Response of Some Thematic Mapper Band Ratios to Variation in Soil Water Content

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ABSTRACT: Bidirectional reflectance to nadir in the reflective Thematic Mapper (TM) bands and a 1.15 to 1.3 μm band was measured in the laboratory as moisture content was varied in ten soils. Stronger absorption by water in TM5 and TM7 was expected to cause ratios of other bands to TM5 and TM7 to increase with water content, but in most cases these ratios were constant or decreased at low to intermediate water content and increased only at high moisture levels. Several possible causes for the failure of these ratios to consistently increase with moisture content were suggested. Because these ratios were found to decrease as illumination elevation angle decreased, it was suggested that increased roughness resulting from our methods of moistening and mixing the soil may have tended to counteract the expected ratio increases.

Of all the ratios, TM5/7 increased most consistently throughout the range of moisture content, but dry soil values and the rate of increase varied between soils. Variation in moisture content is a potential source of error in using this ratio to detect differences in clay or carbonate content of soils.

INTRODUCTION

THE EFFECT OF MOISTURE on soil reflectance may provide the basis for remote sensing methods for detecting moist soil or measuring soil moisture, and may also be a potential source of error in determining other soil properties from reflectance. Wet soil is obviously darker than dry soil, and the inverse relationship between reflectance and moisture content is readily determined under controlled conditions (Bowers and Hanks, 1965; Shockley *et al.*, 1962; Skidmore *et al.*, 1975; Idso *et al.*, 1975). However, development of remote sensing methods based on this relationship has been hindered by the necessity to accurately standardize for variations in the intensity of incident radiation and to account for and remove the effects of other soil factors on reflectance (Jackson *et al.*, 1978). Some of these problems might be avoided by using a band ratio instead of reflectance in a single band, if a suitable band ratio can be found (Reginato *et al.*, 1977).

In this paper we examine the response of some bidirectional reflectance ratios of Thematic Mapper (TM) bands to water content in a variety of soils. Specifically we test the hypotheses that ratios of TM bands 1, 2, 3, or 4 to TM5 or 7 and of TM5 to TM7 will increase with water content. Because the radiometer we used for laboratory measurements of bidirectional reflectance includes an additional near-infrared band (1.15 to 1.3 μm) which should be less sensitive to water than TM5 and 7 (Curcio and Petty, 1951), we also determine whether ratios of this band to TM5 or TM7 will increase with water content.

Band ratioing methods require that bands respond differently to increasing soil moisture. Because reflectance decreases in all wavelengths with moisture content, what is required is a strong contrast in the rate of decrease. The response to moisture content is quite similar within the visible and near-infrared up to about 1.3 μm, so ratios of bands in this spectral region are unlikely to be useful indicators of moisture content (Reginato *et al.*, 1977). The stronger absorption of light by water above 1.3 μm (Curcio and Petty, 1951) suggests that contrasts of shorter wavelengths to those above 1.3 μm should respond to moisture content. The water absorption peaks at 1.45 μm and 1.95 μm respond most strongly to soil water content (Bowers and Hanks, 1965; Skidmore *et al.*, 1975), but absorption by atmospheric water vapor prevents the use of these wavelengths in remote sensing. TM bands 5 (1.55 to 1.75 μm) and 7 (2.08 to 2.35 μm) are less strongly affected by atmospheric water vapor but are strongly affected by wings of the adjacent absorption bands of liquid water, with absorption in TM7 about twice as strong as in TM5 (Curcio and Petty, 1951). Ratios of shorter wavelength TM bands to TM5 or TM7 and the TM5/7 ratio should therefore be expected to increase with soil water content. These predictions are supported by inspection of spectral reflectance curves for soil at varying moisture content (Bowers and Hanks, 1965) and by comparisons between wavebands of the loss of reflectance upon wetting (Peterson and Baumgardner, 1981).

Visual observations indicated that our methods

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TABLE 1. CHARACTERISTICS OF SOIL SAMPLES.

