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Moisture Effects on Soil Reflectance

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ABSTRACT

Models of soil reflectance under changing moisture conditions are needed to better quantify soil and vegetation properties from remote sensing. In this study, measurements of reflected shortwave radiation (400–2500 nm) were acquired in a laboratory setting for four different soils at various moisture contents. The observed changes in soil reflectance revealed a nonlinear dependence on moisture that was well described by an exponential model, and was similar for different soil types when moisture was expressed as degree of saturation. Reflectance saturated at much lower moisture contents in the visible and near-infrared (VNIR) spectral region than in the shortwave-infrared (SWIR) spectral region, suggesting that longer wavelengths are better suited for measuring volumetric moisture contents above ~20%. To explore the potential of a general reflectance model based solely on dry reflectance and moisture, we employed a Monte Carlo analysis that accounted for observed variability in the measured spectra. Modeling results indicated that the SWIR region offers significant potential for relating moisture and reflectance on an operational basis, with uncertainties less than half as large as in the VNIR. The results of this study help to quantify the strong influence of moisture on spectral reflectance and absorption features, and should aid in the development of operational algorithms as well as more physically based models in the future.

Soil moisture is an important factor across a range of environmental processes, including plant growth, soil biogeochemistry, erosion, and land-atmosphere heat and water exchange (e.g., Wigneron et al., 1998). Timely and accurate estimates of soil moisture are therefore highly desirable for understanding and modeling these processes. Remote sensing approaches have primarily focused on microwave wavelengths, where moisture exerts strong control over soil dielectric properties, and where measurements are not impeded by clouds or darkness (Njoku and Entekhabi, 1996; Ulaby et al., 1996). Moisture also greatly influences the reflection of shortwave radiation from soil surfaces in the VNIR (400–1100 nm) and SWIR (1100–2500 nm) regions of the spectrum (Bowers and Hanks, 1965; Skidmore et al., 1975). However, quantification of moisture using these wavelengths remains difficult because of significant variability from other soil chemical and physical properties, such as organic matter and mineralogy, as well as vegetation cover (Asner, 1998; Ben-Dor et al., 1999).

Nonetheless, a quantitative understanding of moisture effects on shortwave reflectance is important for several reasons. First, reflected solar radiation represents the strongest (highest energy) passive signal available to satellites, so that any method using these wavelengths could provide very high spatial resolution (up to 1 m). Second, a variety of methods to infer surface properties such as vegetation cover and density are significantly affected by changes in background reflectance because of moisture (Pinty et al., 1998). Thus, a reliable model for soil reflectance based on soil moisture would improve our ability to detect other soil and vegetation properties.

The familiar darkening of soil upon wetting is because of a change in the real part of the refractive index (n) of the immersion medium from air (n = 1) to water (n = 1.33) (Twomey et al., 1986). This decreases the contrast between soil particles ($n \approx 1.5$) and their surrounding medium, resulting in an increase in the average degree of forward scattering and, thus, an increased probability of absorption before reemerging from the medium. Numerous studies have investigated the relationships between wet and dry soil reflectance, noting an overall decrease in reflectance upon wetting (Baumgardner et al., 1985; Bowers and Hanks, 1965; Ishida et al., 1991; Twomey et al., 1986). Fewer studies have addressed soil reflectance at intermediate moisture levels, although partially wet conditions are more likely than complete saturation in natural soils (Brady, 1990). Idso et al. (1975) provided empirical evidence that soil albedo decreases linearly with reflectance, but subsequent studies have challenged this view (Bedidi et al., 1992; Muller and Décamps, 2001).

In this study, we sought to quantify changes in soil reflectance as a soil proceeded from wet to dry states and to determine the dependence of these changes on soil type and wavelength. The goal of this research was to develop quantitative relationships between soil moisture and reflectance that minimized differences between soil types for use in operational soil moisture retrieval algorithms and canopy radiative transfer models.

