

Spectral Reflectance of Wetted Soils

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Introduction

Soils darken when wet with little apparent color change. This commonly observed phenomenon is an obvious and dominant characteristic of the reflectance of soils. Several explanations for the darkening have been suggested based on at least two, very distinct theoretical hypotheses. Ångström (1925) attributed the reduction to total internal reflection within the film of water coating soil particles. In effect, the multiple interactions of light with the soil that result from repeated reflections increase the probability of absorption and, thus decrease the total light reflected. A number of authors have expanded on this idea, modifying Ångström's formula to account for light that is not totally internally reflected (Lekner and Dorf, 1988) and incorporating the effect of spectral absorption by the water itself (Bach and Mauser, 1994), a necessity when considering spectral reflectance through the short wave infrared (SWIR).

An alternative explanation was put forward by Twomey et al. (1986) who point out that, since the relative index of refraction between water and soil is considerably less than that between air and soil, forward light is much more likely with wetted soil. As with the case of internal reflection, this increases the interaction of light with soil and results in increased probability of absorption by the soil. As with the internal reflectance model, this could account for the decrease in reflectance, but it would still be necessary to extend the model to account for absorption by water in order to account for spectral variations, especially those in the short wave infrared.

Both Ångström (1925) and Twomey et al. (1986) were primarily concerned with the overall darkening effect. It was consideration of the spectral detail of the reflectance that forced the specific consideration of absorption by water to explain the spectral variability observed in the reflectance. In particular, Bach and Mauser (1994) describe a spectral (400-2500 nm) extension of Ångström's model that appears to closely match observed spectral variations in their measurements soil reflectance. Bedidi et al. (1992) consider only the visible range, but consider color change and review the effects of reflectance and transmittance at the soil surface (with and without water) as well as absorption both by the soil and by the water, emphasizing the effect of the relative refractive index on the spectral reflectance.

It seems clear that the darkening of wetted soil could be attributed to multiple mechanisms. What is not clear is which of those mechanisms is the most appropriate or important. Indeed, both fundamental explanations could well be important significant. Another uncertainty is how and when absorption by water becomes important and exactly how that enters into the process. There are still other issues that have not been clearly addressed. For example, the absorption spectrum of pure water is known, but pore water contains dissolved material and the water itself is partially bound to the soil. Both factors may alter the effective absorption by water.

This paper does not attempt to answer these questions; rather it is an attempt to illustrate the process and elucidate the major issues via a very simple conceptual model.

Observations

First consider a series of reflectance measurements of a soil sample in which the water content varies (Figure 1). These observations were reported by Lobell and Asner (2002) in an experiment specifically designed to observe the spectral variations in reflectance with water content. Each of four samples of distinctly different soil types was passed through a 2-mm sieve to remove extraneous material and homogenize the sample. The sample was then oven-dried at 70°C for 2 weeks. After measuring the reflectance of the oven-dried sample (the top, dark blue spectrum in Figure 1), deionized water was applied to the soil with a pipette until the soil was deemed near saturation. At each stage the water content of each sample was determined by weight and expressed on a volumetric basis: the volumetric water content (vwc). Spectral measurements were then collected repeatedly until the soil mass returned to its initial value (the gray spectrum just below the oven-dried spectrum). The reader is referred to the original paper (Lobell and Asner, 2002) for further details of the procedure.

