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Hyperspectral measurements of wet, dry and saline soils from the McMurdo Dry Valleys: soil moisture properties from remote sensing

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Abstract: Soil moisture is a spatially heterogeneous quantity in the McMurdo Dry Valleys of Antarctica that exerts a large influence on the biological community and on the thermal state of Dry Valleys permafrost. The goal of this project was to determine whether hyperspectral remote sensing techniques could be used to determine soil moisture conditions in the Dry Valleys. We measured the spectral reflectance factors of wetted soil samples from the Dry Valleys under natural light conditions and related diagnostic spectral features to surface layer soil moisture content. Diagnostic water absorption features in the spectra at $1.4\,\mu m$ and $1.9\,\mu m$ were present in all samples, including samples doped with high concentrations of chloride salts. The depth of the $1.4\,\mu m$ absorption is shown to increase linearly with increasing gravimetric water content. These results suggest that airborne hyperspectral imaging of the Dry Valleys could generate soil moisture maps of this environment over large spatial areas using non-invasive remote-sensing techniques.

Introduction

Soil moisture is a key physical parameter for understanding biological and physical processes in the McMurdo Dry Valleys of southern Victoria Land, Antarctica. Liquid water is the limiting nutrient in the cold polar desert ecosystem of the Dry Valleys (77–78°S, 161–164°E) (Fig. 1), and its heterogeneous seasonal and spatial distribution in soils is a strong determinant of biological community structure and size (Kennedy 1993, Virginia & Wall 1999, Levy *et al.* 2013). Likewise, soil moisture has a strong effect on physical and thermodynamic processes in the Dry Valleys, such as depth of permafrost thaw (Hunt *et al.* 2007, Ikard *et al.* 2009, Levy *et al.* 2012a). In order to understand the impact of changes to the soil moisture state of the Dry Valleys, which could have significant biological and thermodynamic consequences (e.g. permafrost melting) (Bockheim *et al.* 2007, Gooseff *et al.* 2013), it is important to determine how much water is present in Dry Valleys soils, and how soil moisture distribution changes through time.

Volumetrically, most melt water moving through the Dry Valleys environment flows only during summer months (December–February), and is derived from glacial melt runoff, which flows overland through stream channels to perennially ice-covered lakes (McKnight *et al.* 1999). Meltwater is only delivered to the soil environment by the glaciers-streams-lakes system at stream and lake margins, where hyporheic exchange wicks water into adjacent soils (McKnight *et al.* 1999) or where glacier runoff directly infiltrates into the seasonally thawed active layer. Outside of glacier runoff zones, spatially distributed sources of shallow groundwater to the active layer include melt from seasonal and perennial snow banks (Barrett *et al.* 2009, Levy *et al.* 2011, Gooseff *et al.* 2013), thawing of ground ice (Lyons *et al.* 2005, Harris *et al.* 2007, Levy *et al.* 2011) and exotic processes, such as direct vapour emplacement and salt deliquescence (Wilson 1979, Levy *et al.* 2012b).