MATERIALS AND METHODS

Soil Samples

Four soils from a range of mineralogical, climatic, and biological settings were selected for this study (Table 1). The soils were specifically chosen to span a range of bulk density, porosity, and organic C content. An Argic Aridisol from an arid shrubland in the Chihuahuan Desert, New Mexico was selected for its extremely low organic matter, high bulk density, and low porosity. A Xeric Andisol from a coniferous forest site in Central Oregon was selected for its relatively high organic C concentration and moderate porosity. Two soils from a North Texas savanna, one Ustic Mollisol with high organic C and porosity and one Aridic Entisol with low organic C and high bulk density, were also selected.

Each soil was passed through a 2-mm sieve to homogenize

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Abbreviations: c, rate of change because of soil moisture; D, band depth; f, ratio of saturated to dry reflectance; s, degree of saturation; SWIR, shortwave-infrared; VNIR, visible and near-infrared; θ, volumetric water content.

Table 1. Properties of four soils used in this study.

Soil type	Ecosystem type	Location	Latitude/Longitude	B.D.	Porosity	Total C†
				g cm^{-3}	%	
Argic Aridisol	Arid shrubland	New Mexico	33.31 N 106.82 W	1.54	42	0.19 (0.04)
Xeric Andisol	Temperate coniferous forest	Oregon	44.43 N 121.77 W	1.12	58	3.69 (0.41)
Ustic Mollisol	Temperate savanna	Texas	33.86 N 98.76 W	0.64	76	5.58 (0.50)
Aridic Entisol	Temperate shrubland	Texas	33.91 N 99.45 W	1.35	49	0.57 (0.06)

B.D. = bulk density.
† Values in parentheses are standard deviation based on three samples.

the particles and to remove large detrital material, and then oven-dried at 70°C for 2 wk. Total C measurements were made using a combustion-reduction auto-analyzer (Carlo-Erba, Inc., Milan, Italy) and bulk density (ρ_b) was determined by weighing a 5.0-mL volume of lightly packed soil.

Laboratory Spectroscopy

Reflectance measurements were acquired in a laboratory setting using a full-range (350–2500 nm) spectrometer with a 25° foreoptic (Analytical Spectral Devices, Boulder, CO). The experimental design was as follows: A NIST-calibrated light source (Lowe, Inc., Macon, GA) illuminated the surface of a balance from 15° zenith angle, while spectral measurements were taken from nadir at 4-cm height, resulting in a 1.8-cm diam. field of view. Reflectance was calibrated using a white spectralon panel (LabSphere, Inc., North Sutton, NH). A 1-mm thick sample of each soil was placed in a 5.0-cm wide round aluminum tin, which had been previously weighed and painted with flat black paint to avoid contamination of spectral measurements, and then placed on the balance. After measuring the reflectance of the oven-dried sample, deionized water was applied to the soil with a pipette until the soil was deemed near saturation. Spectral measurements were then collected repeatedly until the soil mass returned to its initial value (after ~1 h).

Water content was determined from mass measurements recorded throughout the experiment, and expressed on a volumetric basis. Although most previous studies of soil reflectance have quantified moisture based on mass (Duke and Guérif, 1998; Skidmore et al., 1975) or pressure (Baumgardner et al., 1985; Bedidi et al., 1992), we considered volumetric water content (θ) to be the most appropriate measurement for analyzing reflectance since photon interactions depend on volume of substances rather than mass or pressure. Volumetric water content was calculated for each spectral measurement from the following equation:

$$\theta = \frac{(m - m_0)/\rho_w}{m_0/\rho_b} \quad [1]$$

where m is the measured mass of the soil sample, m_0 is the initial (dry) mass, ρ_w is the density of water (1.0 g cm^{-3}), and ρ_b is the soil bulk density. The degree of saturation, s, was also considered in subsequent analysis, and was calculated as the ratio of water volume/total soil pore volume:

$$s = \frac{\theta}{1 - \rho_b/\rho_p} \quad [2]$$

Here, ρ_p is the particle density, set to 2.65 g cm^{-3} (Hillel, 1998).