Sample	Series	Taxonomic Classification	Sample Location	Horizon	Particle Size Analysis % Sand	% Silt	% Clay	Carbonates As % CaCO3
A	Red Bay	Rhodic Paleudult	Geneva Co., Alabama	A	74	9	17	0
B	Red Bay	Rhodic Paleudult	Geneva Co., Alabama	B	56	14	30	0
C	Harrisburg	Typic Paleorthid	Dona Ana Co., New Mexico	A	74	12	14	0
D	Mimbres	Typic Camborthid	Sierra Co., New Mexico	A	15	56	29	8.4
E	Marconi	Typic Camborthid	Sierra Co., New Mexico	A	9	34	57	24.9
F	Norge	Udic Paleustoll	Caddo Co., Oklahoma	A	48	41	11	0
G	Nash	Udic Haplustoll	Caddo Co., Oklahoma	A	26	47	27	0
H	Kipling	Vertic Hapludalf	Sumter Co., Alabama	A	12	45	44	0
I	Port	Cumulic Haplustoll	Caddo Co., Oklahoma	A	39	45	16	0
J	Demopolis	Typic Udorthent	Sumter Co., Alabama	A	26	43	31	2.4

TABLE 2. REFLECTIVE BANDPASSES OF THE THEMATIC MAPPER (TM) AND BARNES 12-1000 MODULAR MULTIBAND RADIOMETER (MMR).

λ, (μm)	TM Band	MMR Band
0.45-0.52	1	1
0.52-0.60	2	2
0.63-0.69	3	3
0.76-0.90	4	4
1.15-1.30		5
1.55-1.75	5	6
2.08-2.35	7	7

of moistening and mixing the soil samples resulted in some changes in aggregate size between moisture levels. On the basis of previous studies (Obukhov and Orlov, 1964; Orlov, 1966) we assumed that, although absolute reflectance would be affected by changes in aggregate size and surface roughness, the proportional effect would be identical for all bands, and band ratios would thus be unaffected. However, the failure of some band ratios to consistently respond as expected to changes in moisture content led us to question the assumption that band ratios would be insensitive to surface roughness. We therefore examined the effect of illumination elevation angle on band ratios of aggregated dry soils to determine if changes in the area of shadows cast by surface roughness elements would change band ratios. This approach was chosen in preference to comparing different aggregate size fractions because sieving could result in mineralogical differences between aggregate size fractions.

METHODS

Ten soil samples differing in texture and other properties were used (Table 1). Soil samples were initially air-dried and sieved to pass a 2-mm screen. The samples were moistened by alternately spraying with a small amount of water and mixing by rolling on a cloth and stirring by hand. Moisture levels sometimes approached but never reached saturation. After each increase in moisture content, samples were allowed to equilibrate in sealed containers for 2 to 12 hr before measurement of reflectance. Some moisture levels were obtained by allowing moistened soil to partially air-dry with frequent mixing. Soil water content was determined gravimetrically immediately after each reflectance measurement and is expressed as weight of water per weight of oven-dry soil.

Reflectance to nadir was measured with a Barnes 12-1000 Modular Multiband Radiometer* (MMR), which has wavebands corresponding to those of the Thematic Mapper plus a 1.15 to 1.3 μm band (Table 2). Field of view was 15° and the distance from the soil sample was approximately one metre. Samples were illuminated by a 600-watt type DYH tungsten-halogen lamp at an elevation angle of 50°. The reflectance standard, measured after each soil sample, was a barium sulfate panel cross-calibrated to a polytetrafluorethylene (PTFE) standard. Soil sample trays were rotated 90° between each of four replicate measurements to minimize errors from sample heterogeneity and slight offsets between the fields of view of different bands. Standard errors were generally less than 1 percent of the mean, and exceeded 2 percent of the mean in only seven instances. To increase the number of moisture levels for the Red Bay A and B horizon samples, these laboratory reflectance measurements were supplemented by reflectance measurements previously made in a similar manner but outdoors under natural illumination.

After the moisture experiment, the Red Bay A and B horizon samples and the Kipling sample were thoroughly wetted, air-dried, partially crushed, and sieved to obtain aggregates >2 mm in diameter. Reflectance was then measured as before but at illumination elevation angles of 50°, 59°, and 69°.