Typically, soil moisture is determined in the Dry Valleys as a point measurement. Surface or shallow-subsurface sediments are commonly analysed *in situ* with a soil moisture probe, for example via time domain reflectometry (TDR) or dielectric properties measurements (Barrett *et al.* 2009, Levy *et al.* 2012a), or in the laboratory via gravimetric water content (GWC) analysis. While GWC measurements are extremely robust (high precision and high accuracy), they only provide measurements of soil moisture in a small volume of soil (typically < 1 litre) at one point in time. TDR measurements can provide a time-series of soil moisture values in the monitored soil volume (typically < 1–2 litre), but, like other point measurements, only record conditions at the specific locations of the water
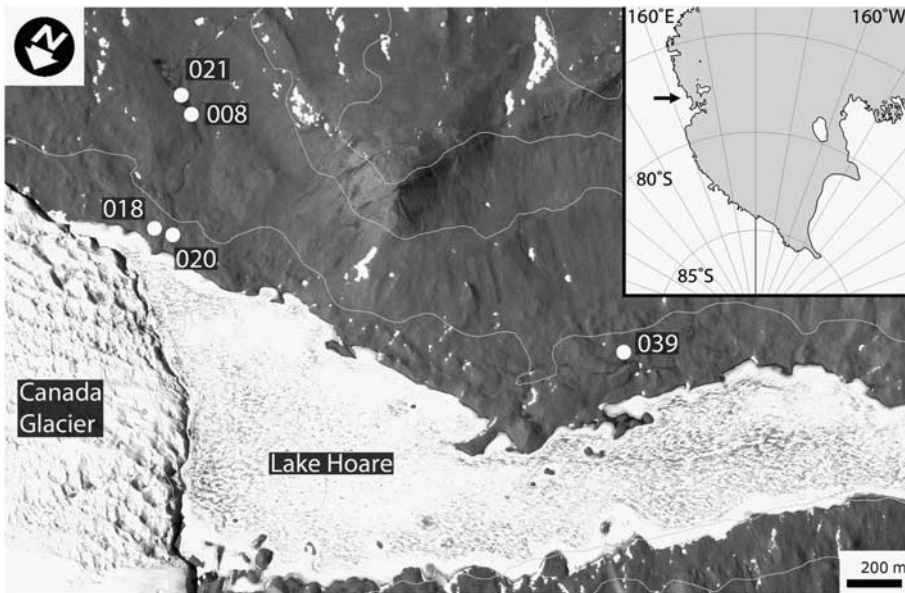
Fig. 1. Sample locations used in this study. Sediments were collected from the Lake Hoare basin in Taylor Valley, McMurdo Dry Valleys. Inset map shows the general location of the Dry Valleys (arrow). Image is a portion of QuickBird image 09FEB01213752.

content probe. The TDR or dielectric measurements can determine GWC with intrinsic instrument accuracy of ± 0.5–1% GWC if soil-specific calibration measurements are made to account for high-salinity Dry Valleys soils (Levy *et al.* 2012a), or $\pm 2\%$ GWC for uncalibrated sensors.

In contrast to ground-based, contact measurements, several remote-sensing techniques could be applied in the Dry Valleys to measure water content at the soil surface. Remote-sensing measurements of soil moisture have the potential advantages of measuring across wide swaths of the soil environment, while also measuring in a non-invasive manner, reducing the chance of contamination or disturbance of fragile and protected Dry Valleys soil ecosystems (Campbell *et al.* 1998).