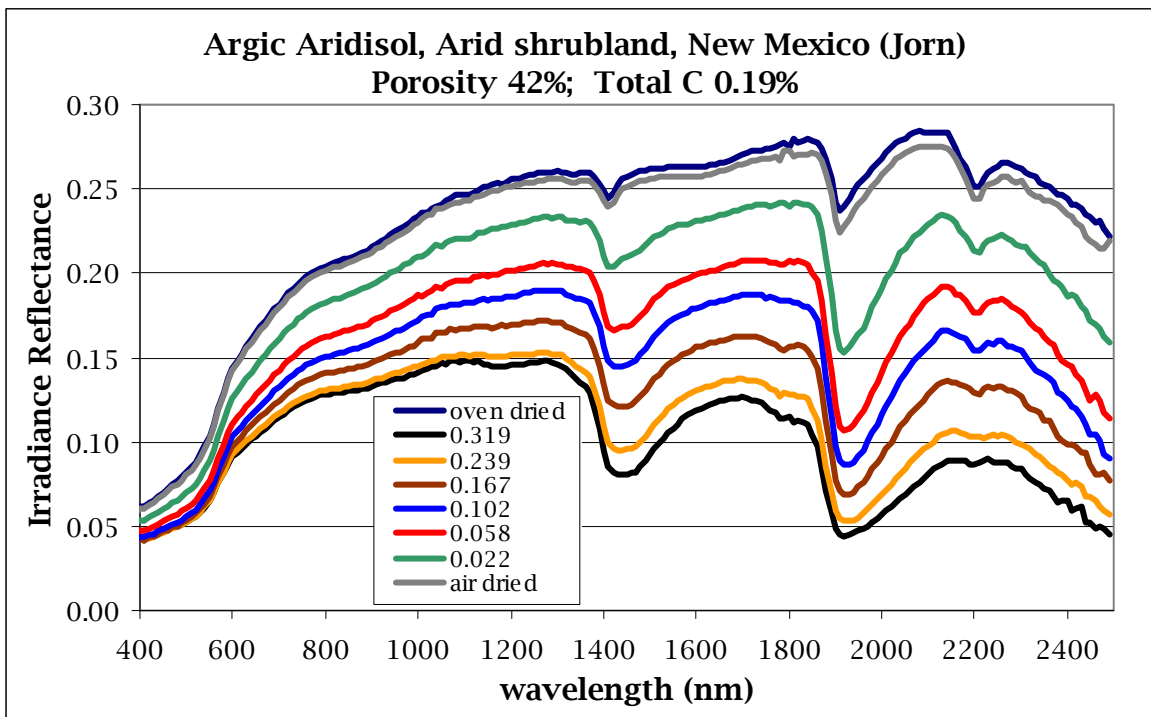


Figure 1: Spectral reflectance of soil with different levels of water content (Lobell and Asner, 2002). Water content based on mass measurements and is expressed in terms of relative volume.

Note that, in the visible (400-700 nm), the shape of the curve does not change greatly, corresponding to the perception that wet soil is darker, but essentially the same color as dry soil. In fact, there are spectral changes in the visible, but they are relatively subtle (Bedidi et al., 1992). The gross change in amplitude is largely true through the near infrared as well. In the short wave infrared, however, there are significant changes in the reflectance spectra that are directly associated with the increased water content. There are the fairly obvious water absorption features centered at 1450, 1900 and 2800 nm that become increasingly dominant as the water content increases, and there are soil absorption features near 1400, 1900 and 2200 nm that are either masked by the water absorption or minimized by the presence of water. It is apparent that, if field spectra or remotely sensed spectra of soils are to be used to evaluate soil properties, it will be necessary to account for the spectral effects resulting from the presence of water in the soil.

A simple model

To begin, let us assume that there is a portion of the reflected light behaves as if it is due to a first surface interaction (i.e, Fresnel reflection) from the water film coating the soil particles (path A in Figure 2). The remaining portion of incident light is transmitted through the water surface and is subject to reflection from the soil particles and absorption by the water (path B in Figure 2).

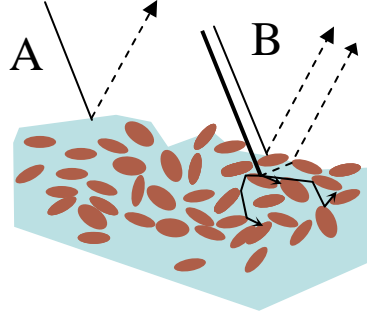


Figure 2: Illustration of a simple, preliminary model of reflectance from wetted soil.

If the fraction of the surface area from which light is reflected directly from the water film is denoted by f_w , then a preliminary expression for reflectance would be:

$$R = f_w \rho_w + (1 - f_w) \rho_s e^{da_w} \quad (1)$$

where: ρ_w = Fresnel reflectance from the water surface
 ρ_s = reflectance from soil particles
 a_w = absorption coefficient for liquid water (1/cm)
 d = average optical path of light through the pore water (cm)

Specifically, Eq. (1) states that water affects reflectance either by surface reflection or by absorption. By implication, the effect of internal scattering within the water (volume reflectance) is negligible. In the absence of water ($f_w = d = 0$), the reflectance is that of dry soil, $R = \rho_s$. In the absence of pore water ($d = 0$), the reflectance is simply an additive combination of soil and water surface reflectance, $R = f_w \rho_w + (1 - f_w) \rho_s$, and in the absence of surface water ($f_w = 0$), the reflectance is that of surface soil reflectance modified by absorption by the subsurface water, $R = \rho_s e^{da_w}$.

For the present, the reflectance of the water surface is approximated using the Fresnel reflectance for light incident normally to a facet surface:

$$\rho_w \approx \left(\frac{n_w - n_a}{n_w + n_a} \right)^2 \approx \left(\frac{n_w - 1}{n_w + 1} \right)^2 \quad (2)$$

where n_w is the index of refraction of the water and n_a is the index of refraction of air. The spectral index of refraction for water is taken from Segelstein (1981) and resulting spectral reflectance factor shown in Figure 3. The surface reflectance is low with very little spectral variation, so the overall effect will be to darken the wetted object but to introduce little spectral change.