RESULTS

Patterns of band ratio response to moisture were generally similar among the three sandy soils (A, B,

*Trade names and company names are given for the convenience of the reader and do not imply preferential treatment or endorsement of a particular product or company over others by NASA.

and C), and the patterns for soils D, G, and H generally resembled those of the remaining soils. Therefore, the ratio values for samples A, B, D, G, and H have been omitted from some of the figures to simplify presentation of the results.

Ratios of TM1, 2, 3, or 4 to TM5 or 7 generally failed to increase with water content until water content approached the highest level achieved for each soil (Figure 1, Figure 2). The general pattern was for the ratios to initially remain constant or decrease and then increase. The inflection point where the ratio began to increase was generally at higher water content for fine-textured soils.

Although some unknown part of the change in absolute reflectance between moisture levels probably resulted from changes in aggregate size, the trends in absolute reflectance are of interest for understanding the ratio changes around the inflection point. Generally, the increase in these ratios at high water content resulted from a levelling out or slight increase in TM1, 2, 3, or 4 reflectance rather than an accelerated decrease in TM5 or 7. Trends in reflectance in TM2 and 5 for the Norge soil are shown as an example (Figure 3). Anomalous increases in reflectance at high soil water content, as displayed by TM2 in Figure 3, have been attributed to specular reflection from free water surfaces (Blanchard *et al.*, 1974).

At low water content for a given soil, the MMR5/TM5 ratio was relatively constant for most soils, but some soils exhibited a decrease and others an increase (Figure 4). The response of this ratio was generally transitional between the first group of ratios and the remaining ones. The MMR5/TM7 ratio increased throughout the range of moisture content for some soils, but for others the ratio was nearly constant until increasing at higher water content (Figure 4).

The TM5/7 ratio showed the most consistent tendency to increase with moisture content of all the

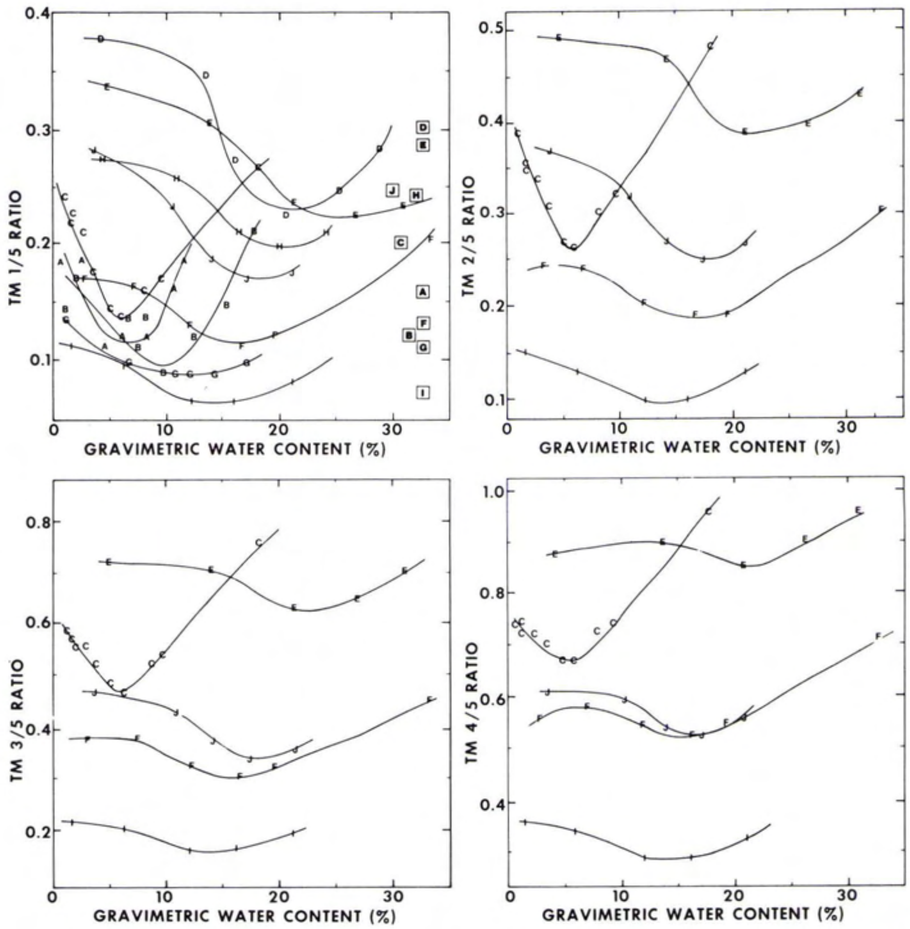

FIG. 1. Response of TM1/5, TM2/5, TM3/5, and TM4/5 bidirectional reflectance ratios to soil water content. Squares denote TM1/5 ratio values predicted for wet soil by Angstrom formula. Symbols correspond to sample designations given in Table 1.