Spaceborne remote-sensing techniques that measure long wavelengths (e.g. thermal infrared or microwave) are very sensitive to soil moisture content and can measure over a large area (sensor footprint), but have the disadvantage of coarse sensor spatial resolution (i.e. pixel size). For example, the Advanced Spaceborne Thermal Emission and Reflection (ASTER) radiometer visible and near-infrared (NIR) data are collected at 15 m pixel[-1] (Abrams 2000), and the Soil Moisture Active Passive mission microwave measurements are made at *c.* 0.4–1 km pixel[-1] (Entekhabi *et al.* 2008, 2010). These sensors are not able to resolve soil moisture in small features, such as water tracks and wet patches (Levy *et al.* 2011, 2012b) that are typically a few metres wide at most.
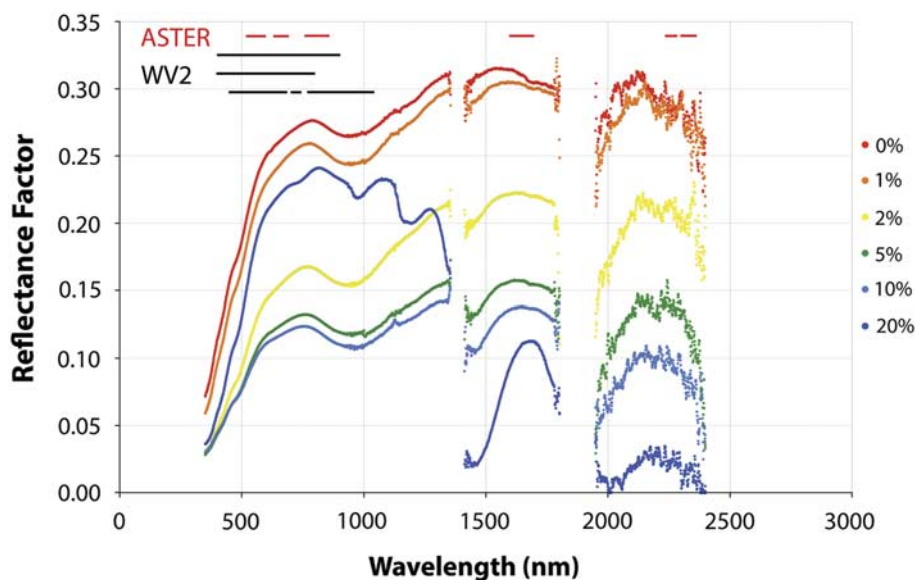
Fig. 2. Example reflectance spectrum (sample 018). Spectra are colour-coded by gravimetric water content (GWC). Bars at the top of the image show the location of existing space-based multispectral sensor observation wavelengths for ASTER and WorldView-2. Note that the increase in visible and near-infrared (NIR) reflectance at 20% GWC, and the presence of unusual absorptions in the NIR at these wavelengths is probably due to specular reflection from pooled water. It is not a result of changes to the reflectance properties of the soil minerals themselves at high GWC.

Fig. 3. Sediment samples prepared for analysis. Based on visual inspection alone, it is very difficult to discern differences in soil colour and texture based on water content. Most darkening occurs in the first few weight percent of water. Sample bags are *c*. 8 cm wide.

Modern panchromatic satellite sensors, such as IKONOS and WorldView-2 (WV2), have sufficiently fine spatial resolution to detect heterogeneous soil moisture on the scale of metres (typical of the Dry Valleys). As a result, these high-resolution imaging tools can be used to qualitatively assess the distribution of soil moisture in the Dry Valleys, distinguishing light and dark soils (e.g. dry versus wet soils) (Langford *et al.* unpublished). However, soil darkening due to wetting occurs rapidly as soil moisture increases from 0% to *c*. 5%, is strongly dependent on soil type and texture, and can be difficult to distinguish from shadowing in remote sensor datasets. These factors make panchromatic albedo an unreliable measurement of quantitative soil moisture content across wide regions, such as the Dry Valleys (Idso *et al.* 1975, Graser & Van Bavel 1982, Bockheim *et al.* 2007, Gooseff *et al.* 2013).

Spectroscopic water absorption features in the NIR, particularly absorptions at 1.4 and 1.9 μm, can be strong determinants of moisture content in soils, with absorption strength (band depth) increasing with increasing moisture content (Clark & Roush 1984, Chinn 1993, Lobell & Asner 2002, Finn *et al.* 2011). However, one hazard of NIR water absorption measurements is that atmospheric water vapour absorbs nearly all photons in the central wavelength of these features (Fig. 2), making it difficult to detect the soil signal. For this reason, most space-based multispectral instruments do not include observation windows in the vicinity of the 1.4 and 1.9 μm water absorption features.