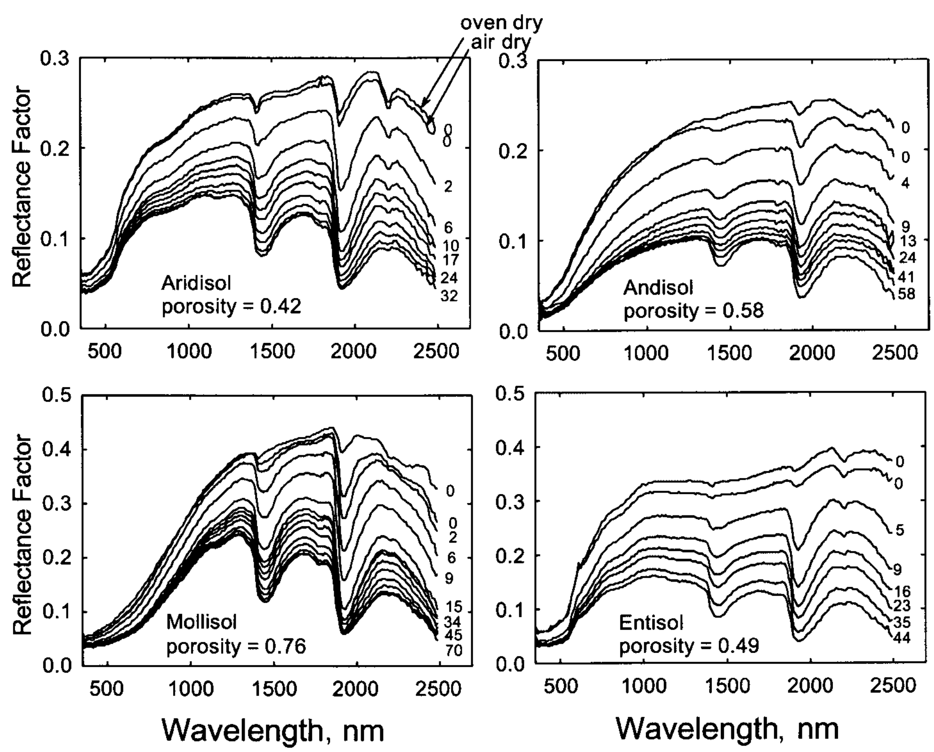

Fig. 1. Laboratory spectra of four soils at different volumetric water contents (θ). Values of θ in percentages by volume are indicated next to select spectra.

Data Analysis

The effect of soil moisture on reflectance was summarized for each sample by determining the best-fit coefficients of an exponential model relating moisture and reflectance (e.g., Duke and Guérif, 1998):

$$R = R_{sat} + (R_{dry} - R_{sat}) \times \exp(-c \times wc) \quad [3]$$

where R_{sat} is the reflectance of saturated soil, R_{dry} is the reflectance of dry soil (at $\theta = 0.0$), c describes the rate of change because of soil moisture, wc is the water content expressed as θ or s, and all values except wc are wavelength dependent.

In addition to observed changes in reflectance, we considered the effect of moisture on the depth of absorption features. Specifically, we focused on the response of the 2.2-μm absorption feature in mineral soils, which is because of clay-lattice hydroxyl vibrational absorptions (Ben-Dor et al., 1999), to changes in soil moisture. Methods to remotely sense soil mineralogy (Clark, 1999) and vegetation and soil extent (Asner and Lobell, 2000) often exploit this diagnostic absorption feature, but do not explicitly consider the potential impacts of soil moisture. The strength of the 2.2-μm absorption feature was measured at each moisture value by the continuum-removed absorption band depth, D (e.g., Clark, 1999):

$$D = 1 - R_b/R_c \quad [4]$$

Here, R_b is the measured reflectance at 2.2 μm, and R_c is the value predicted from a linear interpolation of reflectance at 2.14 and 2.26 μm. Decreases in D, for example because of changes in moisture, signify a reduction in the strength of the absorption feature at 2.2 μm.

RESULTS AND DISCUSSION

Reflectance decreased with increasing moisture for all soils, as demonstrated by the measured spectra in Fig. 1. Figures 2a through 2c show the reflectance at 0.6, 1.2, and 2.2 μm as a function of θ, exhibiting a clearly nonlinear response that was well described by the exponential model. While reflectance exhibited only minor decreases beyond θ ~20% at visible wavelengths, longer wavelengths did not saturate until much higher water contents. For example, reflectance at 2.2 μm continued to decrease until near saturation (Fig. 2c). Since natural soils commonly experience θ between 20% and saturation (Brady, 1990), the sensitivity of SWIR reflectance at these intermediate moisture levels is potentially important.

