Aspects of Applied Biology 60, 2000
Remote sensing of agriculture

New technique for remote estimation of vegetation fraction: principles, algorithms and validation

By R STARK, A A GITELSON

Department of Geological and Environmental Sciences, Ben-Gurion University of the Negev, Beer-Sheva 84105, Israel

U GRITS

Department of Environmental Physics and Energy Research, J. Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Sede-Boker Campus, Israel

D RUNDQUIST

Center for Advanced Land Management Information Technologies, School of Natural Resource Sciences, University of Nebraska-Lincoln, Lincoln, NE 68588-0517, USA

and Y KAUFMAN

NASA Goddard Space Flight Center, Greenbelt, Maryland, MD 20771, USA

Summary

A high degree of covariance was found for paired reflectances (R) at 550 nm versus 700 nm (R_{550} vs. R_{700}) and 500 nm versus 670 nm (R_{500} vs. R_{670}) for wheat canopies with 100% vegetation fraction. Both relationships defined as vegetation lines, were linear with $r^2 > 0.95$ and points were tightly clustered. Using the same coordinates to plot reflectances for a variety of soils, we found a high degree of covariance ($r^2 > 0.94$) and a distinct "soil line." Therefore, these vegetation and soil lines define a two-dimensional spectral construct within which canopy reflectances, regardless of vegetation fraction, may be located. Based on the above, we attempted to estimate vegetation fraction remotely. We suggest using the coordinate location within the spectral construct as a measure of vegetation fraction. The root mean square deviation between predicted values from both spectral spaces and measured values were less than 11%.

Key words: Reflectance, vegetation line, vegetation fraction, wheat

Introduction

Spectral vegetation indices are widely used indicators of temporal and spatial variations in vegetation structure and biophysical parameters. They enable assessment and monitoring of changes in canopy biophysical properties such as vegetation fraction, leaf area index, fraction of absorbed photosynthetically active radiation, and net primary production (Asrar *et al.*, 1984; Holben, 1986; Myneni *et al.*, 1995; 1997*a,b*; Sellers, 1985, 1987; Tucker, 1979; Tucker *et al.*,

1986). Considerable effort has been expended in improving the normalized difference vegetation index (NDVI) and in developing new indices to compensate both for the atmosphere (e.g. Kaufman, 1989; Kaufman & Tanre, 1992), and canopy background (Huete, 1988; Huete *et al.*, 1994). Most vegetation indices combine information contained in two spectral bands, red and near infrared (NIR). The indices have limitations, some of which are due to choices of band location and width. Examples include small sensitivity of the NDVI to moderate to high chlorophyll content (Gitelson & Merzlyak, 1994*a,b*; Gitelson *et al.*, 1996; Myneni *et al.*, 1997*b*) and the minimal sensitivity of NIR reflectance to vegetation fraction at certain growth stages (Stark & Gitelson, 1999; 2000).

We propose to use the visible range of the spectrum to estimate quantitatively vegetation fraction (VF), taking advantage of new satellite technologies including the high spectral and radiometric resolutions achieved in the recently launched SeaWiFS, MODIS, ASTER, MISR and imminent scanners such as MERIS.

Materials and Methods

Site

The study took place in agricultural fields near the city of Beer-Sheva, Israel (31°13'N; 34°48'W), located on the northern edge of the Negev Desert. The crops were irrigated on a regular basis by the water effluent from a nearby reservoir using sprinklers installed in straight parallel lines. Wheat (*T. aestivum*) was the main crop grown during our field investigations, from autumn 1997 to spring 1999. In the first year, experiments were conducted from the middle of December 1997 until the middle of May 1998 (Gitelson *et al.*, 2000).