Accordingly, the goal of this project was to determine if there are suitable hyperspectral parameters in the vicinity of the 1.4 and 1.9 μm water absorption features that could be used by air- or spaceborne sensors to quantitatively determine the soil moisture content of diverse soils in the Dry Valleys. We accomplished this goal by combining laboratory measurements of soil moisture content with spectroscopic measurements of wetted Dry Valleys soils made under natural illumination conditions comparable to those that would be experienced in the field.
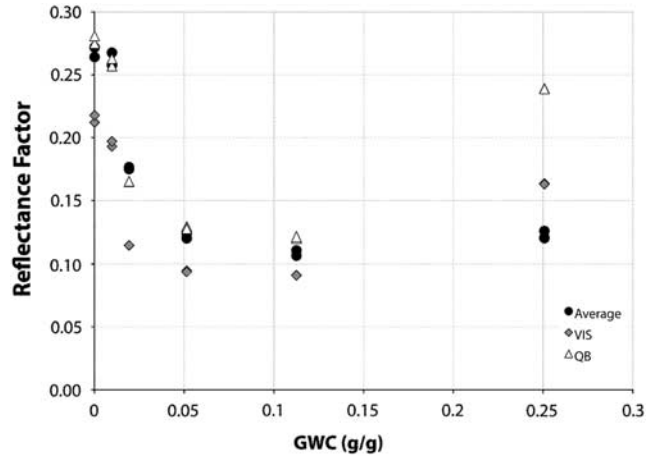

Fig. 4. Reflectance values for sample 018 as a function of gravimetric water content (GWC). Average = mean values for the entire 350–2500 nm measurement range, VIS = average reflectance over visible wavelengths (400–700 nm), QB = average reflectance over QuickBird near-infrared observation wavelengths (760–850 nm).

Methods

Sample collection

Sediment samples were collected from the hill slopes surrounding Lake Hoare in Taylor Valley (Fig. 1) during summer 2010–11. Sediment from the upper 10 cm of the soil column was collected using clean plastic scoops and was placed in Whirl-Pak® bags. No weathering horizons or changes in texture or catena were observed in the sediment sampling pits, which is consistent with the minor role of chemical weathering in Dry Valleys soils (Ugolini & Anderson 1973, Campbell *et al.* 1998), suggesting that these soils have largely homogenous compositions in the upper few centimetres. Accordingly, spectra of these bulk samples can be considered compositionally representative
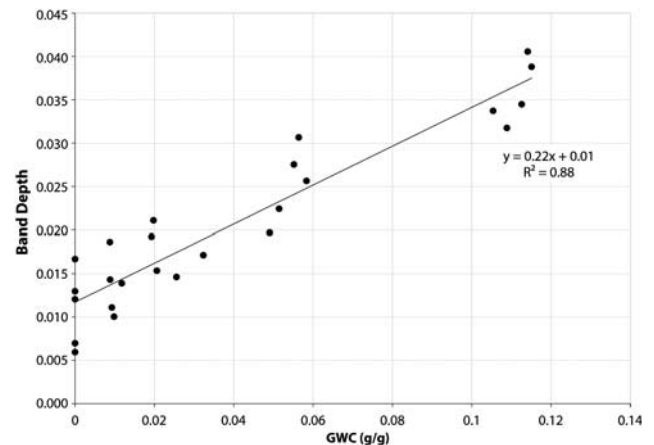

