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Influence of topography and sensor view angles on NIR/red ratio and greenness vegetation indices of wheat

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Abstract. Reflectance factors of winter wheat were measured with a ground-based radiometer to determine the effect of topography and sensor view angle on the diurnal behaviour of two spectral vegetation indices. Data are presented for fields with 10° slopes in a topographically complex area of central Italy. The ratio of reflectances in near-infrared (NIR) (0·78 to 0·89 μm) to red (0·63 to 0·69 μm) was less sensitive to field aspect than greenness. However, when nadir and off-nadir view angles were compared for the same aspect, greenness displayed less variability. Field aspect and view angle had less effect on both indices when solar zenith angles were small.

1. Introduction

In many regions of the world, natural vegetation and cultivated crops occur in complex, uneven terrain. To interpret multispectral observations from these areas it is important to understand how solar angles, sensor viewing angles and topography interact to modify multiband spectral indices used for describing vegetative cover. This problem has been discussed for coniferous forests (Smith *et al.* 1980), mixed deciduous woodlands (Justice *et al.* 1981) and short grass pastures (Stohr and West 1985), and procedures to reduce the terrain effect and improve classification accuracies have been proposed. Field data for agricultural crops in hilly regions are limited. However, it is essential if we are to test models of plant canopy reflectance and devise strategies to maximize the utility of remotely-sensed data.

In this Letter we use a ground-based radiometer to examine the behaviour of near-infrared/red ratio and greenness vegetation indices for fields of winter wheat growing in uneven terrain. Measurements were made over a wide range of solar zenith and azimuth angles for nadir and off-nadir viewing directions. This data base simulated, within a short period of time, observations that might require several months and an extensive range of latitudes to acquire by satellite-based sensors.

2. Field site and cultural practices

This experiment was conducted on rainfed wheat at the Istituto Sperimentale per lo Studio e la Difesa del Suolo located 35 km north of Florence at Fagna, Italy (43·98°N, 11·35°E). The site had undulating terrain from 230 to 275 m in elevation. Soils were light-coloured clays (typic Udorthent). Winter wheat (*Triticum aestivum* L. 'Mec') was planted on 7–11 November 1985 in southeast to northwest rows with a nominal 15 cm spacing.

Reflectance factors were obtained on 13 May 1986 for two fields with similar 9° to 10° slopes: the first field had a south–southeast aspect (SSE, azimuth 161°); the second field was oriented towards the west (azimuth 271°). Panicle emergence had begun 4 days earlier and canopy cover exceeded 95 per cent in both fields. On 10 May above-ground biomass was 770 ± 36 and $562 \pm 39\ \mathrm{g\,m^{-2}}$ for the SSE and west fields, respectively. Corresponding green leaf area index (GLAI) values were $5{\cdot}4 \pm 0{\cdot}6$ and $4{\cdot}1 \pm 0{\cdot}6$.

3. Measurement procedures

3.1. *Radiometric observations*

Data were collected with an Exotech Model 100BX† radiometer that was equipped with 15° field-of-view lens and spectral bandpass filters similar to the first four bands of the Landsat Thematic Mapper (TM) radiometer. Only the red (0·63 to 0·69 μm) and NIR (0·78 to 0·89 μm) will be discussed here. The sensor was hand held approximately 1.25 m above the canopy. Three view angles were achieved using an inclinometer mounted on the radiometer: (*a*) nadir, (*b*) 20° off-nadir towards the east; (*c*) 20° off-nadir towards the west. Six spectral observations were averaged for each of three individual 1 × 3 m targets in each field. A measurement sequence over all canopy targets required 12–14 min to complete.

Reflectance data were collected on most clear days during the first 3 weeks of May. A diurnal set obtained 13 times from 07 42 hours until 17 11 hours (local standard time) on 13 May was the most complete, and was representative of data collected at other times. Sky conditions were mostly clear and there was minimal interference to the direct beam solar radiation. Consequently, this set will be discussed in the remainder of this Letter.

Reflectance factors were computed as canopy radiance (at a particular view angle) divided by total irradiance falling upon a horizontal surface. The latter was inferred from a time-based, linear interpolation of measurements over a horizontal, painted halon reference panel (prepared by J. B. Schutt, NASA). Corrections were applied to compensate for the non-Lambertian reflectance properties of the panel (Jackson *et al.* 1987).