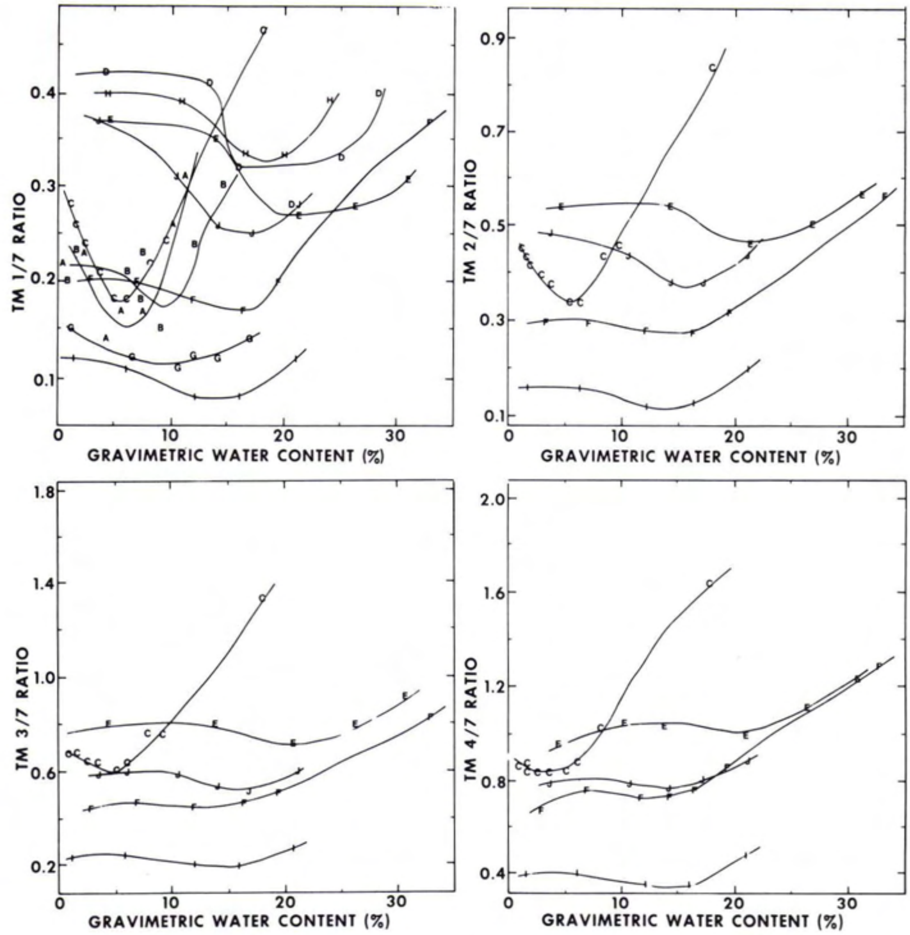

FIG. 2. Response of TM1/7, TM2/7, TM3/7, and TM4/7 bidirectional reflectance ratios to soil water content. Symbols correspond to sample designations given in Table 1.

ratios. With the possible exception of two soils at very low water content (<3 percent), this ratio increased throughout the range of moisture content (Figure 5). The rate of increase tended to be greater for sandy than for fine-textured soils, suggesting that the slopes for different soils may be more similar if water content were expressed as a fraction of water holding capacity.

