Teaching the Physical Principles of Vegetation Canopy Reflectance Using the SAIL Model

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Abstract

A wide range of resources are available to remote sensing teachers to introduce students to the principles and applications of image processing, but, in contrast, there are few resources suitable for teaching the physical principles of the subject. This paper describes how a radiative transfer model of vegetation canopy reflectance may be used to allow students to explore the complex set of factors that control vegetation canopy reflectance. An example of a practical exercise used with undergraduate level students is described, and topics for follow-up discussions are outlined. The model may be obtained from http://www.salford.ac.uk/geog/staff/sail.html and used without restriction.

Introduction

Introductory courses in remote sensing often start by considering the sources and properties of electromagnetic radiation and its interaction with the Earth's surface and atmosphere. With large classes often consisting of a mixture of geographers, geologists, environmental scientists, physicists, and engineers, all with very different academic backgrounds, this part of the course can be very challenging both for the students and for the teacher (Milton, 1994a; Milton, 1994b). It is surprising, therefore, that few resources are available to remote sensing educators to enhance the teaching and learning of the physical principles of the subject. This contrasts sharply with the plethora of resources available for teaching the principles and applications of image processing and for introducing students to Earth observation satellites and sensors. It is possible that this may reflect a view that the "image" should be the basic model for understanding remotely sensed data; this paper is based on the assertion that, in fact, the spectral response or "spectral signature" of Earth surface materials should be regarded as the fundamental building block. Here, it is suggested that this problem can be addressed by using simple models of surface interactions for resource-based teaching and learning. The paper has two main aims, first, to describe a "student-friendly" vegetation canopy reflectance model and second, to illustrate how the model may be used to help students to understand the factors that affect the spectral response of vegetation canopies.

Vegetation Canopy Reflectance

A useful starting point for the teacher is to discuss the mechanisms that control the spectral properties of individual leaves. Here, the concepts of multiple scattering within leaves, caused by refractive index discontinuities between cells and air spaces, and absorption by the various biochemical components of the leaf, must be introduced. A simple graphical two-dimensional model of a leaf cross-section can be used to illustrate the nature of multiple scattering. By tracing the path of several photons through the leaf, the expected pattern of leaf reflectance and transmittance can be shown (e.g., Guyot, 1990). The main absorbing media in leaves are chlorophyll and water, and here, absorption spectra of these constituents can be used to show how the concentration of these biochemicals is a key control on leaf reflectance. More advanced classes could also examine the effects of absorption by other leaf biochemicals, such as starch, lignin, and protein, that have very recently been recognized as having a small, but measurable, effect on the spectral reflectance of leaves (Curran, 1989). Models of leaf reflectance could be used at this point to investigate these issues further. For example, the PROSPECT leaf reflectance model uses just three input variables: leaf chlorophyll content, leaf water content, and a leaf structure parameter to predict leaf reflectance in the 400- to 2500-nm range (Jacquemoud and Baret, 1990). However, the canopy reflectance model described in this paper requires the reflectance and transmittance of the component leaves to be known. These data must, therefore, be derived from archived spectral data, by measurement, or from a leaf reflectance model like PROSPECT.

Although leaf reflectance is the main determinant of canopy reflectance, because leaf size is large compared with the optical wavelengths with which we are concerned, canopies cannot be modeled as one large thick leaf. This is because there is a range of structural variables that also affect canopy reflectance and because we must consider the contribution of the soil to the spectral signature. At this point it is necessary to introduce students to these variables and their likely influence on canopy reflectance. The key variables are described next in such a way to relate directly to the canopy reflectance model introduced later.

Leaf Area Index

Leaf area index (LAI), the one-sided area of leaves per unit ground area, is a convenient measure of vegetation amount. In the real world, it can take values from zero (no vegetation cover) to a maximum LAI of around 16 for the evergreen forests in the western United States. The typical maximum LAI for agricultural crops is normally in the region of 5 to 6. In general, there is a negative relationship between LAI and visible reflectance and a positive relationship with near infrared reflectance (Curran, 1995).