3.2. *Computation of vegetation indices*

The near-infrared/red (NIR/red) ratio and greenness were computed from average reflectance factors

$$\text{greenness} = -77{\cdot}05 \times \text{Red} + 63{\cdot}74 \times \text{NIR}$$

where the linear coefficients were derived according to *n*-space procedures of Jackson (1983) from average red and NIR reflectance factors measured 1 week earlier over dense canopies of wheat and soils at Fagna.

† Trade names and company names are included for the benefit of the reader and do not constitute endorsement by the U.S. Department of Agriculture or the CNR, IATA, of Italy.

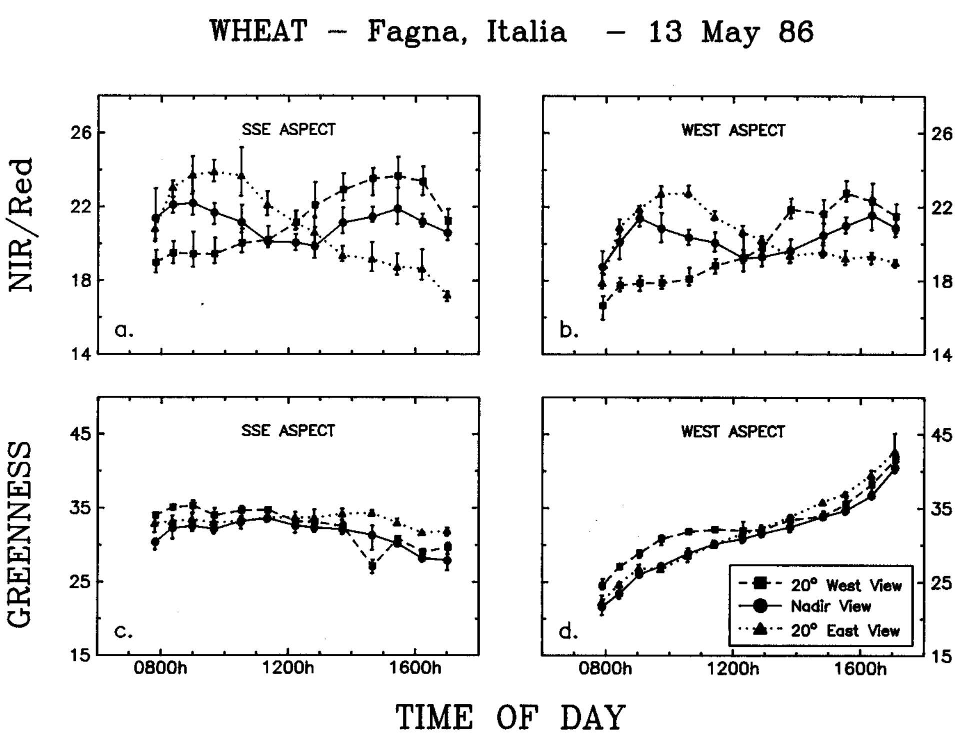
4. Results

4.1. *Band ratio vegetation indices*

Changes in solar angles had a significant impact on the diurnal behaviour of the NIR/red ratio of both fields (figure, (*a*) and (*b*)). Results from the nadir-oriented sensor were similar in amplitude and pattern to those obtained by Pinter *et al.* (1983) for dense canopies of wheat, *T. durum* Desf., in horizontal fields. Maxima were attained mid-morning and mid-afternoon; minima coincided with the high solar position near midday.

Sensor viewing direction was important in determining the magnitude of the ratio despite the full and relatively uniform canopy cover. Off-nadir ratios were significantly different from the nadir view and from each other throughout most of the day. This contradicts laboratory observations that band ratioing tends to normalize for angular changes in viewing geometry (Wardley 1984). Off-nadir ratios were also markedly asymmetric with respect to solar noon (12 11 hours). They were lowest when the sensor was oriented towards the canopy 'hot spot' (ie. pointing west in the morning and east in the afternoon) and highest when viewing in the opposite direction.

