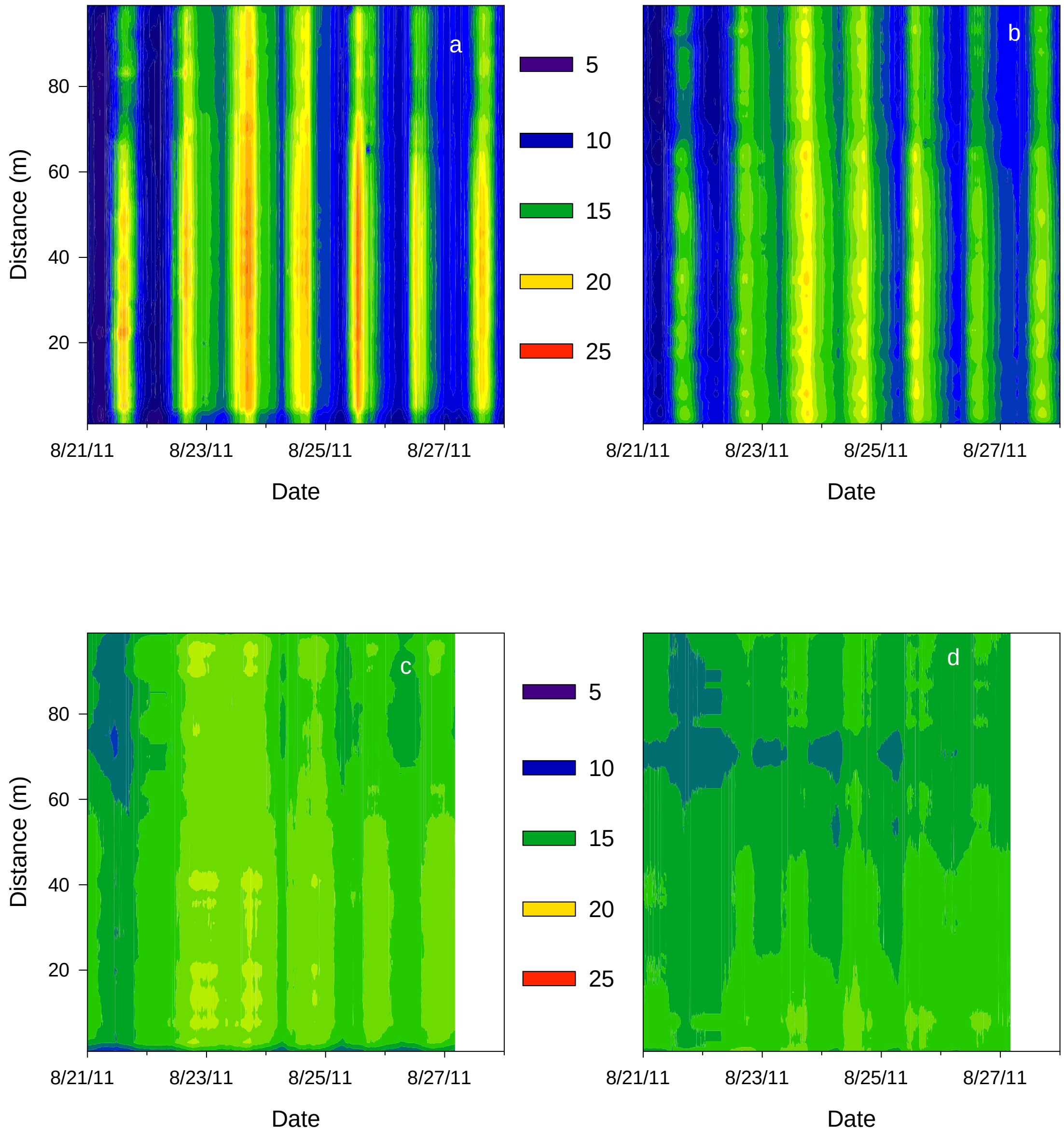

Figure 3. Distributed soil temperature values for the field experiment measured at a) 0, b) 10, c) 50, and d) 90 cm depths.

3.3 *Semivariogram Analysis*

3.3.1 *Physical Properties*

Semivariograms of sand content and bulk density are indicative of a physically homogeneous cover system (Fig. 4). Neither semivariogram in Figure 4 reached a sill, or the point at which spatial autocorrelation is zero. The physical interpretation is that any measurement taken at any point on the transect is correlated with every other measurement, even at the maximum spatial extents. Therefore, a measurement taken at the origin of the transect is still spatially correlated to a measurement taken at the transect terminus. The bulk density semivariogram displayed the same behavior as that for sand content, albeit with a higher nugget value and greater dispersion of points. The higher nugget and greater dispersion is explained by the lower measurement precision of taking bulk density samples of a sand in the field.