Radiometric measurements

Data were collected above the canopy using two high spectral resolution spectroradiometers: a Licor LI-1800 in the range 400-1,100 nm with a spectral resolution of 2 nm and an ASD FieldSpec FR in the range 400-2,500 nm with a spectral resolution of 1 nm. To measure upwelling radiance (L_{up}), an LI-1800 was attached to a telescope with a field of view of 15°, which was positioned above the canopy at a height of about 2 m. The downwelling irradiance (E_{dn}) was measured by a remote cosine receptor. Upwelling readings were repeated at least three times at each sampling station and the average value was used in the analysis. Each reading took approximately 25 seconds. Each measured upwelling radiance spectrum of the canopy was normalized to the appropriate downwelling irradiance spectrum, yielding the reflectance as $R=L_{up}/E_{dn}$. The telescope of the FieldSpec FR spectroradiometer, with a 25° field of view, was positioned at nadir over the object. Five spectra of upwelling radiance were taken from both the wheat and the reference panel. The reflectance (in percent) was calculated as $R_{object}(\lambda)=(L_{object}/L_{ref})*R_{ref}(\lambda)$, where $R_{object}(\lambda)$ is the reflectance of the canopy; $L_{object}(\lambda)$ is the mean of five spectra of raw digital measurement of upwelling radiance over of the canopy; $L_{panel}(\lambda)$ is the mean of five spectra of the raw digital measurement of upwelling radiance over the reference panel; $R_{ref}(\lambda)$ is the reflectance of the reference panel. Reflectance spectra were acquired within the field at a few randomly selected locations, and at least five spectra were measured for each species of crop. Color photos (35 mm) were acquired at each plot at the same height of the radiometric scan, and the vegetation fraction was estimated from these photos.

Results

Our approach was first to study relationships R_{670} vs. R_{500} and R_{550} vs. R_{700} for soil and wheat reflectance in order to understand whether their close leaf-level relationships exist also at the canopy level. Soil brightness varied considerably. In the blue range, the reflectance changed between 3 and 17% and in the NIR range between 12 and nearly 40%. Reflectance increased with wavelength and was a function of soil moisture. For a closed canopy with VF = 100%, the reflectances at 670 nm vs. 500 nm (R_{670}, R_{500}) and 550 nm vs. 700 nm (R_{550}, R_{700}) data are confined to a line in two-dimensional spectral space. For closed vegetation canopies with a wide range of canopy structures and pigment contents, both relationships (R_{700} vs. R_{550} and R_{670} vs. R_{500}) were linear with determination coefficients $r^2 > 0.95$, and the plotted points were tightly clustered. Thus, for a canopy with VF = 100% (as it was found for green leaves), "vegetation points" are, in reality, a "vegetation arc" or "line". Therefore, we refer to this relationship as the "vegetation line." For soils, reflectances R_{670} and R_{500} correlated very closely ($r^2 = 0.94$), forming a "soil line". Root-mean square variation of soil reflectance from the established line was less than 1.5%. A very strong degree of covariance ($r^2 = 0.96$) also was found between reflectances R_{700} and R_{550}. Root-mean square variation of reflectance from the soil line was less than 1.3%. Fig. 1 shows relationships R_{670} vs. R_{500} and R_{700} vs. R_{550} for wheat with VF = 0 to 100%. Vegetation and soil lines define a two-dimensional spectral construct within which canopy reflectance, regardless of vegetation fraction, may be located.