As expected, reflectance of the soil aggregate samples decreased at lower illumination angles, with little qualitative change in the shape of the spectral reflectance curve (Figure 6). However, plotting reflectance at 50° elevation angle as a fraction of reflectance at 69° reveals quantitative differences in response between bands (Figure 7). Reflectance at 50° relative to 69° tended to decrease with wavelength below TM5, especially in the Red Bay samples. Relative decrease in reflectance was inversely related to reflectance at 69° (Figure 8), but again the relationship was different for each soil, and the relative decrease in TM7 appeared anomalously low. Because relative loss of reflectance with decreasing illumination angle was unequal between bands, band ratios were changed (Table 3). All the ratios tested in the moisture experiment decreased except TM5/7, which increased slightly in two soils and decreased slightly in the third.

DISCUSSION

Ratios of TM1-4 and MMR5 to TM5 or 7 were expected to increase with water content throughout the range of moisture levels because absorption by water is greater in TM5 and 7 than in the other bands (Curcio and Petty, 1951). Contrary to this expectation, we observed decreases or no change in these ratios at low and intermediate moisture levels. The effects of wavelength-dependent differences in absorption by water were apparently masked by some phenomenon tending to decrease TM1-4 and MMR5 reflectance more than TM5 or 7 reflectance. We cannot conclusively identify this phenomenon but can only suggest some factors that should be considered.

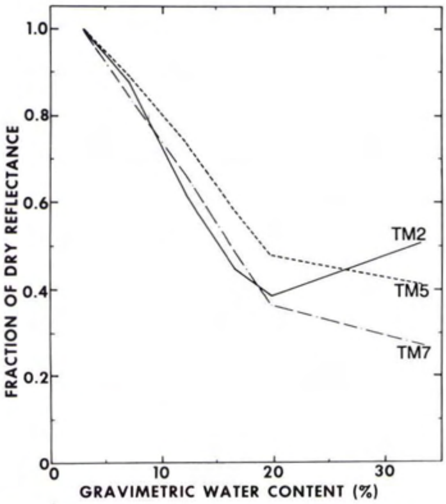

FIG. 3. Response of TM2, TM5, and TM7 bidirectional reflectance to water content in Norge soil. Dry reflectance was 0.101, 0.419, and 0.341, respectively.

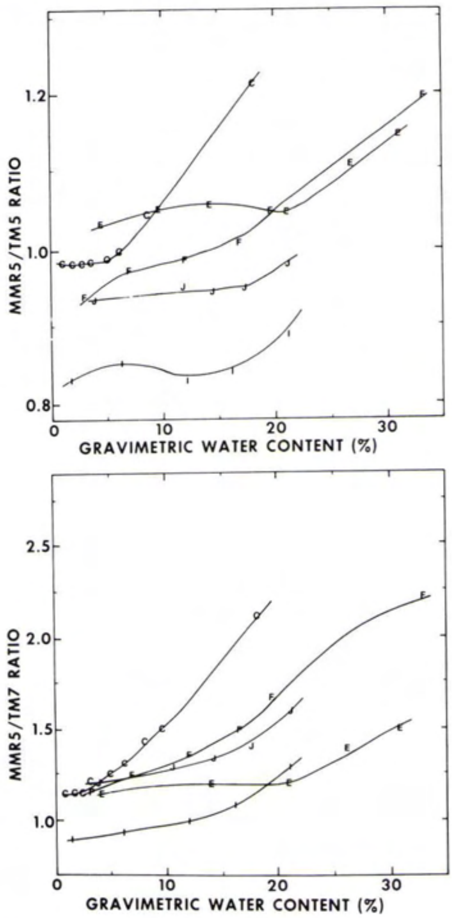

FIG. 4. Response of MMR5/TM5 and MMR5/TM7 bidirectional reflectance ratios to soil water content. Symbols correspond to sample designations given in Table 1.