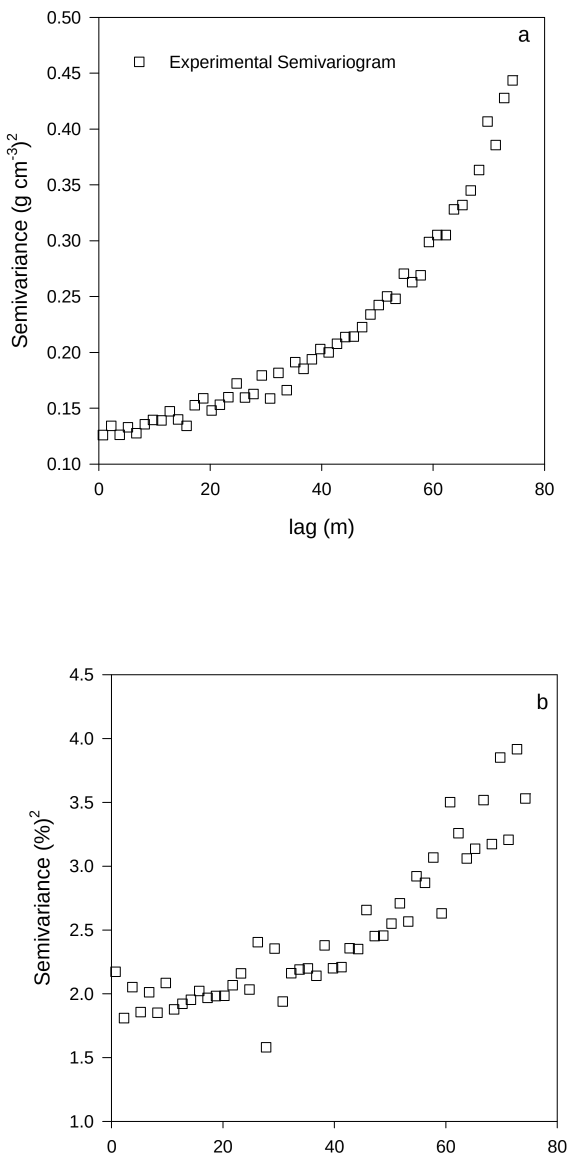

Figure 4. Semivariograms for a) percent sand content and b) bulk density.

Semivariogram analysis of cover system minimum temperatures revealed trends that differed from those of the physical properties (Fig. 5). Minimum temperature Semivariograms demonstrated a consistent nested behavior at all depths. Spatial dependencies were initially moderate and displayed ranges of between 2 to 28 m. However, for each depth a secondary structure was found at approximately 40 m. Strong spatial dependencies for the secondary structure were found, with all depths being less than 25%. Ranges for the secondary structure extended to 97 m, suggesting strong autocorrelation at large spatial scales.

