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A visible band index for remote sensing leaf chlorophyll content at the canopy scale

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ABSTRACT

Leaf chlorophyll content is an important variable for agricultural remote sensing because of its close relationship to leaf nitrogen content. The triangular greenness index (TGI) was developed based on the area of a triangle surrounding the spectral features of chlorophyll with points at (670 nm, R_{670}), (550 nm, R_{550}), and (480 nm, R_{480}), where R_λ is the spectral reflectance at wavelengths of 670, 550 and 480, respectively. The equation is $\mathrm{TGI} = -0.5[(670 - 480)(R_{670} - R_{550}) - (670 - 550)(R_{670} - R_{480})]$. In 1999, investigators funded by NASA's Earth Observations Commercialization and Applications Program collaborated on a nitrogen fertilization experiment with irrigated maize in Nebraska. Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data and Landsat 5 Thematic Mapper (TM) data were acquired along with leaf chlorophyll meter and other data on three dates in July during late vegetative growth and early reproductive growth. TGI was consistently correlated with plot-averaged chlorophyll-meter values at the spectral resolutions of AVIRIS, Landsat TM, and digital cameras. Simulations using the Scattering by Arbitrarily Inclined Leaves (SAIL) canopy model indicate an interaction among TGI, leaf area index (LAI) and soil type at low crop LAI, whereas at high LAI and canopy closure, TGI was only affected by leaf chlorophyll content. Therefore, TGI may be the best spectral index to detect crop nitrogen requirements with low-cost digital cameras mounted on low-altitude airborne platforms.

1. Introduction

Agricultural crops have large nitrogen requirements, but the demand for fertilizer is variable because some nitrogen is supplied by soil biogeochemical processes (Scharf et al., 2002a; Meisinger et al., 2008). Uniform rates of fertilization for a single field may result in large areas having excess nitrogen, which is either leached into the ground water or lost in gaseous forms (e.g. nitrous oxide, a greenhouse gas). As a low-cost alternative to plant or soil sampling, remote sensing of either foliar nitrogen or chlorophyll content may supply information on the spatial variability of soil nitrogen supply (Schepers et al., 1996; Scharf et al., 2002a; Gitelson et al., 2005; Fox and Walthall, 2008; Hatfield et al., 2008; Meisinger et al., 2008).

There are different types of sensors that measure the amount of reflected solar radiation: from low-cost multispectral to high-cost imaging spectrometers, from low spatial to high spatial resolution, and from ground-based to satellite. The forefront of imaging spectroscopy is the estimation of leaf chlorophyll content, leaf nitrogen content, leaf area index (LAI) and other variables by model inversion, including atmospheric and topographic corrections (Botha et al., 2007; Houborg et al., 2009; Jacquemoud et al., 2009; Kokaly et al., 2009; Vohland et al., 2010). Newer techniques for estimating leaf and canopy chlorophyll content use various methods to determine the geometric area bounded by a spectral reflectance curve (Oppelt and Mauser, 2004; Haboudane et al., 2008; Delegido et al., 2010). However, agricultural management generally requires information within very short windows of time (Moran et al., 1997; Pinter et al., 2003). Furthermore, it is uncertain that more detailed information from imaging spectrometers will lead to better decisions for crop nitrogen management, for example, compared to ground-based on-the-go sensors (Shanahan et al., 2008). Digital cameras and aerial photography are low-cost methods used for determining areas with nitrogen deficiency (Blackmer et al., 1996; Adamsen et al., 1999; Scharf et al., 2002a; Dani et al., 2005). However, these low-cost methods need better methods to extract the information desired by managers (Hunt et al., 2005).

Spectral indices are an important method for extracting information from remotely sensed data because indices reduce, but do not eliminate, effects of soils, topography, and view angle (Jackson

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Table 1
Various remote sensing indices related to vegetation cover and chlorophyll content.