While wet and dry reflectance varied greatly between soils, the rate of exponential change, c, was less variable (Fig. 3). Again, the lower values of c at longer wavelengths demonstrate the larger dynamic range in this region. Interestingly, replacing θ with s as a measure of soil moisture markedly reduced the variability of c between soil types. In addition, the variability of c was observed to be lowest in the SWIR region.

The larger range of sensitivity and lower soil dependence of SWIR reflectance changes are both attributed to the strong absorption of water in this region, combined with the high SWIR reflectance of dry soils. In visible wavelengths, the sole effect of water is in changing the relative refractivity at the soil particle surfaces. As soil moisture increases, water is first adsorbed to particles surfaces, and then proceeds to fill micro and macropores (Hillel, 1998). Therefore, once soil water is sufficient to cover most of the particle surfaces, additional water that fills large pore spaces will have little effect on reflectance. In contrast, the significant absorption of water at wavelengths >1.0 μm causes any added water to have a significant effect on reflectance. This effect is enhanced by the high reflectivity of dry soils in the SWIR (see Fig. 1), which produces a large contrast between wet and dry soils.

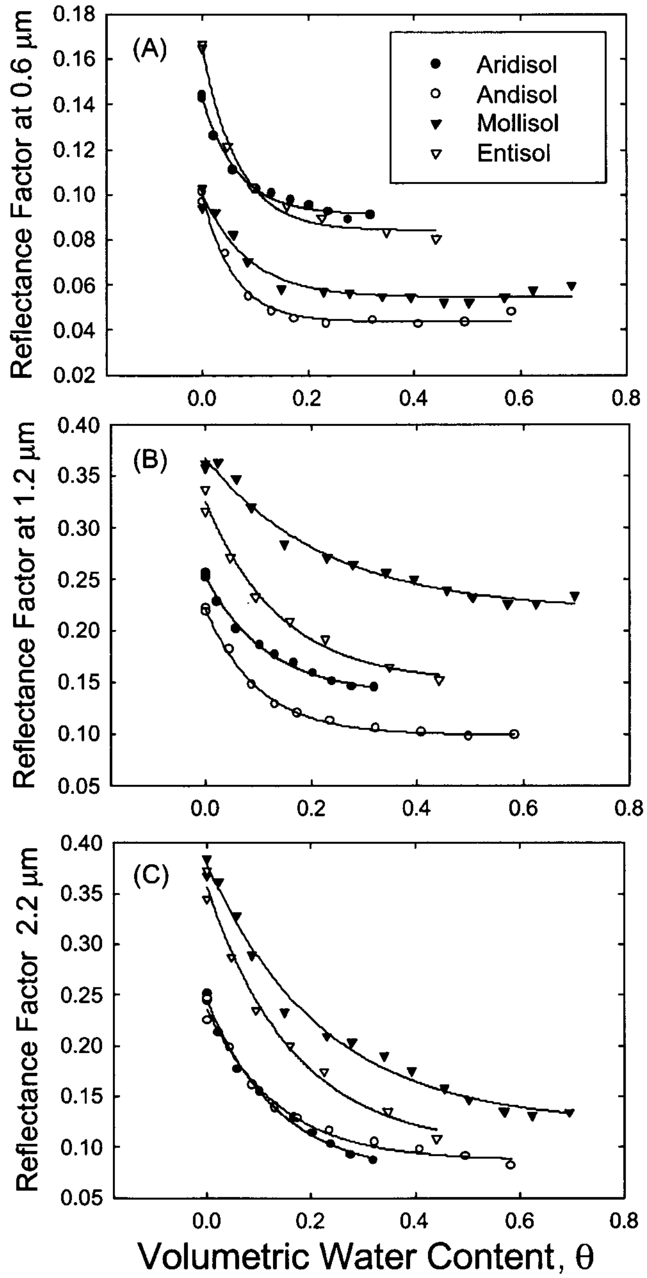

Fig. 2. Changes in reflectance because of soil moisture for four different soils at (a) 0.6 μm, (b) 1.2 μm, and (c) 2.2 μm, along with best-fit exponential model.

