Evaluation of Hyperspectral, Infrared Temperature and Radar Measurements for Monitoring Surface Soil Moisture

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Abstract

Remote sensing techniques for monitoring soil moisture were tested by comparing hyperspectral reflectance and spectral indexes; surface temperature (T_s) and thermal indexes; and normalized radar backscatter to soil moisture. A laboratory study indicated that hyperspectral reflectance and T_s were sensitive to surface soil moisture (r^2 range from 0.72 to 0.96). However, T_s was the only optical measurement that appeared insensitive to soil type. An index derived from differences between measurements of dry and wet soils (Δ-index) was presented and tested on the optical data as well as on data collected from two radar field studies at the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) Walnut Gulch Experimental Watershed (WGEW). Using the Δ-index, radar backscatter measured by different satellite sensors was merged into a single relationship with surface soil moisture. Furthermore, the radar Δ-index may be physically related to surface soil moisture such that field-based empirical relationships may be unnecessary in sparsely vegetated environments.

Keywords: hyperspectral, thermal infrared, radar, soil moisture

Introduction

Soil moisture conditions at both the surface and deeper layers are primary determinants of cross-country mobility, irrigation scheduling, pest management, biomass production, and watershed modeling. Remote sensing has several advantages over other methods for monitoring surface soil moisture, such as synoptic, timely coverage with repeat passes, and efficiencies of scale that cannot be matched by traditional means. For these reasons, there is much interest in developing remote sensing techniques for monitoring surface soil moisture over large areas.

In this paper we examined two analytical methods, spectral and thermal measurements, and remote sensing radar observations obtained for surface soil moisture assessment. The goals of this work were to determine sensitivity of hyperspectral reflectance, thermal infrared (TIR) temperature and radar backscatter to changes in soil moisture.

Background

Hyperspectral

Soil moisture affects soil reflectance in two basic ways. First, a dry soil will almost always have a higher albedo because light is easily reflected out of soil interstices due to the large difference in the real index of refraction between air and soil mineral

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constituents. Radiation entering soil pores filled with water will have a greater chance of being absorbed or transmitted (Whalley et al. 1991). Second, dry soils have higher reflectance in specific spectral bands (1.450 &m, 1.940 &m, and 2,950 &m) due to lack of water absorption (Bowers and Hanks 1965, Twomey et al. 1986).

Spectral band ratios to ascertain water content in soil have met with qualified success. Musick and Pelletier (1988) found an overall weak correlation ($r^2 = 0.23$) between the ratio of two Landsat TM bands (TM5/TM7) and surface water content for 10 different soils but for any one soil in the group the r^2 ranged from 0.88 to 0.99. Hunt and Rock (1989) developed the Moisture Stress Index (MSI) by ratioing TM bands 4 and 5 (TM5/TM4) and compared it to relative water content in tree leaves and obtained r^2 values ranging from 0.75 to 0.95. A narrow band ratio index was proposed by Whalley et al. (1991) using the 1.45 &m water absorption band. Their index (which we call WISOIL) is the waveband ratio 1.45&m /1.3 &m. They found a curvilinear relationship with gravimetric water content for sandy and sandy loam soils up to 1 cm depth.

Thermal infrared

The temperature of the soil surface (T_s) is primarily dependent on the thermal inertia of the soil solution, which is strongly dependent on soil water content (Price 1982). Consequently, T_s has been related to surface soil moisture content for bare soils (Davidoff and Selim 1988). Because of the strong diurnal variations in T_s due to differences in solar radiation and atmospheric humidity, most applications are based on the difference between air temperature (T_a) and T_s, rather than simply T_s. The T_s-T_a has been the basis for many algorithms linking temperature measurements to soil evaporation and plant transpiration (i.e., as water evaporates, the surface cools).