The spectral absorption coefficient of water, a_w , shown in Figure 3, is a composite of measurements reported by Pope and Fry (1997) for the near ultraviolet and visible portion of the spectrum, and those

reported by Kou et al. (1993) from the red through the short wave infrared. (Note: a compendium of water absorption measurements can be found at <http://omlc.org.edu/spectra/water/abs/>).

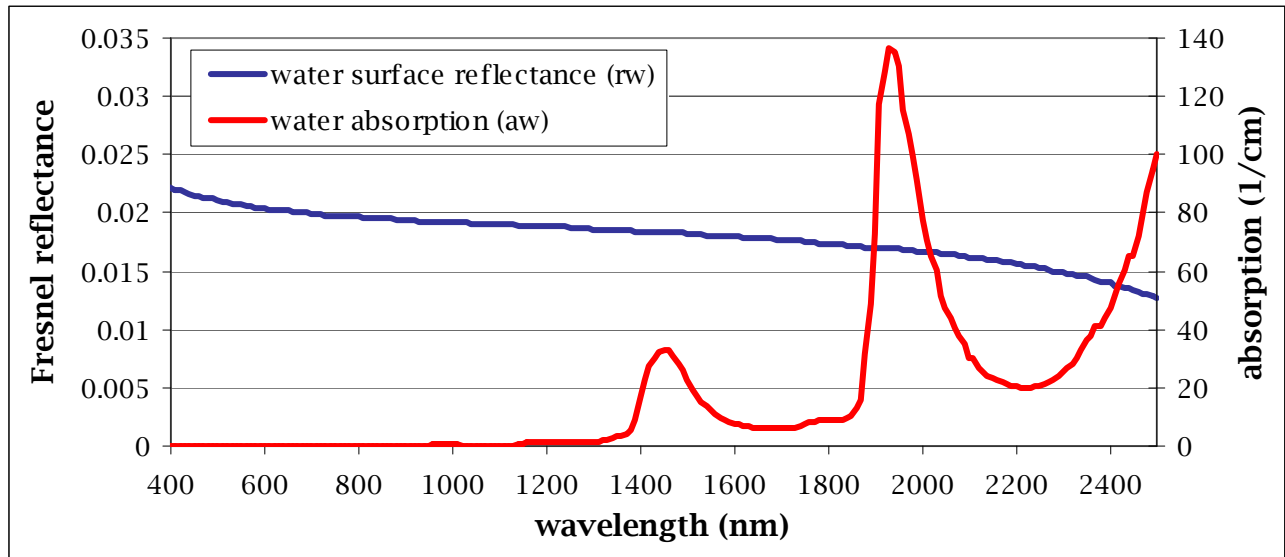


Figure 3: Spectral reflectance and spectral absorption for water

An example

To illustrate the way Eq. (1) controls the spectrum, we begin with the oven dried spectrum and adjust the parameters f_w and d to match the blue curve in Figure 1 ($vwc = 0.102$). Since the water surface reflectance will only alter the amplitude and that will be the major overall effect, we begin by ignoring the pore water content (i.e., $d = 0$), and adjust the parameter f_w to reduce the reflectance down to, but not below, the reflectance of the target spectrum. In this particular example, $f_w=0.22$, and the fit is represented by the dashed line in Figure 4. Next d , the parameter representing the effective optical path length through the pore water is adjusted to match the absorption features which is achieved with $d=93 \mu m$ and illustrated by the dotted line in Figure 4 [It is encouraging that the order of magnitude of the optical path is reasonable, but it is only a model parameter.]

The overall fit is remarkably good, with the modeled curve following the overall shape of the observed reflectance. There are some notable deviations: the modeled reflectance is too high in the visible, and is too low at water absorption peaks. One possible explanation is that absorption by the pore water is not the same as absorption by pure water. For example, the difference between the observed and predicted reflectance is suggestive of absorption by dissolved organic material. Absorption by dissolved organic material (also called yellow matter, cdom, or gelbstoff) is described by a model suggested by Bricaud et al. (1981):

$$a_{dom}(\lambda) = a_{dom}(\lambda_o) \exp[-0.014(\lambda - \lambda_o)] \tag{3}$$

where: a_{dom} = absorption coefficient for dissolved organic material (1/cm)
 λ = wavelength
 λ_o = reference wavelength (440 nm)

The absorption curve for dissolved organic matter (DOM) is shown in Figure 5.

