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Research papers

Monitoring soil water content at a heterogeneous oil sand reclamation site using a cosmic-ray soil moisture probe

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A B S T R A C T

Soil water content (SWC) measurements are important for numerous applications including climate and weather prediction, agriculture and irrigation activities, and monitoring the progress of reclamation on land disturbed by mining or other industrial activities. We assessed the SWC measurement accuracy of a cosmic-ray soil moisture probe (CRP) and explored the possibility of downscaling the CRP measurement to the plot scale. The experiments were conducted at a highly heterogeneous reclamation site in the Alberta Oil Sands near Fort McMurray, Alberta, Canada. The study site is unique because it consists of 36 one hectare plots composed of 12 different reclamation covers made up of various layering schemes of peat and coarse-textured soil. The one-hectare plots also contain different vegetation (species and density). A CRP was installed in the center of the reclamation study site and calibrated using soil core samples. CRP-measured SWC was compared to weighted average SWC measured from soil cores and a network of soil moisture probes within the CRP footprint over two summers. The CRP responded clearly to precipitation events with peaks in the measured SWC and the CRP estimates of SWC were very close to SWC estimated with soil cores and in-situ soil moisture probes with a RMSE of 0.027 $cm^3\ cm^{-3}$ and 0.027 $cm^3\ cm^{-3}$, respectively, over the two summers. We also attempted to downscale the CRP measurements from the 2014 season to the plot scale using HYDRUS-1D modeling and the known soil texture in order to unweight the CRP-measured SWC. The modeled SWC (optimized with the CRP measurements) within the CRP footprint was relatively close to the CRP-measured SWC with a RMSE of 0.047 $cm^3\ cm^{-3}$. Overall, the CRP provided accurate average SWC measurements at the reclamation site despite the soil and vegetation heterogeneity.

1. Introduction

Soil water content (SWC) is required for a better understanding of and predicting hydrological processes below and above the soil surface (Vereecken et al., 2008). It also affects the magnitude of energy transfer and water infiltration at the soil surface - thus it is crucial for predicting climate and weather at local and global scales (Ochsner et al., 2013). SWC measurements are also important for agricultural production and irrigation management, where accurate knowledge of water content can have economic benefits by limiting over-use of water (Fares and Alva, 2000). In addition, SWC affects land and ecosystem restoration success, especially in water-limited environments (Alberta Environment, 2010).

Methods of measuring SWC at small scales (cm^2) with various *in situ* probes and large scales (km^2) with remote sensing are common and generally reliable (Robinson et al., 2008). Until recently, there remained a measurement scale gap for SWC between point and large scale measurements. The Cosmic-ray soil moisture probe (CRP) was developed in recent years to address the lack of field or landscape scale SWC measurement tools (Zreda et al., 2008). The CRP has been an instrument of great interest because it provides an estimate of average SWC within an often assumed measurement radius of ~300 m (Desilets and Zreda, 2013). Recent work has shown that the measurement radius might be closer to ~200 m (Kohli et al., 2015). Like most SWC instruments, the CRP does not measure SWC directly, but rather measures neutrons above ground. These neutrons, referred to as moderated neutrons in this study, are in the fast to epithermal range and have energies in the range of 1–1000 eV (Hess et al., 1961). The neutrons are formed from primary and secondary cosmic rays entering Earth's

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atmosphere. Moderated neutrons travel at high velocities, and when they collide with other particles or matter, they lose energy (Zreda et al., 2012). Collisions with hydrogen atoms cause the greatest velocity decreases for moderated neutrons compared to all other collisions. This means that fewer collisions with hydrogen molecules are needed to greatly reduce the energy of moderated neutrons compared to other atoms. Thus, hydrogen in water near the soil surface is one of the main controls over the intensity of moderated neutrons above the soil surface.

There are a few advantages associated with the CRP (Desilets et al., 2010). The CRP is non-invasive, passive, and not sensitive to differences in soil texture. CRPs can be easily transported and installed in remote locations and data can be remotely obtained from a CRP via satellite telemetry. The CRP provides a time-continuous measurement of SWC and can operate year-round with little maintenance. Most importantly, the CRP has a landscape scale measurement footprint. The CRP also shows promise for the use of monitoring snow water equivalent (SWE) at a similar landscape scale (Desilets et al., 2010).