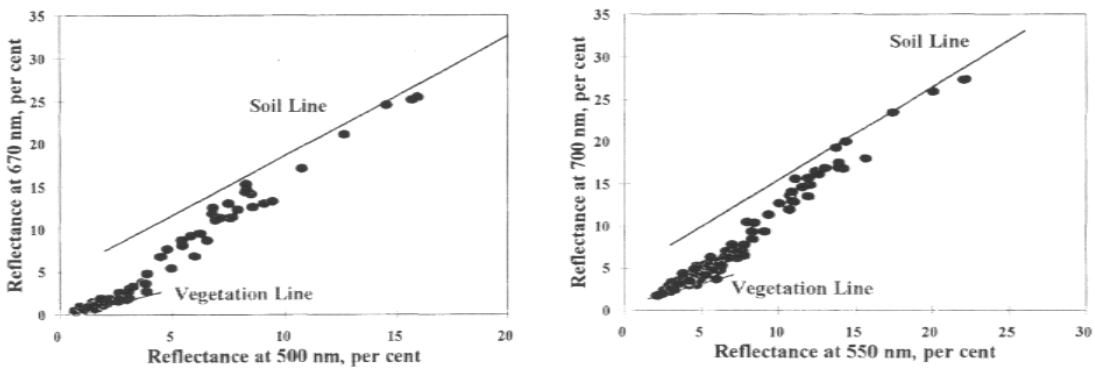

Fig. 1. Reflectance R_{670} vs. R_{500} (A) and R_{700} vs. R_{550} (B) for wheat with vegetation fraction 0 to 100%.

The vegetation line is formed by reflectance of wheat with VF = 100%. Although the variation of vegetation brightness was less than for soils, it was nevertheless pronounced: three fold at 550 nm and even more at 700 nm. In R_{670} vs. R_{500} spectral space, reflectance ranged from 2 to 4% at 500 nm and even less at 670 nm. When the VF is near zero, the plotted point is near or on the soil line. When the VF reaches 100%, the plotted point is near or on the vegetation line. Points that are near or on the soil line and that have low reflectance, corresponded to dark soils. Points that are near or on the soil line and that have high reflectance corresponded to light-colored soils. Thus, an increase in VF caused an orderly decrease in reflectance. When VF reached 60-70% (nearly closed), reflectance dropped to extremely small values (less than 3% for R_{670} vs. R_{500} and less than 5% for R_{700} vs. R_{550}). The topology of this two-dimensional construct will change as vegetation brightness and soil color change. The position of a point within this construct with the same VF will also change as the vegetation brightness and soil color change.

We suggest using the position of actually measured reflectance, which must be located between the soil line and vegetation line, as a measure of VF. The probable range of vegetation and soil

brightness for measured reflectance, point O, in spectral space (R_{700}, R_{550}) is shown in Fig. 2. The segment of the soil line between points A_1 and A_6 represents the probable range of soil brightness. The segment of the vegetation line between points B_1 and B_6 represents the probable range of vegetation brightness. Thus, VF may lie in the range of ratios A_1O/A_1B_1 and A_6O/A_6B_6.

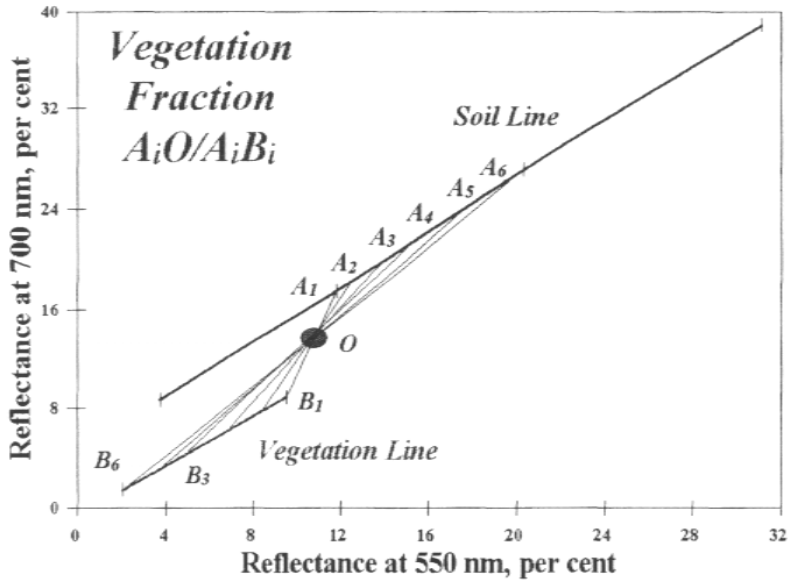

Fig. 2. Probable range of vegetation and soil brightness for measured reflectance in spectral space (R_{700}, R_{550}).

The errors of VF estimation are caused by the range of likely variation between soil and wheat (VF = 100%) reflectance. The range of VF estimates was calculated as a difference between VF estimates by ratios A_1O/A_1B_1 and A_6O/A_6B_6 (Fig. 2). This difference depends strongly on the range of probable variation of soil and wheat reflectance, as well as relative positions of the soil and vegetation lines. For the wheat studied, and the expected soil reflectance, the uncertainty of VF estimation was found to be less than 10%.