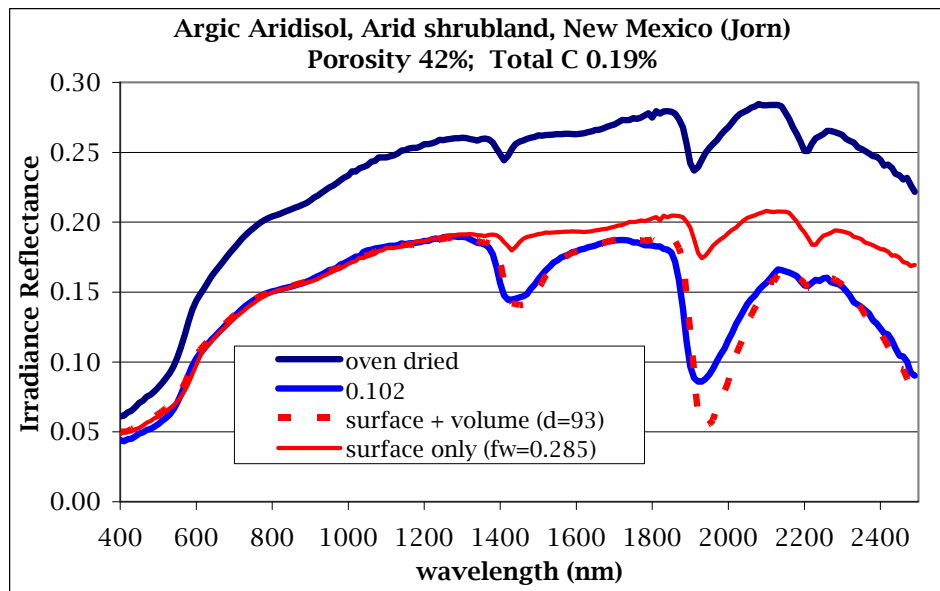


Figure 4: Illustration of how Eq. (1) alters the bare soil reflectance to account for the addition of surface and pore water.

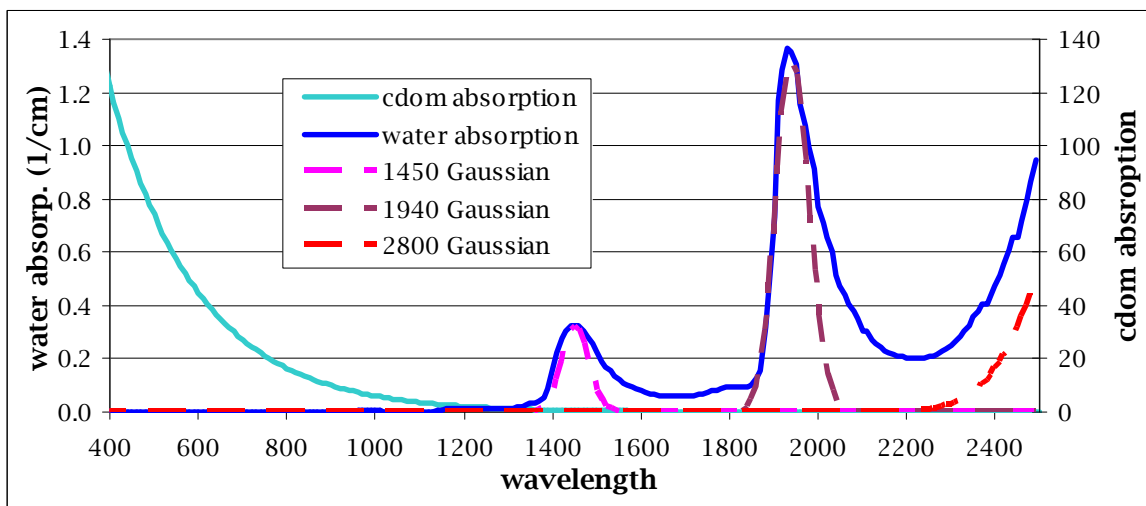


Figure 5: Absorption spectrum for dissolved organic material (DOM) and Gaussian approximations of water absorption features centered at 1450, 1940 and 2800 nm,

The fact that the overall fit of the modeled absorption curve is good except for the prominent water absorption bands suggests that absorption at these locations has been altered. Bach and Mauser (1994) also noted a similar disparity in their model of soil reflectance spectra, and suggested that the differences could be explained by a wavelength-independent, amplitude dependence of the absorption coefficient. They attributed the diminution in absorption to water being chemically bound to the soil particles. Such a global effect does not appear to be the case in the Lobell and Asner (2002) data; the mismatch appears to be restricted to the prominent, narrow water absorption bands. Thus, for these data we also assume that the pore water is partially bound to the soil, limiting the effective absorption; however we assume that the effect is limited to specific bands. Since different vibrational modes are responsible for each of these features, it follows that each one would be modeled separately. As a first attempt, these absorption

bands are modeled with a Gaussian distribution centered at the three major absorption bands, 1450, 1940 and 2800 nm. The fitting functions are illustrated in Figure 5.