CRPs are quite widely used globally as can be seen from the COsmic-ray Soil Moisture Observing System (COSMOS) probe map (cosmos.hwr.arizona.edu). There also have been a handful of studies validating the method at various sites in the USA and Europe. However, these studies generally involved using the CRP at relatively homogeneous study sites. Desilets et al. (2010) studied the use of a CRP in Arizona, USA at Mt. Lemmon Cosmic Ray Laboratory and Lewis Springs. Franz et al. (2012b) applied the CRP at a desert site in Tucson, AZ, USA. Again, this site appeared quite homogenous. Bogena et al. (2013) examined the use of a CRP in a humid forest in Germany. Their site did show some clear heterogeneity in terms of soil types, but was mainly dominated by older Norway spruce (*Picea abis L.*, planted in 1946) which covered 90% of the studied catchment. Franz et al. (2013b) studied the effect of horizontal SWC heterogeneity on neutron counts and average water content measurement by a CRP, but the study was based on simulated soil water and neutron counts. Distinct soil heterogeneity leading to large SWC variability occurs in many environments within distances relevant of the CRP footprint, such as transition zones from wet peatlands to dry uplands in boreal forests of Canada and Russia (Bhatti et al., 2006; Dimitrov et al., 2014). The main objective of this study is to assess the performance of a CRP for estimating SWC at a study site that possesses strong heterogeneity in soil and some variation in vegetation within the CRP footprint. The study site is a mining reclamation site consisting of various test plots composed of different soil layer and tree planting treatments. An additional objective is to explore the possibility of downscaling the CRP measurements to the plot scale.

2. Materials and methods

2.1. Study site description

The study site for this research was the Aurora Soil Capping Study (ASCS) site (57.3346 °N, 111.5351 °W) situated at Syncrude Canada Ltd.'s Aurora North mine. The Aurora North mine is one of several oil sand mining operations located north of Fort McMurray, AB, Canada. The ASCS site is a large experimental reclamation site composed of 36 one-hectare plots of varying soil layer and tree planting treatments (Fig. 1). It is located on an out-of-pit overburden disposal area that is composed of lean oil sand (LOS) material removed during mining to expose the oil sand ore body. LOS generally ranges from loamy sand to sandy loam and contains an oil content less than 7%. The soil reclamation treatments of the study are surface soil materials salvaged during mining within the disturbance footprint. The surface soil (topsoil) materials of the study include peat and surface salvage material (SSM). Subsoil materials of the study include a variety of coarse-textured (loamy sand to sand) materials, including Bm horizons salvaged from approximately 0.15 to 0.5 m below the pre-disturbance surface, B/C horizon salvaged from approximately 0.5 to 1.0 m, and a deep subsoil salvage from approximately 0.15 m to 2.5 m. The peat is high in organic matter content and was salvaged from bogs and fens in the mine footprint. The SSM is forest floor material and the underlying coarse textured surface A horizon material to approximately 0.15 m. Beyond the southern and northern borders of the ASCS, but within the CRP footprint, the area consists of lean oil sand overburden awaiting soil reclamation placement. Twelve soil layer treatments are triplicated in a completely randomized design at the ASCS site providing a total of 36 plots. Fig. 2 shows the 12 different layer profiles at the ASCS site. The sampling footprint of the CRP included all of 15 plots and a portion of an additional 10 plots with at least one of each of the 12 profile treatments.

In May 2012 each plot was planted with a mix of aspen (*Populus tremuloides*), jackpine (*Pinus banksiana*), white spruce (*Picea glauca*)

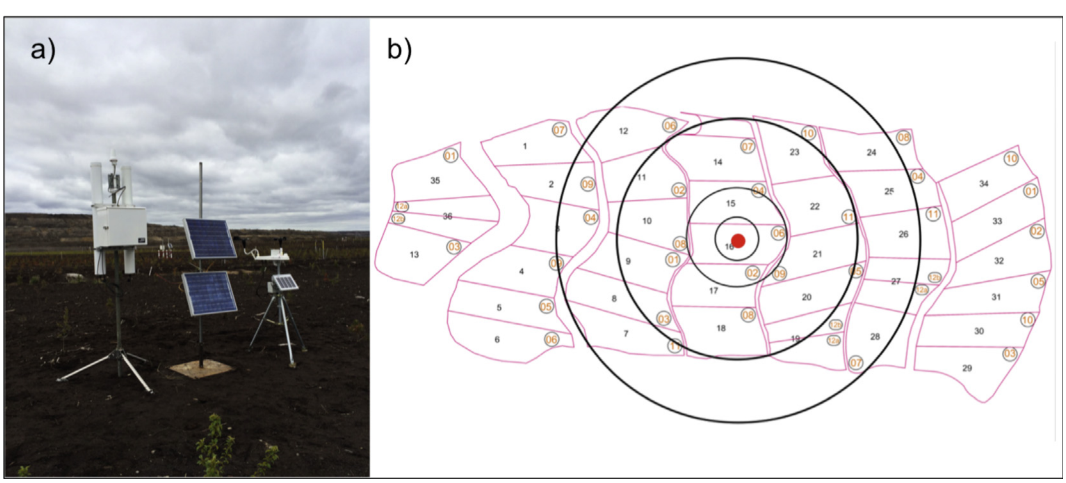

Fig. 1. Image of CRP and weather station installed at the study site (left) and an areal view of the location of the CRP (green dot) at the study site (right). The black circles around the CRP location represent the 25, 75, and 200 m radials used for soil sampling and calibration. The outer black radial represents the estimated 300 m radius CRP footprint. The red polygons in the image on the right represent the one-hectare soil cover plots with the red numbers representing which layer treatment was used in the plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)