Ratios for a given view direction showed parallel diurnal behaviour for both fields. The band ratioing technique minimized topographic effects because terrain-induced changes in red irradiance were accompanied by proportional changes in NIR. Smith *et al.* (1980) reached similar conclusions for non-agricultural targets. Ratios from the



Diurnal NIR/red and greenness vegetation indices computed from ground-based measurements of reflectance factors in TM waveband intervals at Fagna, Italy. Each symbol represents the mean for three wheat targets in each field aspect; vertical bars show the range of measured values.

west aspect remained lower throughout the day, an observation that was consistent with that field's lower green biomass and GLAI.

4.2. *Greenness vegetation indices*

The diurnal behaviour of greenness was quite different (figure, (*c*) and (*d*)). Topographic effects were large, obscuring real differences in biomass and GLAI between the fields and overwhelming the variation caused by sensor view angle. On the west-facing aspect, greenness increased two fold from morning to afternoon and assumed a sigmoidal shape with time of day. The most rapid rise in greenness occurred before 1000 hours and after 1600 hours when the azimuth of the field was aligned with the principal plane of the Sun and rapidly changing zenith angles produced large changes in illumination intensity. Diurnal variation was less extreme in the SSE field because its orientation was more perpendicular to the principal plane of the Sun early and late in the day. Holben and Justice (1980) found a similar response with a nadir-pointing sensor over a non-vegetated sand surface. Greenness values were similar for each field between 12 30 hours and 14 00 hours when the azimuthal differences between Sun and field azimuths were at a minimum.

The reflectance factors we used to compute greenness were determined from irradiances falling on a horizontal surface as opposed to irradiances normal to the surface presented by the canopy. Uneven terrain would produce similar variation in greenness from satellite radiances (ignoring the complex effects of atmospheric transmission and path radiance).

Each viewing direction showed small but consistent differences in greenness through most of the day. Within a given aspect, the nadir view generally produced the lowest values. Off-nadir viewing revealed a 'hot spot' effect that was subdued but opposite from which we observed for the NIR/red ratio. A diffuse jet contrail caused a brief reduction in direct beam solar irradiance during the 20° west viewing measurements of the SSE field at 14 30 hours. It resulted in an abrupt drop in greenness (figure (*c*), 20° west view) that was not seen in the NIR/red ratio, emphasizing another difference between the two types of vegetation indices.

5. Implications

An ideal spectral vegetation index (VI) should retain maximum sensitivity to crop characteristics while being relatively unaffected by solar angles, topography and viewing direction. Since NIR/red and greenness differ markedly in their response to these non-plant parameters, choice of an appropriate VI becomes an important consideration whenever data are collected from ground, air- or space-based platforms.

Our results show that NIR/red ratios for wheat at >95 per cent cover are essentially unaffected by field aspect. They can be used to infer vegetation parameters without an adjustment for terrain-induced illumination changes. However, ratios are sensitive to changing solar angles and off-nadir viewing angles. Thus, day-to-day sequential data acquisitions should be consistent in both these areas.

Linear band combinations such as greenness are strongly affected by terrain. A Lambertian model which includes a cosine response function to compensate for irradiance distribution on sloped fields (Holben and Justice 1980) could be included as a first-order correction to limit variation in greenness and reduce interpretation errors. Off-nadir viewing introduces less variation in greenness than in ratio indices but systematic differences between east and west views persisted and were dependent upon the time of day. Consideration should also be given to appropriate slope, aspect and solar angles when acquiring the initial vegetation and soil reflectances used to derive greenness coefficients.

A better understanding of topographic effects on VIs is becoming more important as additional sensors expand our capability to make observations at various times of the day and with different viewing directions. Our diurnal field data mimic the wide range of solar angles encountered seasonally or at different latitudes from satellites and indicate that terrain and view angle will have less effect on VIs when the solar zenith angles are small. The mid-morning overpass times of Landsat-5 and SPOT can be expected to yield VIs that change with topography and/or viewing direction. Variation should be minimal near the summer solstice and increase during the winter and at high latitudes. Additional complications are introduced by wavelength dependent atmospheric absorption and path radiance (Gerstl and Simmer 1986). These factors can be expected to alter the VI performance in detecting stress and canopy characteristics from satellites (Jackson *et al.* 1983, Jackson and Pinter 1986).

Acknowledgments

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