Radar

The basis for soil moisture measurements using radar is the difference in dielectric constant, έ, for dry soil (έ = 2) and water (έ = 80). As the water content of a dry soil increases, so does the dielectric constant, which directly affects microwave backscatter, σ^o (Henderson and Lewis 1998). Microwave energy penetration of soil is on the order of several centimeters (van Oevelen and Hoekman 1999), but surface roughness and vegetation affect backscatter and their effects must be eliminated to accurately measure soil moisture (Sano et al. 1998). Other researchers have reported that surface roughness and vegetation influence backscatter as much or more than soil moisture (Zribi and Dechambre 2002, van Oevelen and Hoekman 1999). For this reason, the predictive capability of single polarization or single incidence angle radar for soil moisture is generally positive, but weak with $r^2 = 0.06$ and 0.09 for grass and shrub dominated sites respectively (Sano et al. 1998). Moran et al. (2000) reported better results when they took the difference between a reference (dry) image and changed (wetter) image ($r^2 = 0.93$). In this way, the difference in σ^o was due solely to change in water content when changes in vegetation and surface roughness were minimal.

Methods

The indexes used in this paper include T_s-T_a, WISOIL, MSI and the Δ-index. WISOIL and MSI indexes are defined as

$$\text{WISOIL} = \rho 1.45\ \&\text{m} / \rho 1.3\ \&\text{m} \tag{1}$$

where ρ = reflectance in a particular wavelength, and

$$\text{MSI} = (\text{TM5}/\text{TM4}) \tag{2}$$

where TM5 = Landsat Thematic Mapper band 5, and TM4 = Landsat Thematic Mapper band 4.

Every T_s, ρ and σ^o measurement had a concurrent measurement of the same soil in a dry state allowing normalization of all data to a dry reference condition. We call this the Δ-index, defined as

$$\text{N } \Delta\text{-index} = \text{abs}[(M_{wet}-M_{dry})/ M_{dry})*100] \tag{3}$$

where M_{dry} = measurement (T_s, ρ or σ^o) of dry soil and M_{wet} = measurement (T_s, ρ or σ^o) of wet soil.

Optical

The optical experiment was conducted on pans of soil with a boom-mounted sensor under natural outdoor light May 7-9, 2003 in Tucson, AZ. The three soils used in the experiment were the Barnes, a dark colored silt/loam Mollisol with approximately 5% organic matter, the Whitehouse (B horizon), a red colored clay and iron rich Aridsol, and the Gila, a light colored, sandy loam Entisol.

The soils were sieved using a 2 mm screen and two samples of each were placed 3 cm deep in pans 21 cm in diameter. One sample of each soil served as a control and was never wetted. The other samples were filled with water to saturation and allowed to drain until all ponded water had soaked into the soil. Measurements were made of all samples with an Analytical Spectral Devices FR radiometer which measures radiation from 0.350 to 2.5 &m at 0.004 &m bandwidths. These measurements were made relative to a pressed halon panel to derive reflectance values. At the same time, soil surface temperature was measured with an Everest Interscience Infrared Thermometer with a 15 degree view angle. Soil moisture measurements were made with a factory calibrated Dynamax ML2X capacitance probe to 3 cm. Three soil moisture measurements were made in each sample and averaged. This procedure was repeated 10 times over a period of three days to document the change in spectral and surface thermal characteristics as the wetted soil samples dried.

Radar

The radar experiment was conducted between 1996 and 2003 on rangelands near Tombstone, AZ using soil moisture data collected from the field concurrent with satellite image acquisition. Radar backscatter, σ^o, from ERS-2 and RADARSAT-1 satellite sensors (Table 1) and corresponding soil moisture data were obtained for 12 and 18 locations respectively. The ERS-1 backscatter coefficients were computed as the average of a 7 X 7 pixel window (8,100 m^2), while the backscatter coefficients for the RADARSAT-1 images were computed as the average of a 13 X 11 pixel window (9,100 m^2).

Table 1. Characteristics of radar imagery used in the study.