The estimate of VF was calculated as a difference between two extremes in the form $(A_1O/A_1B_1 - A_6O/A_6B_6)/2$ (see Fig. 2). In both spectral spaces, relationships are exponential. In the range of VF from 0 to 50%, the VF estimate was very sensitive to VF variation (nearly 80% of maximal variation). For VF from 60 to 100%, the range of VF estimates was narrow. This non-linear behavior is probably due to wheat self-shadowing. With increase of canopy density, self-shadowing increases, the soil contribution to reflectance drops, and measured reflectance decreases. We analyzed the relationship between VF estimate in (R_{700}, R_{550}) spectral space and VF measured (i.e., retrieved from the corresponding digital images) for two years of observations. Root-mean square variation of points measured in the 1997/98 growing season from a best-fit function for data obtained in 1998/99 season did not exceed 7%. Thus, the functions $VF_{estimate}$ versus $VF_{measured}$ in spaces (R_{700}, R_{550}) and (R_{670}, R_{500}) were found to be repeatable and stable in time (two years observations) for five types of wheat. The relationship $VF_{measured}$ vs. $VF_{estimate}$ has been inverted and functions $VF_{predicted} = 8 + 2.6*\exp(VF_{estimate}/28.5)$ for space (R_{700}, R_{550}) and $VF_{predicted} = 12 + 0.3*\exp(VF_{estimate}/18)$ for space (R_{670}, R_{500}) have been used to predict VF.

Vegetation fraction retrieved from digital images was compared with vegetation fraction predicted in coordinates R_{670} vs. R_{500} (Fig. 3A), and in coordinates R_{700} vs. R_{550} (Fig. 3B). Determination coefficient, r^2, for both spectral spaces was higher than 0.89 and estimation error of vegetation fraction prediction did not exceed 10.3%.

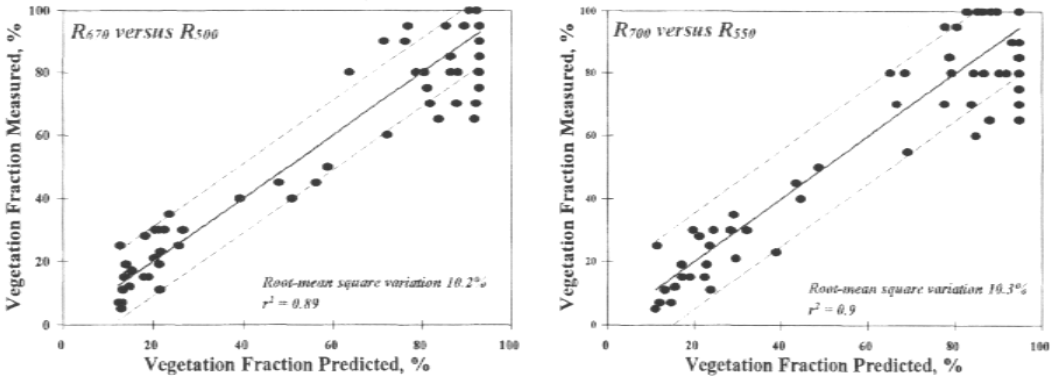

Fig. 3. Vegetation Fraction Predicted Versus Measured.

Discussion

Reflectance of the wheat with 100% vegetation fraction, despite various canopy structures and pigment contents, forms a vegetation line defined by the linear relationships R_{700} vs. R_{550}, and R_{670} vs. R_{500}. The position and orientation of the lines, in two-dimensional spectral space, were repeatable for five types of wheat during two years of observations. Soils of very different types and wetness also form soil lines in the R_{700} vs. R_{550} and R_{670} vs. R_{500} coordinate systems. The soil lines have also proven to be repeatable over the course of two years of data collection. Two-dimensional spectral space, as defined and constrained by soil and vegetation lines, includes all possible canopy reflectances with VF ranging from 0 to 100%. Reflectance for each vegetation fraction plotted in this spectral space is represented by the coordinates R_i and R_j. We suggest using the location of reflectance in these spectral spaces as a quantitative measure of vegetation fraction. The relationship between estimated and measured VF was found to be repeatable and stable for five wheat types in time (two years of observations) and space (sampling has been done in variety of sample sites and fields). Predicted vegetation fraction was linearly proportional to measured VF with root-mean square variation of predicted values from measured of less than 11%.