In addition to effects on overall reflectance, absorption by water in the SWIR region impacted mineral-associated absorption features. For the two soils with low organic matter (those having a significant 2.2 μm absorption feature), the D exhibited a near-linear decrease with θ (Fig. 4).

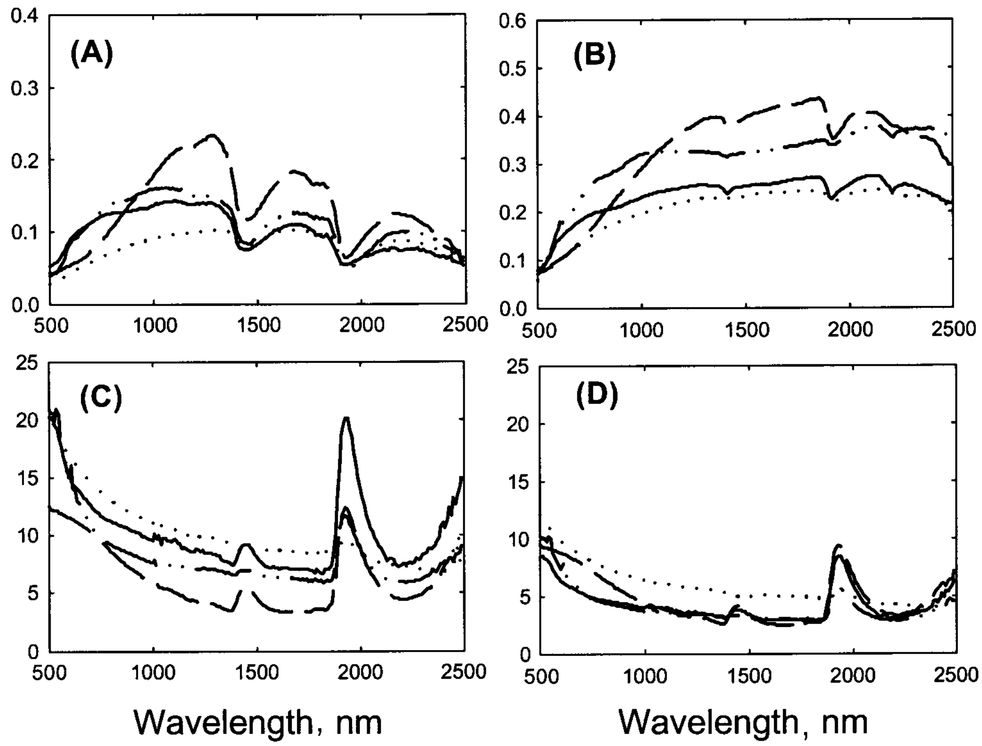

Fig. 3. Best-fit coefficients for Aridisol (solid line), Andisol (dotted), Mollisol (dashed), and Entisol (dash-dotted) in a model of exponential decrease in soil reflectance with moisture, $R = R_{sat} + (R_{dry} - R_{sat}) \times \exp(-c\theta)$. (a) R_{sat}; (b) R_{dry}; (c) c; (d) Same as in (c) but using degree of saturation, s, in place of θ.

Toward a General Model of Moist Soil Reflectance

While simple models based on empirical relationships will always suffer from uncertainties, such models can still be very useful if these uncertainties are well quantified. In this context, we extended the experimental results to develop a simple model of moist soil reflectance based solely on R_{dry} and s. This required parameterization of R_{sat}, which was done by expressing R_{sat} as a fraction, f, of R_{dry}. Rewriting Eq. [3] then gives:

$$R = f \times R_{dry} + (1 - f) \times R_{dry} \times \exp(-c \times s) \quad [5]$$

or,

$$s = \frac{-\ln\{(R - f \times R_{dry})/[(1 - f) \times R_{dry}]\}}{c} \quad [6]$$

Figure 5 shows the ratio of saturated to dry reflectance, f, for the four different soils in this study, again demonstrating significant variability but less so at SWIR wavelengths. Comparing Fig. 5 to Fig. 3a reveals the utility of using f, since variability in this parameter is less than for R_{sat}. In other words, uncertainty in R_{sat} for each soil was reduced when knowing the value of R_{dry}.