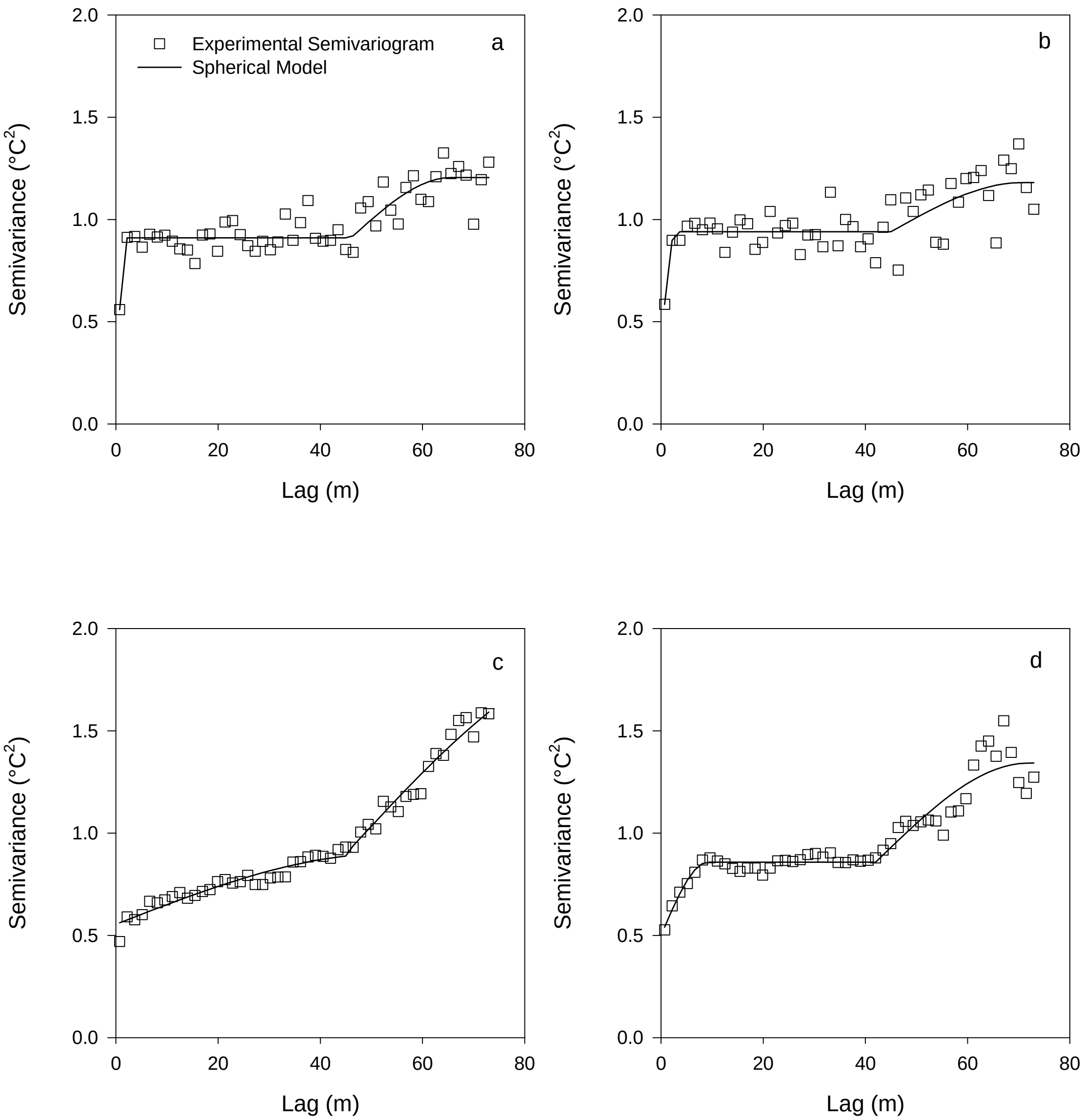

Figure 5. Semivariograms of minimum spatial temperature the experimental transect at a) 0, b) 10, c) 50, d) 90 cm.

4 DISCUSSION

Analysis of spatially distributed cover system temperatures revealed the spatial scales of variability at the field experiment. Initial analysis indicated a physically homogeneous cover system with low coefficients of variability. Temperatures monitored at a single point did not provide any indication of differential behavior at other locations. Spatially distributed temperatures demonstrated areas of distinctly different thermal behavior for each day of the field experiment.

However, discussion of the differences remained qualitative unless more advanced data analysis techniques were applied.

Geostatistical analysis using semivariograms quantified what was seen qualitatively with temperature contours. Semivariograms for all depths reached a sill at short ranges from 2 to 28 m. Secondary structure was found at approximately 40 m for all depths. Although semivariograms do not convey any information as to the location of a certain process, the sharp division between plateau and slope allow some room for inference. The plateau extends a distance of 60 m and is south facing. The lack of vegetation or microtopography allows the plateau area to heat and cool as a distinct unit. Strong spatial dependencies at this scale mean that any measurement take on the plateau will be similar to another measurement taken at any other location on the plateau, even if they are separated by 60 m. For the slope, however, spatial dependencies were not as strong, and in some cases, two measurements could be separated by as little as 2 m before any autocorrelation was lost.

5 SUMMARY

The field experiment presented above represents a fairly simplistic case: the borrow material was homogenized during salvage and placement, and the landform was designed to be devoid of topographical heterogeneity. The only major macroscopic difference in the cover system was the division of the system into plateau and slope areas. Clearly some difference between the plateau and slope would be expected. However, the salient point remains that any differences in performance or the effect of governing process would remain as speculation unless verified through spatially distributed monitoring as demonstrated. The techniques demonstrated in the current manuscript can be applied to larger systems designed with greater heterogeneity.

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