Our observations of ratio changes in response to changes in illumination elevation angle indicate that our assumption that ratios would be unaffected by variation in aggregate size and surface roughness may be invalid. Theoretical considerations suggest that roughness should have some effect on bidirectional reflectance ratios. Areas shaded from direct illumination will be partially illuminated by reflectance from adjacent, fully illuminated roughness elements (Hapke and Van Horn, 1963). By secondary reflection, the light emerging from the shaded areas will be further enriched in wavelengths with high reflectivity and relatively depleted in those which are strongly absorbed, relative to light from the unshaded areas. Secondary reflection should thus tend to decrease band ratios less than unity and increase those above unity, and ratios deviating most strongly from unity should be most strongly affected. Coulson *et al.* (1965) found that the ratio of red (0.643 μm) to blue-green (0.492 μm) reflectance from a red clay soil changed with view angle in a direction consistent with these predictions. The red/blue-green ratio increased from 1.9 to 2.5 as view angle was changed from the illumination angle (elevation = 37°) to an elevation angle of 70° and an azimuth of 180° from the illumination source (Figure 6 in Coulson *et al.* (1965)).

The response of ratios to illumination angle in our experiment (Table 3) was generally consistent with the predicted effects of secondary reflection from shadows, as described above, and with the observations of Coulson *et al.* (1965). There were some anomalous decreases among the ratios above unity, but changes this small in ratios this near unity could have resulted from our slight experimental errors in reflectance. In the moisture experiment, the band ratios that failed to increase with moisture content were generally less than unity (Figures 1 and 2). The expected increases with moisture content may have been counteracted to some degree by the tendency of ratios less than unity to decrease with increasing shadow area, if our methods of moistening and mixing the soil did indeed increase aggregate size, surface roughness, and shadow area.

This effect of secondary reflectance from shadows should be strongest for unidirectional illumination and absent under totally diffuse illumination. Obukhov and Orlov (1964) and Orlov (1966) found no effect of roughness on the spectral distribution of reflectance because they used an integrating sphere which distributed the illumination evenly over all incidence angles. Under natural illumination, the importance of secondary reflection from shadows would vary with wavelength and atmospheric conditions affecting scattering.

The decrease in soil reflectance upon wetting has

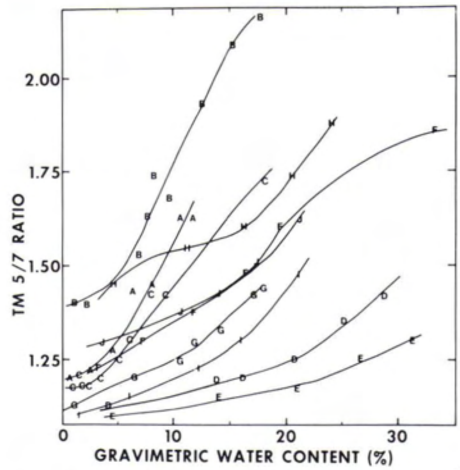

FIG. 5. Response of TM5/7 bidirectional reflectance ratio to soil water content. Symbols correspond to sample designations given in Table 1.

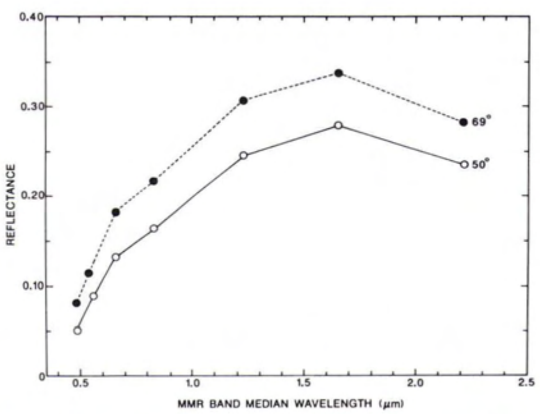

FIG. 6. Bidirectional reflectance in MMR bands of Red Bay A horizon aggregates at illumination elevation angles of 50° and 69°. Reflectance at 59° (not shown) was intermediate but nearer that of 50°.

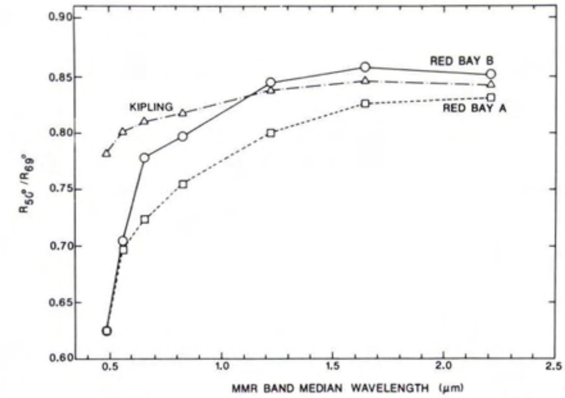

FIG. 7. Bidirectional reflectance in MMR bands of soil aggregates at illumination elevation angle of 50° ($R_{50°}$), expressed as fraction of reflectance at 69° elevation ($R_{69°}$).