	ERS-2	RADARSAT-1
pixel resolution	12.5	8
polarization	V V	H H
incidence angle	23^o	46^o
frequency	C-band (5.3 GHz)	C-band (5.3 GHz)
wavelength	5.6 cm	5.6 cm

Coincident with the ERS-2 scene acquisitions, soil moisture was determined gravimetrically at 49 locations within each pixel cluster. Coincident with the RADARSAT-1 scene acquisitions, soil moisture was determined at 5 cm depth with factory calibrated Vitel probes in one location per pixel cluster. It was necessary to aggregate observations of soil moisture and backscatter for the RADARSAT-1 scenes because it was unlikely that a single isolated sensor could adequately represent soil moisture in large pixel clusters. Thus, the field sites were grouped according to antecedent moisture falling 3 days prior to RADARSAT-1 scene acquisition. This resulted in sample sizes of 9, 5, and 4 for the 3-day cumulative precipitation ranges of 0 to 0.5 cm, 0.5 to 1 cm and > 1 cm, respectively.

Results

Optical

The physical and chemical properties of the soils were apparent in the visible region, where the lighter colored soils were more reflective (Figure 1). Regression of waveband reflectance on water content indicated reflectance and simple indexes explained as much or more of the variation in soil moisture (Table 2) as the Δ-index ratios (Table 3) in most cases. Even though the solar zenith angle varied from 16^o to 64^o throughout the experiment, the soil surfaces were quite smooth, thus sun angle had less of an effect than it would in a field setting.

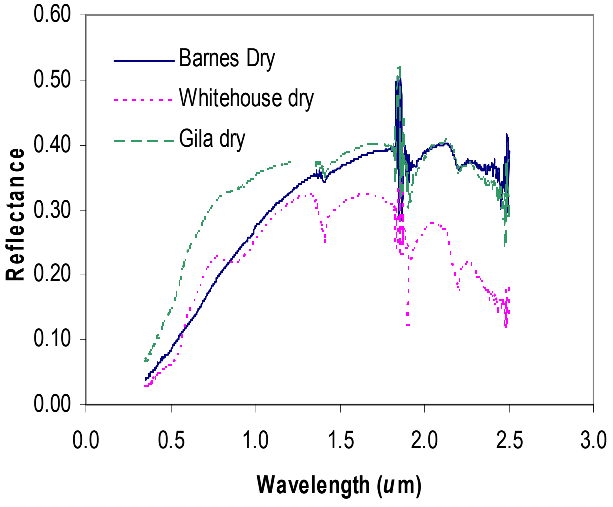

Figure 1. Reflectance signatures for soils used in the optical experiment.

The differences in reflectance of the soils were also apparent in the range of slopes and intercepts reported for any relationship between soil moisture and or reflectance index (Table 2). This finding was expected in light of the variation in soil color properties due to iron and organic matter content. However, the wide range of slopes and intercepts seen in the Δ-indexes for the three soils was unexpected (Table 3). The ratioing technique normalizes some of the spectral properties inherent in the different soils (Figure 2). If the soil surface had been more like a rough field soil, the Δ-index would likely have outperformed the other indexes.

Table 2. T_s and optical indexes versus soil moisture.

Index	Regress. Params.	Barnes	Whitehouse	Gila
		emittance versus soil moisture		
T_s	r^2	0.73	0.85	0.79
	slope	-0.65	-0.75	-0.76
	intercept	39.52	44.53	37.84
		index versus soil moisture		
T_s-T_a	r^2	0.85	0.86	0.80
	slope	-0.28	-0.75	-0.55
	intercept	4.68	18.35	6.56
WISOIL	r^2	0.96	0.88	0.76
	slope	-0.02	-0.02	-0.02
	intercept	1.17	1.28	1.01
MSI	r^2	0.86	0.79	0.79
	slope	-0.02	-0.02	-0.01
	intercept	2.29	1.77	1.15

The Gila soil generally demonstrated the weakest relationship between moisture content and reflectance due to a prominent step function between soil moisture and spectral properties (Figures 2a and 2b). There was a threshold at approximately 10 percent soil moisture where the spectral properties changed dramatically for a small change in the 3 cm integrated soil moisture. This may have been due to breakage of water menisci at the surface as it became dry while the deeper portion remained moist.