Soil Reflectance

Soil reflectance (percent) is wavelength-dependant and must be defined for each waveband that is to be modeled. Soil re-

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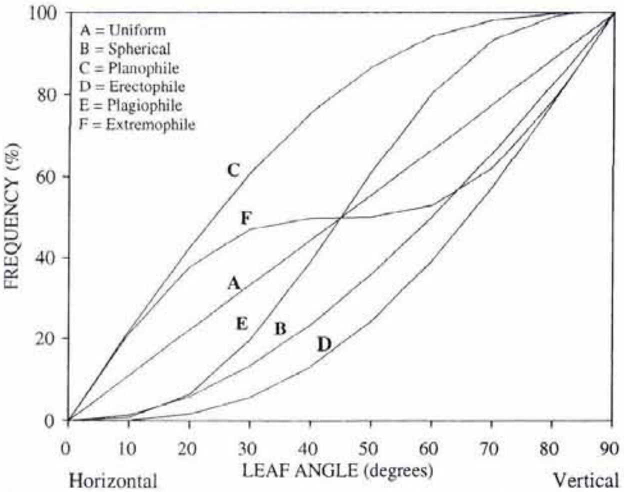

Figure 1. Cumulative frequency for six leaf angle distributions.

flectance is determined by a wide range of soil properties, including moisture content, mineral composition, organic matter content, and roughness (Curran, 1985). Vegetation canopy reflectance increases as soil reflectance increases, and the effect is most important for sparse canopies (low LAI) where a large amount of the background is visible (Huete, 1988).

Diffuse Skylight
In the field environment, canopies are illuminated by direct beam radiation from the Sun and by diffuse skylight scattered by the atmosphere. With complete cloud cover, the irradiance field is entirely diffuse (100 percent) but, on cloud free days with low haze, diffuse skylight can be less than 10 percent. The proportion of diffuse skylight is inversely related to wavelength and must be defined for each waveband modeled. Vegetation canopy reflectance may vary by 30 percent, depending on the amount of diffuse radiation (Deering and Eck, 1987).

Leaf Angle Distribution
Leaves in vegetation canopies are rarely horizontal but are inclined at a range of angles described by the leaf angle distribution (LAD) function that quantifies the frequency of leaves at a given inclination angle. A number of idealized LAD have been defined to describe the structure of vegetation canopies. Canopies dominated by vertical leaves (90° inclination) are described as erectophile and canopies dominated by horizontal leaves (0° inclination) as planophile (Figure 1, Table 1). Erectophile canopies, which tend to trap radiation, generally have a lower reflectance than planophile canopies (Guyot, 1990).

Illumination and Viewing Geometry
The reflectance of a vegetation canopy is non-Lambertian and therefore dependent on the angle at which it is illuminated by the Sun and viewed by the remote sensor (Milton *et al.*, 1995). Students should be introduced to the concept of the bidirectional reflectance distribution function and its approximation the bidirectional reflectance factor. Four angles define the illumination and viewing geometry: the solar zenith and azimuth angle, and the view zenith and azimuth angle (Milton, 1987). Some remote sensing systems view the Earth's surface at different zenith view angles, and there is a large literature on the effects of view angle on vegetation canopy reflectance (e.g., Barnsley, 1994).

The SAIL Model
The SAIL (Scattering by Arbitrarily Inclined Leaves) model, developed from an earlier model by Suits (Suits, 1972), uses the Kubelka-Munk approximation of the radiative transfer equations to characterize radiative transfer through a vegetation canopy as three "streams": a downward flux of direct radiation and an upward and downward flux of diffuse radiation (Verhoef, 1984). It is a turbid medium model that assumes that the canopy may be represented by small absorbing and scattering elements, with known optical properties, distributed randomly in horizontal layers and with a known angular distribution (Goel, 1988).

The SAIL model has been widely used in remote sensing research for investigating the spectral and directional reflectance properties of vegetation canopies. It has been used to simulate the effects of off-nadir viewing, to simulate spectral shifts of the red-edge, and in studies that have attempted to invert the model to estimate canopy properties directly from remotely sensed data (e.g., Jacquemoud *et al.*, 1995).

The Teaching Model
The purpose of the teaching model is to give students an opportunity to explore the factors which control vegetation canopy reflectance and, more importantly, how they interact. The implementation of the model allows any of the variables to be modified and a simulation carried out to predict canopy reflectance in up to seven wavebands. The main screen