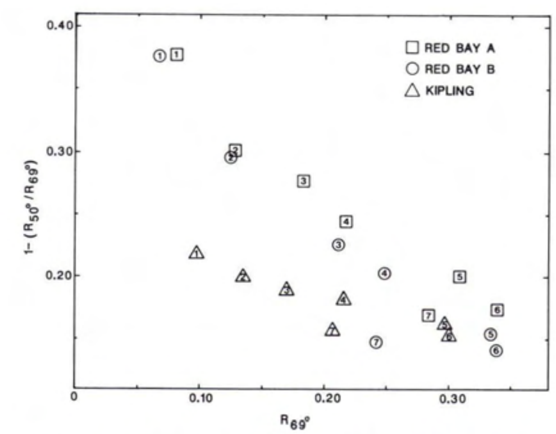

FIG. 8. Relationship of relative decrease in reflectance as illumination elevation angle was decreased from 69° to 50° [≡1 − ($R_{50°}/R_{69°}$] to reflectance at 69° for aggregates of three soils. Number indicates MMR band.

been attributed to internal total reflection in the water film (Angstrom, 1925; Planet, 1970; Reginato *et al.*, 1977), and on this basis the relationship between wet and dry reflectance was described by Angstrom (1925) as

$$\rho' = \frac{\rho}{n^2(1-\rho) + \rho}$$

where ρ' = wet reflectance,
ρ = dry reflectance, and
n = index of refraction of the liquid.

It follows from this formula that variation in the refractive index of water with wavelength can cause band ratios to change upon wetting, but this effect is barely detectable (Reginato *et al.*, 1977). Planet (1970) noted that dissolved soil constituents could affect reflectance of moist soil through their effects on either the transmissivity or the index of refraction of the liquid. Therefore, a differential effect of dissolved soil constituents on TM1-4 versus TM5 or 7 could have contributed in some degree to the anomalous response of these ratios. We consider such an effect unlikely to be significant.

Because the relationship of wet reflectance to dry reflectance is non-linear in the Angstrom formula, ratios may also change if dry reflectance in the two bands differs greatly. Within the reflectance range of most soils (<0.60), the formula predicts that ratios less than unity should decrease upon wetting. This non-linearity effect might therefore account for the failure of the TM1-4/TM5 and TM1-4/TM7 ratios to consistently increase with water content, if the effect were sufficiently strong. The Angstrom formula applies only to saturated soil; use of the formula to predict reflectance of soils at intermediate moisture content would require some model for interpolating

TABLE 3. EFFECT OF ILLUMINATION ELEVATION ANGLE ON BIDIRECTIONAL REFLECTANCE RATIOS OF THREE SOILS IN AGGREGATED CONDITION.

Soil	Illumination Elevation Angle	Ratio						
		TM1/5	TM4/5	TM1/7	TM4/7	MMR5/ TM5	MMR5/ TM7	TM5/7
Red Bay A	69°	0.239	0.640	0.286	0.765	0.910	1.089	1.196
	50°	0.180	0.585	0.214	0.695	0.882	1.048	1.188
Red Bay B	69°	0.199	0.733	0.279	1.024	0.983	1.374	1.397
	50°	0.145	0.681	0.204	0.958	0.968	1.363	1.407
Kipling	69°	0.325	0.719	0.471	1.043	0.990	1.436	1.450
	50°	0.300	0.694	0.437	1.012	0.980	1.429	1.458

between dry and wet reflectance. Although at least one interpolation model has been suggested (Menenti, 1984), experimental verification is lacking. Because there is no generally accepted means of applying the Angstrom formula to intermediate water content, we chose instead to compare the observed ratio changes with the maximum possible effect of non-linearity, which we assumed would occur in saturated soil. For the soils used in this study, the non-linearity effect should be greatest on the TM1/5 ratio because this band pair had the greatest difference in reflectance. Even in this case the observed ratio values decreased well below the values predicted by the Angstrom formula for saturated soil (Figure 1). The effects of the non-linear relationship between wet and dry reflectance thus appear too weak to fully account for the failure of the TM1-4/TM5 and TM1-4/TM7 ratios to increase with water content at low and intermediate moisture levels.