Surface temperature, T_s, was the only observation that had relatively uniform slopes and intercepts for all three soils (Tables 2 and 3 and Figure 2c). Therefore, it may provide a measure of surface soil moisture that is relatively independent of soil type.

Table 3. Optical Δ-indexes versus soil moisture.

Index	Regress. Params.	Barnes	Whitehouse	Gila
		---------------Δ/d Index---------------		
Δ-T_s	r^2	0.91	0.81	0.88
	slope	2.31	2.23	2.16
	intercept	-8.20	-17.92	4.17
Δ-narrow ρ1.45 μm	r^2	0.91	0.84	0.72
	slope	2.63	3.82	3.68
	intercept	-18.00	-70.86	-26.26
Δ-wide ρTM 5	r^2	0.84	0.81	0.71
	slope	2.02	2.75	2.86
	intercept	-14.84	-53.99	-23.14
Δ-Albedo	r^2	0.86	0.80	0.70
	slope	1.98	2.59	3.10
	intercept	-8.91	-54.11	-28.28
Δ-T_s-T_a	r^2	0.66	0.78	0.87
	slope	3.79	5.09	6.63
	intercept	19.08	-28.43	-3.10
Δ-WISOIL	r^2	0.95	0.89	0.76
	slope	1.65	2.38	1.86
	intercept	-13.67	-33.92	-2.22
Δ-MSI	r^2	0.86	0.74	0.79
	slope	1.08	1.27	0.59
	intercept	-22.02	-10.33	7.40

Radar

ERS-2 data from Moran et al. (2000) plus three additional data points from RADARSAT-1 were plotted together against soil moisture (Figure 3). In this case, soil moisture and the Δ-index nearly followed a 1:1 line, with scatter due to variability in soil moisture measurements and speckle in the radar backscatter.