Table 1. Leaf Angle Distribution Data

Range (degrees)	Mid-point (degrees)	Frequency of leaves at given angle (%)					
		Uniform	Spherical	Planophile	Erectophile	Plagiophile	Extremophile
0.0-9.9	5	11.11	1.52	22.00	0.22	0.88	21.34
10-19.9	15	11.11	4.51	20.68	1.54	5.67	16.55
20-29.9	25	11.11	7.37	18.22	4.01	13.00	9.22
30-39.9	35	11.11	10.00	14.89	7.33	19.45	2.77
40-49.9	45	11.11	12.33	11.11	11.11	22.00	0.22
50-59.9	55	11.11	14.28	7.33	14.89	19.45	2.77
60-69.9	65	11.11	15.80	4.01	18.22	13.00	9.22
70-79.9	75	11.11	16.84	1.54	20.68	5.67	16.55
80-81.9	81	2.22	3.45	0.11	4.34	0.43	4.02
82-83.9	83	2.22	3.46	0.07	4.38	0.26	4.18
84-85.9	85	2.22	3.48	0.03	4.41	0.14	4.31
86-87.9	87	2.22	3.49	0.01	4.43	0.05	4.39
88-90.0	89	2.22	3.49	0.00	4.44	0.01	4.44

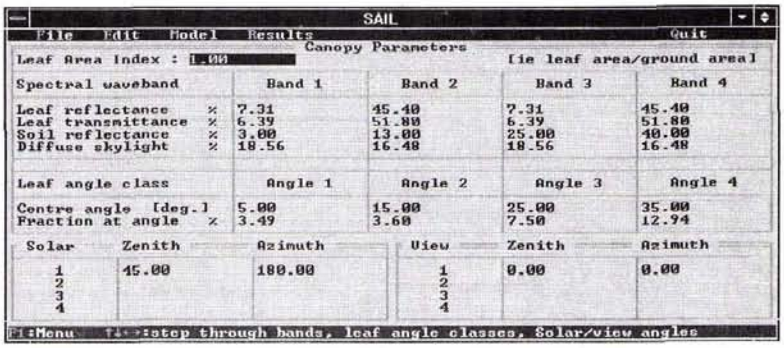

Figure 2. Main screen of teaching model.

(Figure 2) provides a student-friendly interface with the model set to default values or to values defined in a setup file by the teacher. Experience has shown that students need to first relate the variables descibed above to the corresponding model components displayed on the screen. Students should therefore spend some time familiarizing themselves with the layout of the main screen, identifying the variables, and then running an initial simulation. The output can be sent to the screen or to a file and again the output may need some initial explanation.

Modification of the model variables is achieved with a single mouse click and the entry of a new value. A new simulation can then be run. So, for example, examining the effects of change in LAI on reflectance in a given waveband is very easy. In a teaching situation, the model, which is DOS-based, is normally run in a Windows environment to enable students to enter the results of simulations into a spreadsheet/graphics package in a second open window. This setup has been used successfully in classes at Salford although it does require some prior knowledge of Windows. Instructors can often tailor a spreadsheet window for a specific task, leaving students simply to enter the data and visualize and interpret the results.

Example Exercise

Once students have familiarized themselves with the model, it is possible to use it in a variety of teaching and learning situations ranging from direct instruction through to student-centered problem solving. The type of activity undertaken is clearly dependent on the background of the students, the level of the course, and the objectives of the work. However, the following example describes an exercise that is used with a third-year class of geographers and environmental scientists.

The Problem

The normalised difference vegetation index (NDVI) has been correlated with the leaf area index (LAI) of vegetation canopies and it is now used routinely to monitor change in vegetation at regional to continental scales. However, it has a number of well known limitations, including its sensitivity to variation in soil background reflectance. Alternative indices have been designed to overcome this problem, including the Soil-Adjusted Vegetation Index (SAVI) proposed by Huete (1988). Use the SAIL model to examine the relationships between LAI and the NDVI for a "dark" soil and a "light" soil and compare the results with simulations for the SAVI. Present your results in graphical form and briefly outline the outcome of your simulations.

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R})$$

$$\mathrm{SAVI} = 1.5 * [(\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R} + 0.5)]$$

where NIR is the near-infrared reflectance and R is the red reflectance expressed as a fraction (not a percentage).

The Simulation

In this exercise, the students must compute the red and near-infrared reflectance of a vegetation canopy, as LAI increases, for a "dark" soil and a "light" soil substrate. In the simulation described below, the soil reflectances (Table 2) were derived from the graphical data in Huete (1988), LAI was increased from 0 to 6, and the other variables were fixed at their default values (LAD data are from Goel (1988)). Referring to Figure 2 and Table 2, the red and near-infrared reflectances over the dark soil are simulated using the data given for Band 1 and Band 2 and over the light soil using the data for Band 3 and Band 4. This setup allows the simulation of red and near-infrared reflectances over both soils in a single run of the model.