These adjustments alter the effective absorption of the pore water and result in a new version of Eq. (1):

$$R = f_w \rho_w + (1 - f_w) \rho_s \exp \left[d (a_w + c_{dom} a_{dom} + c_a a_a + c_b a_b + c_c a_c) \right] \quad (4)$$

where: c_{dom} = concentration coefficient for DOM

c_a = coefficient for absorption reduction at 1450 nm

c_b = coefficient for absorption reduction at 1900 nm

c_c = coefficient for absorption reduction at 2800 nm

The resulting fit, shown in

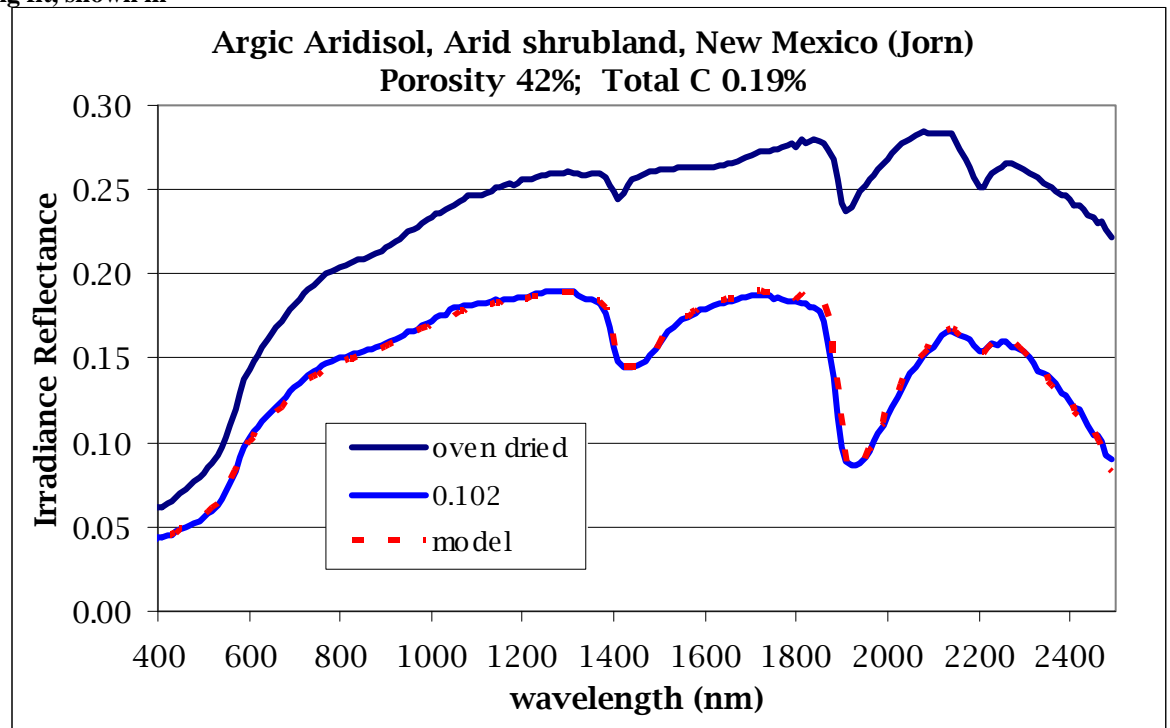


Figure 6, is truly remarkable given the simplicity of the model. The only obvious misfit is a slight overestimate of reflectance in the region near 1800 nm.