Fig. 5. Water absorption feature at 1.4 μm band depths for all samples versus gravimetric water content (GWC).
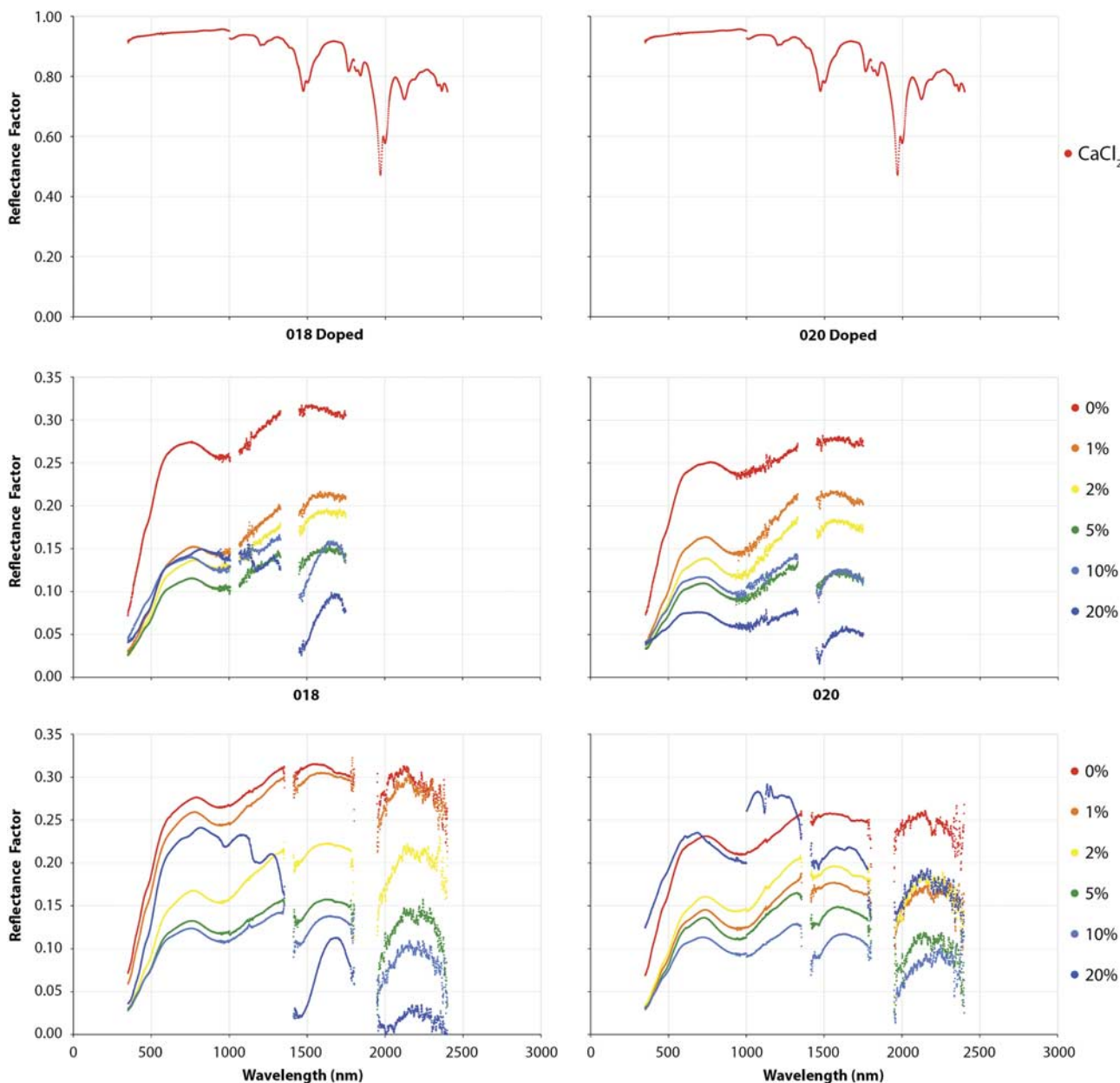
Fig. 6. (Top) Reflectance spectra of CaCl$_2$ made under laboratory lighting conditions. Hydration of CaCl$_2$ is apparent based on the presence of water absorption features near 1.4 and 1.9 μm. (Middle) Reflectance spectra of soil samples doped with CaCl$_2$ in order to produce CaCl$_2$ saturated brines. (Bottom) Reflectance spectra of soil samples hydrated only with deionized water. Note detector noise above 1.8 μm resulted in truncation of the doped-sample spectra.