References

Arsar G, Fuchs M, Kanemasu E T, Hatfield J L. 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Agronomy Journal* **76**:211-220.

Gitelson A A, Merzlyak M N. 1994*a*. Spectral reflectance changes associated with autumn senescence of *Aesculus hippocastanum L.* and *Acer platanoides L.* leaves. spectral features and relation to chlorophyll estimation. *Journal Plant Physiology* **143**:286-292.

Gitelson A A, Merzlyak M N. 1994*b*. Quantitative estimation of chlorophyll using reflectance spectra: Experiments with autumn chestnut and maple leaves. *Journal Photochemistry Photobiolgy* (B), **22**:247-252.

Gitelson A A, Merzlyak M N. 1996. Signature analysis of leaf reflectance spectra: algorithm development for remote sensing of chlorophyll. *Journal Plant Physiology* **148**:494-500.

Gitelson A A, Grits U, Stark R, Rundquist D, Kaufman Y. 2000. Novel algorithms for remote estimation of vegetation fraction. Proceedings of *The Second International on Geospatial Information in Agriculture and Forestry Conference*, pp. 1-8.

Holben B N. 1986. Characteristics of maximum value composite images for temporal AVHRR data. *International Journal of Remote Sensing* **7**:1417-1437.

Huete A R. 1988. A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment* **25**:295-309.

Huete A R, Justice C, Liu H. 1994. Development of vegetation and soil indices for MODIS-EOS. *Remote Sensing of Environment* **49**:224-234.

Kaufman Y J. 1989. The atmospheric effect on remote sensing and its corrections. In *Theory and Application of Optical Remote Sensing,* pp. 336-428. New York: John Wiley & Sons, Inc.

Kaufman Y J, Tanre D. 1992. Atmospherically resistant vegetation index (ARVI) for EOS-MODIS. *IEEE Transactions on Geoscience and Remote Sensing* **30**:261-270.

Myneni R B, Hall F G, Sellers P S, Marshak A L. 1995. The interpretation of spectral vegetation indexes. *IEEE Transactions on Geoscience and Remote Sensing* **33**:481-486.

Myneni R B, Keeling C D, Tucker C J, Asrar G, Nemani R R. 1997*a*. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* **386**:698-702.

Muneni R B, Nemani R R, Running S W. 1997*b*. Estimation of global leaf area index and absorbed par using radiative transfer models. *IEEE Transactions on Geoscience and Remote Sensing* **35**:1380-1393.

Sellers P J. 1985. Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing* **6**:1335-1372.

Sellers P J. 1987. Canopy reflectance, photosynthesis and transpiration. II. The role of biophysics in the linearity of their interdependence. *Remote Sensing of Environment* **21**:143-183.

Stark R, Gitelson A A. 1999. Light distribution in field communities of irrigated wheat plants. Proceedings of *The Fourth International Airborne Remote Sensing Conference and Exhibition/21st Canadian Symposium on Remote Sensing*, pp. 321-326.

Stark R, Gitelson A A. 2000. Radiation regime in irrigated wheat. Proceedings of *The Second International on Geospatial Information in Agriculture and Forestry Conference,* pp. 89-96.

Tucker J C. 1979. Red and photographic infrared linear combination for monitoring vegetation. *Remote Sensing of Environment* **8**:127-150.

Tucker J C, Fung I Y, Keeling C D, Gammon R H. 1986. The relationships between atmospheric CO_2 variations and satellite-derived vegetation index. *Nature* **319**:195-199.