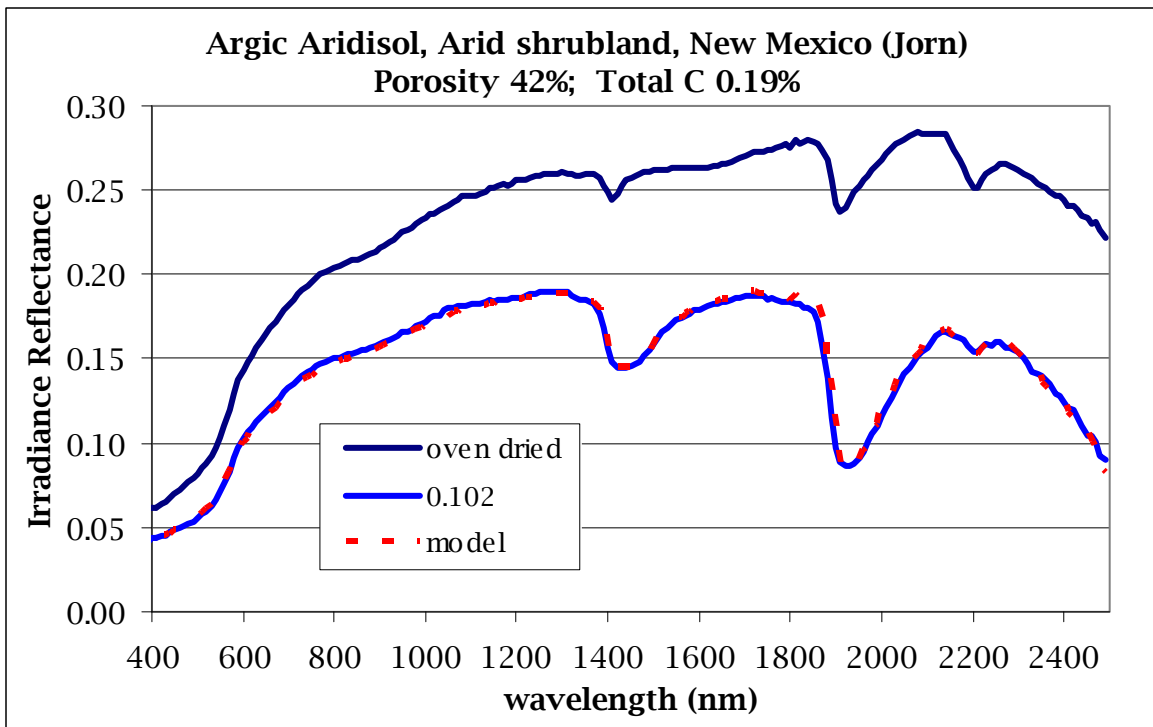


Figure 6: Final fit with $c_{DOM}=20$; $c_a=0.0$; $c_b=0.27$; and $c_c=0.2$.

Results

The simple formulation represented in Equation (4) was applied to the four different soil types and ranges of water content explored by Lobell and Asner (2002) and was generally effective in all cases. A subset of the data with the accompanying model functions are shown in