of the soil surface in the Dry Valleys. Sediments were kept frozen and brought to McMurdo Station, where they were oven dried at 105 °C for 24 hours and allowed to cool. Sediments were then shipped to the USA for further analysis. Samples collected in this study came from a variety of hydrological environments, including wet water track soils (Barrett *et al.* 2009, Levy *et al.* 2011, Gooseff *et al.* 2013) (021 and 008; GWC at collection = 2.5% and 4.2%, respectively), typically dry Dry Valleys hill slope soils (018 and 020; GWC at collection = 1.2% and 0.5%,

respectively), and damp wet patches (Lyons *et al.* 2005, Harris *et al.* 2007, Levy *et al.* 2011, 2012b) (039; GWC at collection = 1.3%). Salt content of the soils in this study are 0.9%, 0.01%, 0.4%, 1.5% and 0.2% by mass for samples 021, 020, 039, 008 and 018, respectively. All soils in this study are sandy calcic haplorthels dominated by medium-to-coarse sand and containing less than 5% clays (Wilson 1979, Levy *et al.* 2012b, 2013). Typical clays in these soils include illite, smectite, chlorite, aragonite, calcite, sepiolite, talc and vermiculite (Levy *et al.* 2013).

Sample preparation

Spectroscopic measurements described below were conducted on sediment samples that were rehydrated in the laboratory. Oven-dried samples were split into six *c.* 20 g subsamples that were placed into individual zipper-seal sample bags (Fig. 3). Each sample was then rehydrated with a measured mass of deionized water in order to reach GWC targets of 0%, 1%, 2%, 5%, 10% and 20%. Water plus sediment mixtures were then agitated in the sample bags for 1 minute to disperse the water and were allowed to equilibrate for 24 hours. In order to test whether extremely high salt contents, typical of Dry Valleys soils, would have an effect on water absorption features, replicate splits of two samples (018 and 020) were each doped with oven-dried calcium chloride ($CaCl_2$), a common Dry Valleys salt (Wilson 1979, Barrett *et al.* 2009, Levy *et al.* 2012a, Toner *et al.* 2013), and mixed with water to form saturated $CaCl_2$ brines. Like the non-doped samples, doped samples were allowed to equilibrate for 24 hours.

Spectroscopic measurements

Reflectance spectra of the experimentally wetted soils were collected using an Analytical Spectral Devices Full-Range Portable Field Spectrometer™ (ASD-FR). The ASD-FR measures spectral radiance across the wavelength range 0.35–2.5 μm with spectral resolution of 0.003 μm at $\lambda \approx 0.7$ μm and 0.01 μm at $\lambda \approx 1.4$ μm and 2.1 μm. Values for its nominal noise equivalent change in radiance (neΔL) are 1.4 x 10^{-9} W cm^{-2} nm^{-1} sr^{-1} at 0.7 μm, 2.4 x 10^{-9} W cm^{-2} nm^{-1} sr^{-1} at 1.4 μm and 8.8 x 10^{-9} W cm^{-2} nm^{-1} sr^{-1} at 2.1 μm. Spectral measurements were made using the ASD-FR equipped with an 8° foreoptic. The foreoptic was held *c.* 15 cm above the sediment sample, producing a *c.* 2 cm diameter field of view. Soil samples were transferred from the mixing pouches into uncovered petri dishes for measurement. Spectra were measured under natural solar illumination within 1 hour of solar noon during July 2012 in Corvallis, OR (44.6°N, 123.3°W). Reflectance factor (Schaepman-Strub *et al.* 2006) is reported as the ratio between the soil reflectance spectrum and a calibrated and levelled Spectralon® white reference target, and is reported as relative reflectance.

Results

The example reflectance spectrum of sample 018 is shown in Fig. 2, and the full collection of dry (0% GWC) spectra along with the complete set of wetted reflectance spectra are shown in the supplementary material (found at http://dx.doi.org/10.1017/S0954102013000977). The Dry Valleys soils measured in this experiment all have the same general spectral shape. They have generally higher reflectance at longer wavelengths in the ultraviolet–visible, typical of the tan/buff coloured soils in the Dry Valleys that contain some oxidized iron. The soils have a broad absorption near 1 μm, consistent with the presence of mafic sand grains in the sediments.