Internal total reflection may not be the sole cause of decreased soil reflectance at low and intermediate water content. The physical model assumed by Angstrom (1925) was a plane water surface over a diffuse reflecting soil surface. Although this model may be appropriate for saturated soil, it is not a realistic description of partially moist soil. At low water potentials most of the water films are only a few millimicrometres thick (Taylor and Ashcroft, 1972). When water films are thin relative to soil particle dimensions, the air-water and water-soil particle interfaces will tend to be parallel, and internal total reflection will not occur. A comprehensive theory of the effect of moisture on soil reflectance would probably include consideration of the optical effects of thin films (Wendlandt and Hecht, 1966) and the influence of moisture on effective particle size. Recent advances in the theory of bidirectional reflectance of intimate mixtures (Hapke, 1981) are difficult to apply to soil-water mixtures because the theories are based on the assumption that the different constituents of the mixture exist as discrete particles. There is need for improved theoretical understanding of the effects of moisture on soil reflectance.

Crist and Cicone (1984a, 1984b) suggest that soil moisture content is a major influence on the dimension of TM data variability they term "Wetness", which is essentially a measure of the contrast of TM5 and TM7 versus TM1-4. Our observation of the general failure of TM1-4 to TM5 or TM7 ratios to increase with moisture content at low and intermediate moisture levels suggests that the response of Wetness to soil moisture levels should be examined more closely. We shall do so in a subsequent paper.

With only minor exceptions, the TM5/7 ratio increased most continuously with soil moisture content. Because this ratio was greater than unity in all our soils, the effect of increases in roughness with moisture content would have tended to reinforce the effect of differential absorption by water. However, it seems unlikely that such uniform increases with moisture content could be solely attributable to the effects of increased roughness, especially in view of the relatively small effects on this ratio of a 19° change in illumination elevation angle. Thus this ratio or other measures of the contrast between bands would appear to have some potential as a basis for remote sensing of soil moisture content. Practical application may be difficult because atmospheric effects or errors in sensor calibration might result in ratio changes comparable to those resulting from variation in moisture content. Also, the relationship of ratio values to moisture content would need to be determined for each soil. Expressing moisture status on some basis other than gravimetric moisture content might reduce differences in curve shape between soils, but ratio values for dry soil would still be required.

The TM5/7 ratio is widely used in geological remote sensing for detection of clay- or carbonate-rich rocks (Goetz *et al.*, 1983), and the possibility that clays and carbonates might similarly be detected or measured in soils is under investigation (Musick and Pelletier, in prep.). The probable sensitivity of the TM5/7 ratio to water content indicates that variation in wetness is a potential source of error in determining clay or carbonate content from this ratio. This should rarely be a problem in geological applications because rock surfaces are rarely moist, especially in arid regions where methods based on spectral differences between rocks are usually applied. This source of error would be more commonly encountered in soils applications, especially for cultivated areas in more humid climates where the surface is less frequently dry.

SUMMARY

Stronger absorption by water in TM5 and TM7 was expected to cause ratios of TM1-4 to TM5 or TM7 to increase with soil water content, but in most cases these ratios were constant or decreased at low to intermediate water content and increased only at high moisture levels. These results, and the evidence that band ratios are affected by illumination angle, indicate that ratios or other measures of the contrast between TM1-4 versus TM5 or TM7 may not be as suitable a basis for remote sensing of soil moisture as previously thought.

The TM5/7 ratio increased most consistently with soil moisture content. However, the problems in using this ratio as a basis of remote sensing of soil moisture content include possible effects of illumination angle and surface roughness, and the differences between soils in dry soil ratio value and rate of increase with moisture content. The sensitivity of TM5/7 to water content could be a source of error in using this ratio for remote sensing of soil clay and carbonate content unless soils are uniformly dry.

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