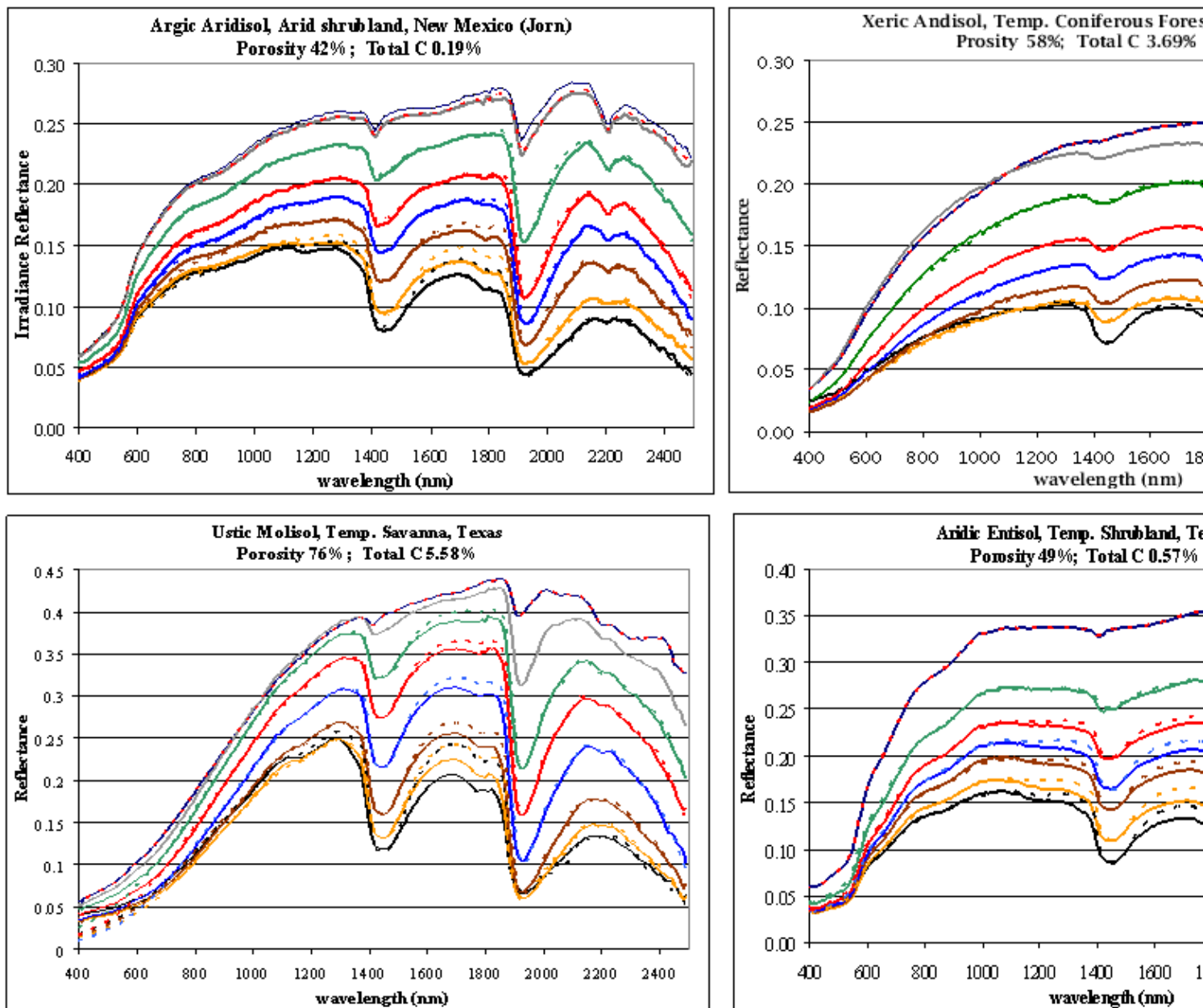


Figure 7. There are some characteristic problems with the modeled spectra: a) a consistent overestimate of reflectance in the 1100-1400 nm and 1600-1800 nm ranges at higher water concentrations; b) a relatively poor fit in the blue, most noticeably for the Ustic Molisol (the problem is generally difficult to see because of the very low reflectance); and, c) a generally poor fit in the 1900-2500 nm range in the Xeric Andisol.

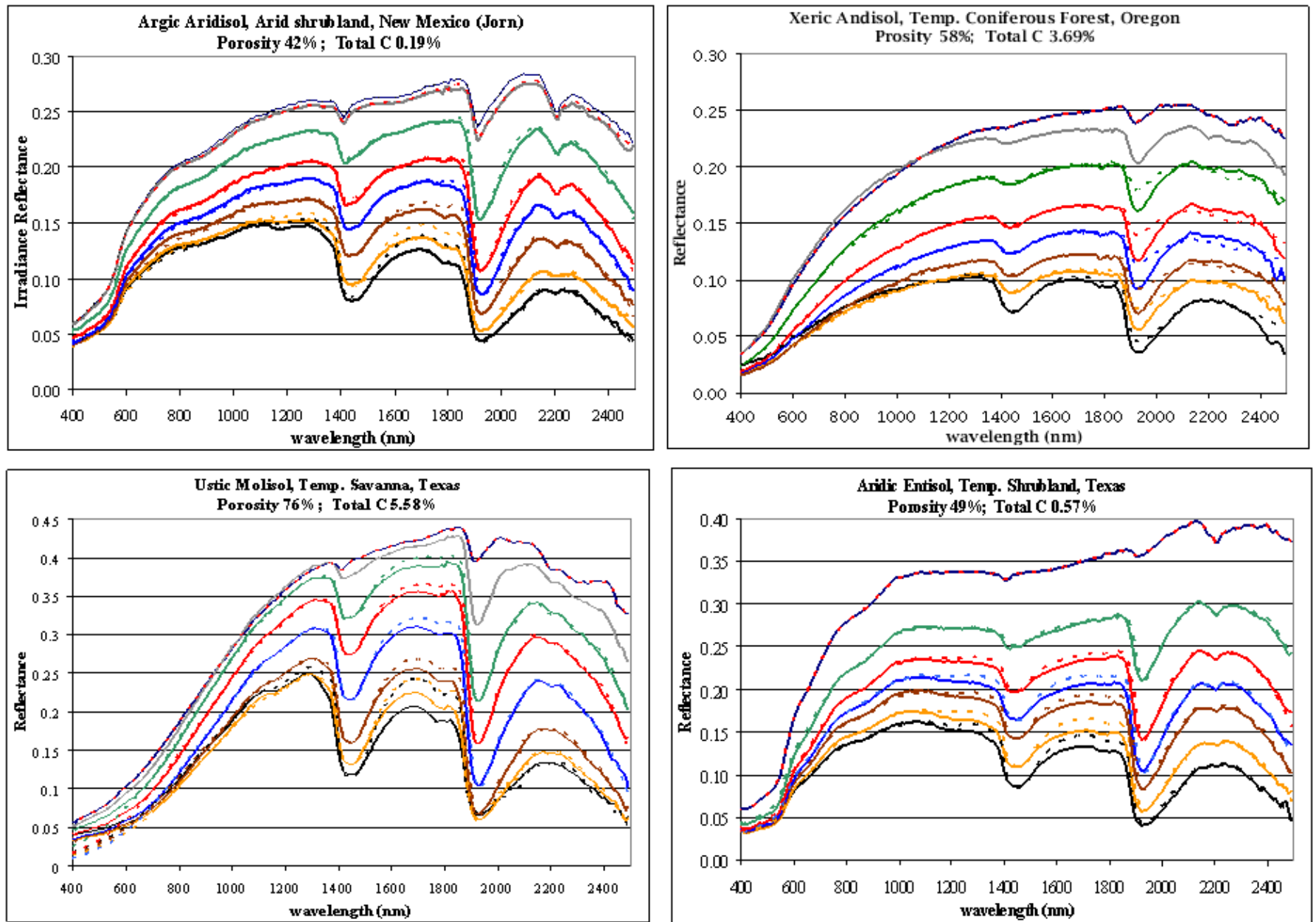


Figure 7: Reflectance spectra and the corresponding modeled spectra for four different soil types at a range of different water concentrations.