At visible (0.4–0.7 μm) and panchromatic sensor (0.45–0.9 μm) wavelengths, reflectance generally decreases with increasing soil moisture, but increases at high soil moisture contents (Fig. 4). Water absorption features at 1.4 μm and 1.9 μm are present in all wetted samples and increase in band depth with increasing GWC (Fig. 5, see discussion for details).

Finally, soil salinity has little effect on the signature of soil moisture content (Fig. 6). Maximum 1.4 μm band depth varies only ± 0.0025 over the full range of soil salinities measured, which would produce at most ± 0.01 GWC; indicating that the calculated GWC offset resulting from saline fluids is smaller than the inherent model uncertainty.

Discussion

Here we discuss the spectroscopic properties of Dry Valleys soils as they relate to soil moisture and salinity. A more detailed description of the spectroscopic characteristics of Dry Valleys rocks, soils and sediments can be found in Wyatt *et al.* (2010) and Salvatore *et al.* (2013).

Panchromatic albedo

As noted by Langford *et al.* (unpublished), visible wavelength reflectance drops precipitously (more than 50%) from 0–5% GWC, indicating that Dry Valleys soils darken efficiently with small additions of liquid water. However, beyond 10% GWC, reflectance increases in most samples owing to specular reflection from pooling bulk water in the samples near saturation (Lorenz 1966, Levy *et al.* 2012a). It should be noted that at visible wavelengths, relative reflectance for dry samples ranges between *c.* 0.28 and *c.* 0.12, and could be a consequence of several factors including soil colour, soil albedo, grain packing, self-shadowing, etc. For this reason, in order to quantify the amount of soil moisture in the samples, a different observable quantity is needed that can use reflectance differences to normalize between dry-wet and dry-dark sediments to produce a linear relationship between spectral properties and GWC.

Water absorption feature band depth

Water absorption features at 1.4 μm and 1.9 μm are present in all wetted samples. These absorption features are wavelengths of reduced reflectance by the wetted soils, relative to the Spectralon® target, resulting from absorption of infrared photons of these wavelengths by

water molecules in the soil. For a given path length through the soil, more soil moisture results in greater chances for photon absorption, leading to decreased reflectance at these wavelengths (Clark & Roush 1984). Some samples (e.g. 018) also contain a small 2.2 μm absorption, consistent with the presence of hydroxyl ions in clays. Shifting of the 1.4 μm absorption towards 1.450 μm may be a result of the presence of chloride salts in the soils, notably $CaCl_2$ (Crowley 1991).

Water absorption feature band depth was calculated by averaging two spectral regions outside of the water absorption feature (for the 1.4 μm band, 1.319–1.349 μm and 1.619–1.639 μm were used; for the 1.9 μm band, 1.623–1.647 μm and 2.100–2.130 μm were used). A flat continuum slope was fitted between the central value of the two averaging regions, defining the inferred shape of the spectrum had a water absorption feature not been present (Clark & Roush 1984). Average reflectance on the deepest measureable part of the absorption feature was then measured (the actual absorption feature centre cannot be measured under natural illumination because atmospheric water vapour absorbs nearly all incoming photons at these wavelengths) (Fig. 2). Wavelength regions used in this study were 1.950–1.960 μm for the 1.9 μm feature and 1.415–1.435 μm for the 1.4 μm feature. Band depth was then calculated by subtracting the actual measured reflectance mean from the predicted reflectance value along the linear continuum slope (calculated at 1.955 μm and 1.425 μm, respectively).