Results of Simulation and Interpretation

After running the model for LAI values in increments of 0.5, the data are compiled in a spreadsheet and prepared for data analysis. The spreadsheet may be tailored to a particular practical exercise or problem-solving task. Students will be required to enter the relevant data, compute the vegetation index for each value of LAI and for both indices, and produce a graphical summary.

A typical graphical output is given in Figure 3, which clearly shows the differences in sensitivity to soil reflectance for the NDVI and SAVI. For the NDVI, the index exhibits lower values over the lighter soil, particularly when LAI is small. As LAI increases, and the soil becomes covered with vegetation, the difference in NDVI between the two soil types decreases. Above an LAI of around 3, the background soil reflectance has little influence on the NDVI. For the SAVI, there is a small difference in the index values over the two soil types at all LAI values. The SAVI is evidently less sensitive to difference in soil reflectance than is the NDVI at low values of LAI. Another interesting observation, however, is that at higher values of LAI there is a significant difference in

TABLE 2. REFLECTANCE VALUES USED TO SIMULATE DARK AND LIGHT SOIL

	Dark soil	Light soil
Red reflectance	0.03	0.25
Near-infrared reflectance	0.13	0.40

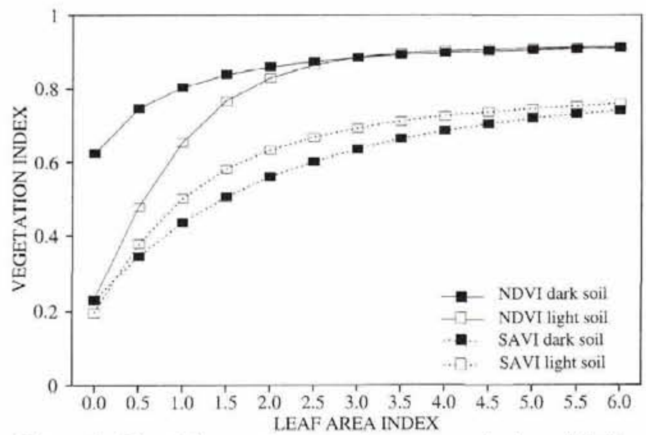

Figure 3. Simulations of NDVI and SAVI over dark and light soil.

the value of SAVI over the two soils when the difference for the NDVI is very small.

Discussion

This simple example illustrates the powerful way in which the SAIL model may be used to investigate the application and the limitations of two widely used spectral vegetation indices. The exercise could lead to a class discussion on the implications of using vegetation indices in regions where soil reflectance varies over space, or to further simulations to test other spectral indices like TSAVI and MSAVI (Baret and Guyot, 1991; Qi *et al.*, 1994). The model may be used to perform a wide range of simulations to examine the influence of the other variables on vegetation canopy reflectance. For example, students could be asked to investigate the effects of variation in canopy leaf angle distribution by using the data from Table 1. The effects of change in sensor view angle, which are important for several current and future satellite systems, could be simulated easily as could the effects of change in solar zenith angle, which influence all remotely sensed data.

Models like SAIL have a role to play in helping students develop a deeper understanding of some of the more difficult concepts which underlie the application of remote sensing. At Salford the model is currently used to reinforce lectures and as a starting point for group-based mini-projects where students explore particular problems and present the results of their modeling work to the rest of the class. It also serves as a very useful starting point for further discussion of the implications of the use of vegetation indices, for example, and of the wider issue of the validity of the model for describing heterogeneous canopies, like forests, which do not meet the assumption of a turbid scattering medium required by SAIL.

Conclusions

The basic principles of remote sensing are now taught in many geography, geology, and environmental science degree courses in the United States, UK, and elsewhere. The teaching and learning resources currently available for such courses are, however, very limited; learning about the complex set of factors which control the reflectance properties of vegetation canopies can be perplexing for students. Ideally, a practical approach based on laboratory or field experiments would be adopted to reinforce lectures and reading; however, large student groups, limited resources, and the pressure of time may make this approach impossible. This paper has outlined the use of a computer-based vegetation canopy reflectance model that may be used in a variety of teaching and learning situations. The model may be used as a "virtual laboratory" to simulate canopy reflectance under different experimental conditions. It may be used as a tool to test theories derived from the literature and as a springboard into further investigations of vegetation canopy reflectance and computer modeling in remote sensing.

The model may be obtained from the Internet and used without restriction:

http://www.salford.ac.uk/geog/staff/sail.html

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