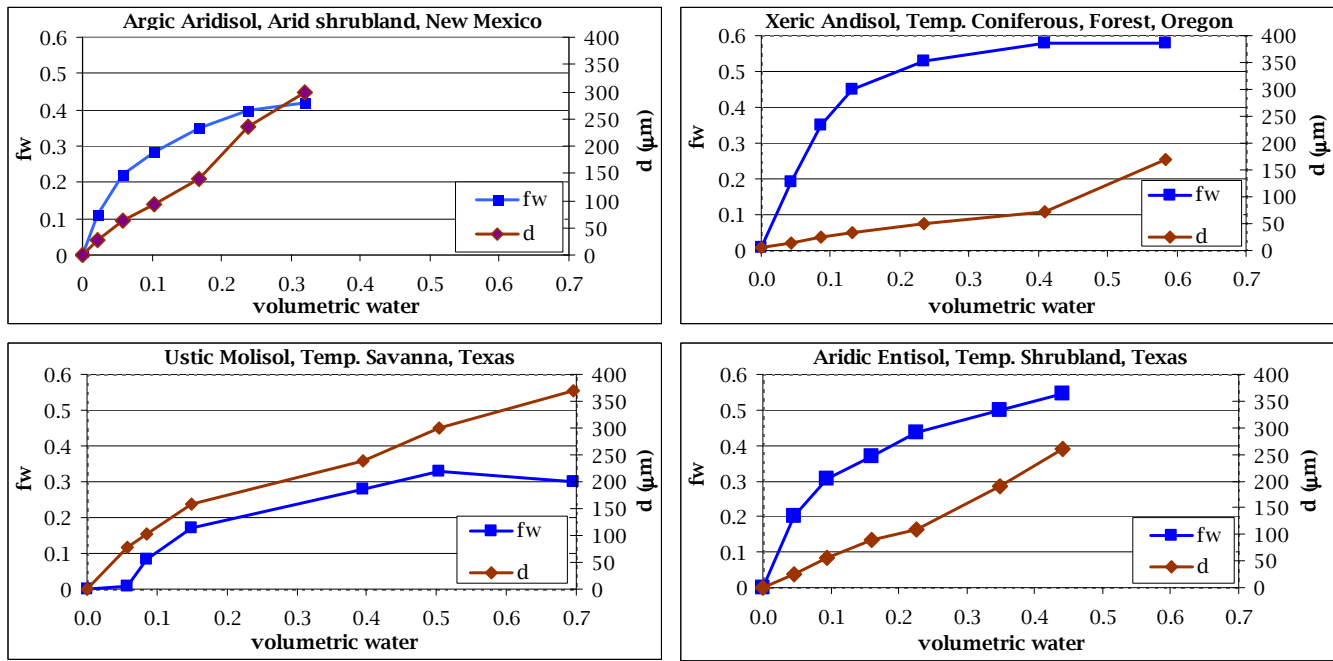


Figure 8: Variation of the major parameters with the volumetric water content of the soil samples.

Finally, one might expect that the two main parameters, f_w and d , should correlate with the volumetric water content. The relationship is illustrated in Figure 8, which shows that the proportion of surface water reflectance increases smoothly over the entire range of water concentrations, appearing to approach a maximum value asymptotically, while the effect of the pore water – parameterized as an effective optical path within the pore water – increases almost linearly. This general pattern is consistent for all four soil types.

Conclusions

A simple model describing the reflectance from wetted soils has been presented. In spite of the fact that the model is superficial, it has described the major variations of changes in the spectral reflectance exhibited in experimental observations. While this is encouraging, the model should be regarded with skepticism and used with great care, if at all. On the other hand, while the conceptual design of this model leaves much to be desired, its success suggests that there is some truth captured by the model structure. There are at least three general conclusions that can be drawn:

1. The darkening effect appears to be spectrally bland and largely independent of absorption effects of the water.
2. Absorption by water is significant in the infrared suggesting that there is a substantial optical path in the pore water.
3. The absorption spectrum of water is modified, probably due to absorption by substances dissolved in the water and/or as a result of water being partially bound to the soil.

References

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