Water absorption feature band depth varies with GWC, as would be expected in relatively simple soils like those from the Dry Valleys (Abrams 2000, Lobell & Asner 2002). The relationship between the 1.4 μm band depth and GWC is shown in Fig. 5. Across the full range of GWC values, band depth varies linearly with GWC for wetted Dry Valleys soils, and can be approximated by the function, band depth = 0.22 x GWC (in g/g) + 0.01. The coefficient of determination value, r^2, for this model is 0.88, and the result is statistically robust, with a linear regression *P* value of < 0.01. Data spread along this model is approximately ± 0.5% in relative reflectance, producing calculated GWC uncertainties of ± 2.5% GWC. For comparison, most dielectric soil moisture probes produce instrument measurement uncertainties of ± 1–2% GWC.

Effect of salts

Soil salinity has little effect on the signature of soil moisture content for Dry Valleys soils. Maximum 1.4 μm band depth varies only ± 0.0025 over the full range of soil salinities measured, which would produce at most ± 0.01 GWC, indicating that the calculated GWC offset resulting from saline fluids is smaller than the inherent model uncertainty. Water absorption features at 1.4 and 1.9 μm are apparent and readily measured even in the most saline sample, 008 (see supplementary material). Small shifts in the position of the absorption features are present in the $CaCl_2$-doped samples, consistent with laboratory spectra of sulfate- and chloride-doped sediments (Entekhabi *et al.* 2008, Massé *et al.* 2012).

Implications for remote sensing in the McMurdo Dry Valleys

This pilot investigation of the reflectance properties of wetted Dry Valleys soils suggests that hyperspectral measurements of Antarctic soils may provide a low-impact, contamination-free approach to measuring surface soil moisture properties across wide regions of the Dry Valleys and other ice sheet-free portions of Antarctica. These results are similar in accuracy to airborne measurements of soil moisture using reflectance spectra collected at temperate latitudes by Finn *et al.* (2011). Spectroscopic measurements of soil moisture content in this study produce GWC estimates with very similar uncertainty to contact measurements made via TDR or dielectric probes, suggesting that accuracy does not have to be significantly impacted in order to achieve wide spatial coverage. In addition, for soil moisture studies over small areas, contact-probe-based reflectance spectroscopy could be used to determine soil moisture conditions at the ground surface, providing an independent measurement technique to compare to traditional (TDR, mass-based) point measurements.

This investigation also highlights the need for hyperspectral imaging capabilities in the Dry Valleys if this laboratory tool is to be expanded to provide regional measurements of soil moisture content in support of biological or hydrogeological research (Stichbury *et al.* 2011, Gooseff *et al.* 2013). Existing multispectral satellite sensors, such as WV2 and QuickBird, have widespread spatial coverage over the Dry Valleys with high temporal return rates. However, our results show that these sensors do not have the necessary spectral resolution to discern the water absorption bands described in this study. In addition, these multispectral observatories avoid the vicinity of water absorption features in order to minimize atmospheric interference, making them even less able to determine surface soil moisture content quantitatively. Airborne imaging spectrometers, such as the Airborne Visible InfraRed Imaging Spectrometer (AVIRIS) (Green *et al.* 1998), have hyperspectral measurement capabilities similar to the spectroscopic range and resolution of the field spectrometer used in this study, and also have mature atmospheric correction algorithms. These spectrometers could be used to measure the water absorption features described here in order to determine the spatial and temporal distribution of surface soil moisture in Antarctic soils.

Conclusions

The spectral reflectance factors of wetted Dry Valleys soils were measured under natural illumination conditions in order to determine whether spectroscopic tools can be used to quantitatively determine surface soil moisture content. Characteristic water absorption band depth, particularly at 1.4 μm, was found to vary linearly with GWC. The reflectance of dry soils at visible wavelengths was found to vary by over a factor of two, suggesting that visible wavelength measurements of soil moisture may be difficult to quantify, while these hyperspectral measurements of soil moisture have comparable accuracy to TDR soil moisture probes. These results indicate that future hyperspectral measurements of Dry Valleys soils could be used to quantitatively determine surface soil moisture content over wide areas using remote-sensing tools.

Acknowledgements

Supplemental material

Two supplemental figures will be found at http://dx.doi.org/10.1017/S0954102013000977.

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