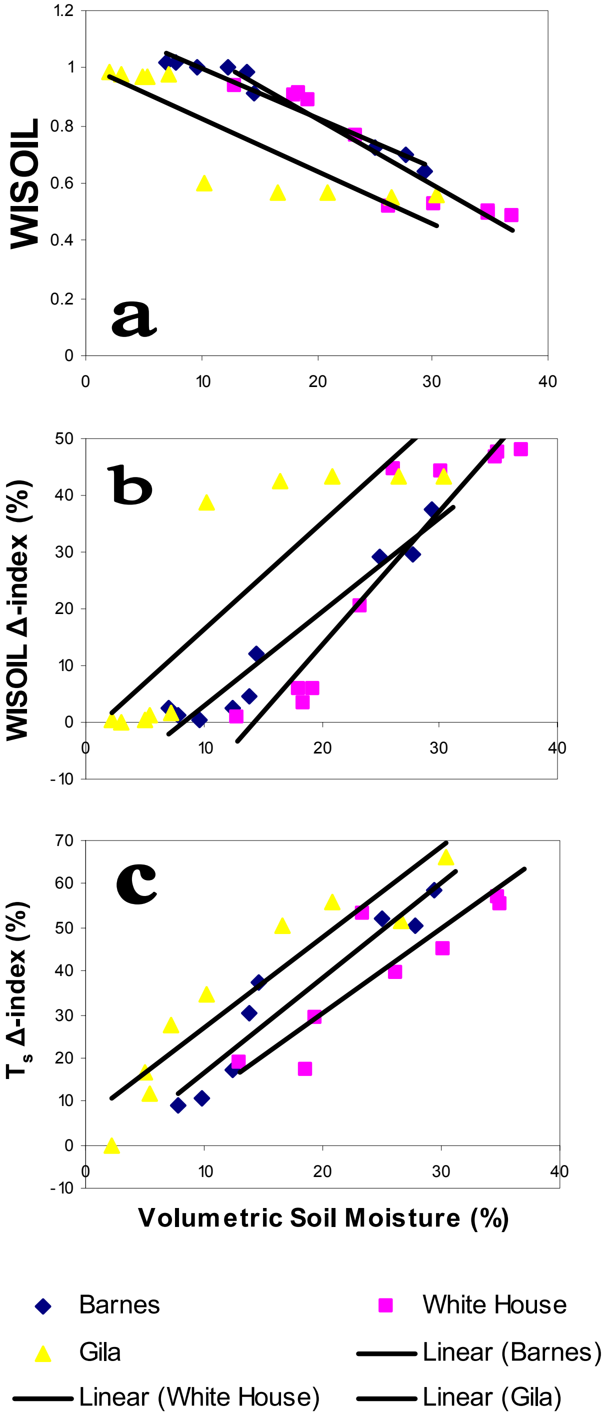

Figure 2. (a) The WISOIL index, (b) the WISOIL index when plotted as a Δ-index, and (c) surface temperature T_s plotted as a Δ-index.

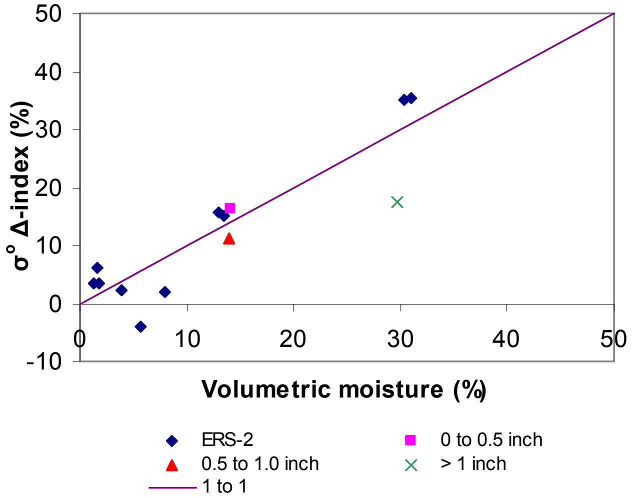

Figure 3. Relationship between delta index and observed soil moisture for ERS-2 and RADARSAT satellites. Diamonds represent ERS-2 observations, and all others RADARSAT-1. Depths indicate cumulative precipitation that fell on soil moisture recording sites 3 days prior to RADARSAT-1 scene acquisition.

Conclusions

Results specific to this study:

1) Reflectance of optical wavelengths were strongly related to soil moisture integrated over a 3 cm depth as indicated by high r^2 values, though a unique equation may be required for each soil type. Additionally, abrupt changes in surface reflectance with small changes in integrated moisture were observed which require further investigation.

2) T_s was the only optical measurement that had relatively similar slopes and intercepts for all three soils. This indicated it might be capable of accurate soil moisture predictions on a wide variety of soil types without the development of empirical relationships for different soils.

3) ERS-2 and RADARSAT-1 data plotted against soil moisture approximated a 1:1 line that suggested data from multiple satellites could be merged to derive surface soil moisture where vegetation is minimal. Additionally, this suggests that empirical relationships between soil moisture and the Δ-index may be unnecessary.

These three results should be evaluated in terms of watershed applications. In that context, several issues need to be addressed.

Data availability is an issue common to all approaches. Although optical remote sensing data are more easily obtained and typically costs less, availability is often limited by poor weather conditions. Thermal remote sensing systems are uncommon and generally provide spatial resolution that is too coarse for watershed scale monitoring. Though radar has good spatial resolution and all weather capability, it is generally more expensive than optical data.

All approaches examined here measure only surface soil moisture (to depths of millimeters in optical bands and centimeters in radar) though management decisions are often based on estimates of root zone soil moisture to depths of 0.5 to 1 m. Methods to extend surface measurements to meaningful depths will make remote sensing of surface soil moisture more useful in watershed management.

Though it may be possible to use ρ, T_s or σ^o to determine surface soil moisture, only σ^o offers the potential for directly measuring soil moisture without the need to derive field-based empirical relationships. For this reason, and because radar data from existing satellite platforms is available, provides a good combination of spatial resolution, and depth integration, it is a powerful tool for watershed soil moisture monitoring.

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