To quantify the impact of soil variability on determining reflectance from moisture content, we employed a Monte Carlo technique where distributions (e.g., mean and standard deviation) for c and f were defined from the four samples above. These distributions were then used to perform repeated calculations of R based on measured values of R_{dry} and s, with a resulting distribution of predicted values at each wavelength. Conversely, we also performed Monte Carlo estimates of s based on measured R_{dry} and R for each soil. These simulations allowed us to quantify the effects of variability in c and f on estimates of soil moisture from reflectance. For example, Fig. 6 shows the Monte Carlo results for predicting s from Eq. [6] for an entisol sample with a true s of 33%. In this case, R_{dry} and R corresponded to the measured values for the entisol, as shown in Fig. 1. While the standard deviations of moisture estimates were ~20% in the VNIR, they were only ~10% at SWIR wavelengths resulting from a combination of lower uncertainty in c and f. Similar results were seen for other soils and at other moisture values. While these results demonstrate the lower variability of moisture estimates in the SWIR, further experiments with different soils are needed to establish the absolute uncertainties in this spectral region.

CONCLUSIONS

The results of this study can be summarized by the following:

1. Reflectance changes because of soil moisture were well explained by an exponential function when moisture content was expressed on a volumetric basis. Using the degree of saturation (s) instead of volumetric water content (θ) as a measure of soil wetness reduced differences between soil types. This facilitated a general model of moisture effects on reflectance, in contrast to previous work that established soil-specific relationships based on mass water content (Muller and Décamps, 2001). The utility of one measure of moisture versus another depends on the

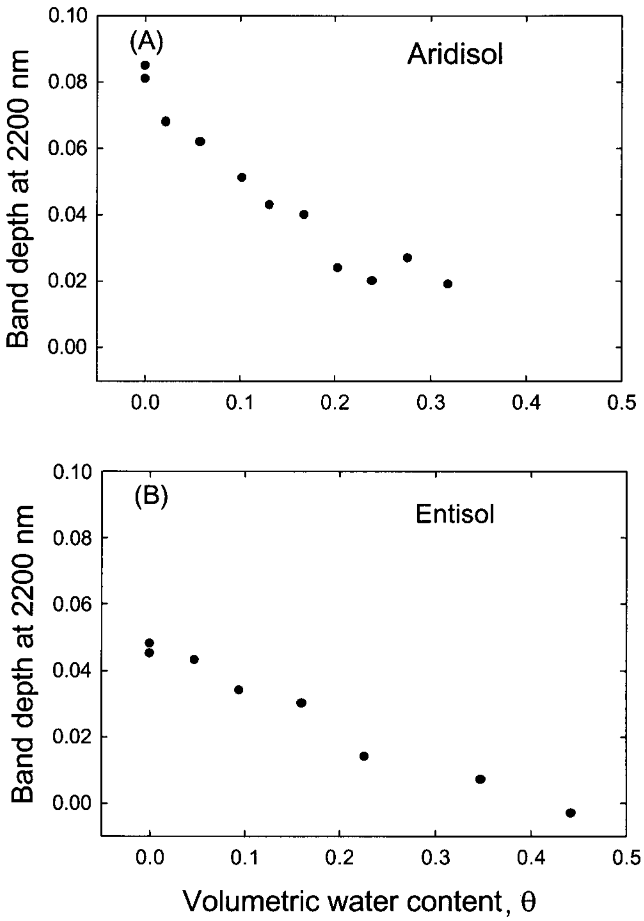

Fig. 4. (a) Continuum-removed absorption band depth (D) at 2200 nm for the Aridisol at different volumetric water contents. (b) same as in (a) but for the Entisol.

application. In cases were volumetric or mass water content is desired, estimates of s would require simultaneous bulk density estimates, which are not readily derived from remote sensing. In other cases, s may be a more direct measure of the desired property, such as water-filled pore space.

2. The SWIR region was better suited than the VNIR to measure soil moisture changes for several reasons.

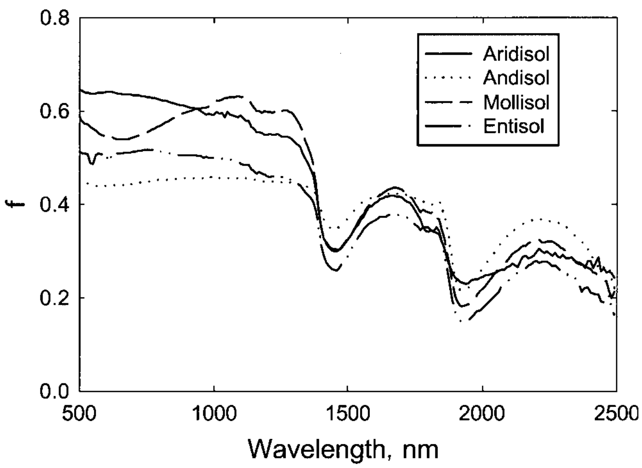

Fig. 5. Ratio (f) of saturated to dry reflectance for four soils.

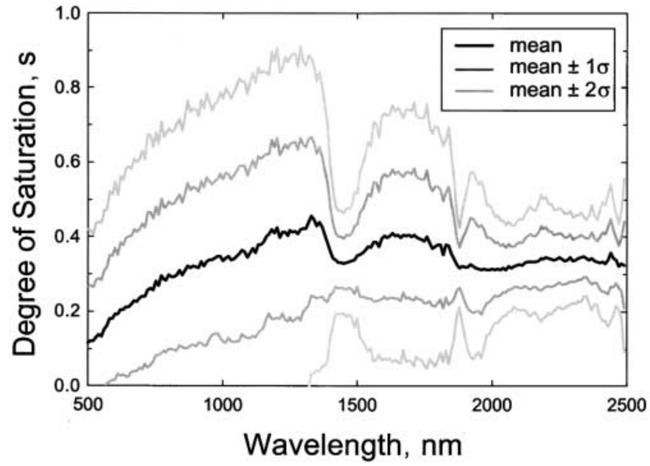

Fig. 6. Predicted values of s from 1000 iterations of Eq. [6] for an Entisol spectra. Values of c and f were randomly selected for each model run based on measured variability. Gray lines indicate one and two standard deviations (σ) from the mean value (67 and 95% confidence intervals, respectively), while the horizontal dashed line shows true s for sample (0.325).

First, reflectance continued to respond to soil moisture values up to 50%, while visible wavelength saturated at values near 20%. A volumetric moisture range of 0 to 50% spans the most common conditions found in arid and semi-arid ecosystems and in other areas (e.g., dormant agricultural fields) containing sufficiently low vegetation cover to allow for soil reflectance measurements. In addition, the variability between soils in the exponential coefficient of a soil moisture-reflectance model, as well as in the ratio of wet to dry reflectance, was lowest in the SWIR. As a result, estimates of soil moisture based on a general model of SWIR reflectance contained only half the uncertainty as estimates based in the VNIR.

3. The strength of the 2.2-μm absorption feature in mineral soils was greatly reduced with increasing levels of moisture. Thus, methods highlighting SWIR absorption features in soils should account for moisture effects.
4. These results provide additional experimental evidence needed to develop empirical and physical models of soil moisture and reflectance. In particular, the relatively robust relationship between degree of saturation and SWIR reflectance suggests that this link will be the most conducive to moisture remote sensing in the shortwave spectrum, especially where moisture values exceed 20%. The simple moisture-reflectance model presented here, which required only dry soil reflectance as input, demonstrated the potential for monitoring moisture conditions in exposed soils from airborne and spaceborne vantage points. Such models will also be useful for constraining soil reflectance in spectral unmixing algorithms and radiative transfer models to derive canopy characteristics (Pinty et al., 1998).
5. Additional research is required to extend and test the soil moisture-reflectance relationships presented here. Sensitivity analyses with respect to soil roughness, viewing geometry, and other features should

be conducted with new experiments. If more broadly applicable, the SWIR region of the spectrum may provide an opportunity to estimate soil moisture on an operational basis.

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