Name	Type[a]	Abbrev.	Equation[b]	References
Ratio vegetation index (also called simple ratio)	Red–NIR	RVI	R_n/R_r	Jordan (1969) and Pearson and Miller (1972)
Normalized difference vegetation index	Red–NIR	NDVI	$(R_n-R_r)/(R_n+R_r)$	Rouse et al. (1974) and Tucker (1979)
Soil adjusted vegetation index	Red–NIR	SAVI	$(1+0.5)\,(R_n-R_r)/(R_n+R_r+0.5)$	Huete (1988)
Modified soil adjusted vegetation index	Red–NIR	MSAVI	$0.5\{2 \cdot R_n+1-\surd[(2 \cdot R_n+1)^2-8\,(R_n-R_r)]\}$	Qi et al. (1994)
Optimized soil adjusted vegetation index	Red–NIR	OSAVI	$(1+0.16)\,(R_n-R_r)/(R_n+R_r+0.16)$	Rondeaux et al. (1996)
Enhanced vegetation index	Vis–NIR	EVI	$2.5(R_n-R_r)/(R_n+6 \cdot R_r-7.5 \cdot R_b+1)$	Huete et al. (2002)
Triangular vegetation index	Vis–NIR	TVI	$0.5[120(R_n-R_g)-200(R_r-R_g)]$	Broge and Leblanc (2000)
Second modified triangular vegetation index	Vis–NIR	MTVI2	$1.5[2.5(R_n-R_g)-2.5(R_r-R_g)]/$ $\surd[(2 \cdot R_n+1)^2-6 \cdot R_n-5 \cdot \surd(R_r)-0.5]$	Haboudane et al. (2004)
Chlorophyll vegetation index	Vis–NIR	CVI	$R_n \cdot R_r/R_g{}^2$	Vincini et al. (2008)
Green normalized difference vegetation index	Green–NIR	gNDVI	$(R_n-R_g)/(R_n+R_g)$	Gitelson et al. (1996)
Chlorophyll index – green	Green–NIR	CI-G	R_n/R_g-1	Gitelson et al. (2003)
Normalized green red difference index	Vis	NGRDI	$(R_g-R_r)/(R_g+R_r)$	Tucker (1979)
Green leaf index	Vis	GLI	$(2 \cdot R_g-R_r-R_b)/(2 \cdot R_g+R_r+R_b)$	Louhaichi et al. (2001)
Visible atmospherically resistant index	Vis	VARI	$(R_g-R_r)/(R_g+R_r-R_b)$	Gitelson et al. (2002)
Normalized difference red edge index	RE–NIR	NDREI	$(R_n-R_{re})/(R_n+R_{re})$	Gitelson and Merzlyak (1994)
Chlorophyll index – red edge	RE–NIR	CI-RE	$R_n/R_{re}-1$	Gitelson et al. (2003)
MERIS total chlorophyll index	RE–NIR	MTCI	$(R_{750}-R_{710})/(R_{710}-R_{680})$	Dash and Curran (2004)
Modified chlorophyll absorption reflectance index	Red–RE	MCARI	$[(R_{700}-R_{670})-0.2(R_{700}-R_{550})](R_{700}/R_{670})$	Daughtry et al. (2000)
Transformed chlorophyll absorption reflectance index	Red–RE	TCARI	$3[(R_{700}-R_{670})-0.2(R_{700}-R_{550})(R_{700}/R_{670})]$	Haboudane et al. (2002)
Triangular chlorophyll index	Red–RE	TCI	$1.2(R_{700}-R_{550})-1.5(R_{670}-R_{550}) \cdot \surd(R_{700}/R_{670})$	Haboudane et al. (2008)
Combined index with TCARI	Red–RE–NIR		TCARI/OSAVI	Haboudane et al. (2004)
Combined index with MCARI	Vis–RE–NIR		MCARI/MTVI2	Eitel et al. (2007, 2008)
Triangular greenness index	Vis	TGI	$-0.5[(\lambda_r-\lambda_b)(R_r-R_g)-(\lambda_r-\lambda_g)(R_r-R_b)]$	Hunt et al. (2011)

[a] Indices are grouped based on the major wavelengths used: NIR (n, 760–900 nm), red edge of chlorophyll absorption (re, 700–730 nm), red (r, 630–690 nm), green (g, 520–600 nm), blue (b, 450–520 nm), and visible (vis, 450–690 nm). Red–RE and RE–NIR indices typically use narrow bands, whereas Red–NIR and Vis indices may use either broad or narrow wavebands. Wavelength ranges for overlapping digital camera bands are: red 580–670 nm, green 480–610 nm, and blue 400–520 nm (Hunt et al., 2005).

[b] R_λ is the reflectance at wavelength λ; R_n, R_{re}, R_r, R_g, and R_b are the reflectances for NIR, RE, red, green, and blue bands, respectively.

and Huete, 1991; Hatfield et al., 2004, 2008; Hatfield and Prueger, 2010). Spectral indices are also an important method for analyzing imaging spectrometer data (Gitelson, 2012; Zhu et al., 2012). Visible and near-infrared spectral indices are sensitive to both chlorophyll content and LAI (Gitelson et al., 2002; Baret et al., 2007), so development of better indices with increased sensitivity to chlorophyll and decreased sensitivity to LAI may help fertilizer management for crops.

Most spectral indices today are calculated using ratios or normalized differences of two or three bands (Table 1), although originally, there was more diversity among spectral indices (Jackson and Huete, 1991). Broge and Leblanc (2000) developed the triangular vegetation index (TVI) based on the area of a triangle with vertices at green, red and NIR wavelengths (Table 1), which is sensitive to both chlorophyll content and LAI. In order to predict leaf nitrogen status, Haboudane et al. (2008) created the triangular chlorophyll index based on green, red and red-edge (710–730 nm) bands. Red-edge bands are deployed on many satellite sensors (Eitel et al., 2007; Herrmann et al., 2011; Ramoelo et al., 2012) and increase sensitivity to chlorophyll content (Gitelson et al., 2005; Gitelson, 2012). However, red-edge bands are generally not available on low-cost multispectral sensors, which have broad bands at visible wavelengths; therefore, a visible-band index called the triangular greenness index (TGI) was developed (Hunt et al., 2011).

In 1999, a group of investigators funded by the NASA Earth Observations Commercialization and Applications Program (EOCAP) pooled resources and conducted a nitrogen fertilization experiment with irrigated maize at Shelton, NE USA. Using Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data from the experiment, derivative indices were evaluated by Estep and Carter (2005) and other spectral indices were evaluated by Perry and Roberts (2008). We used datasets acquired during this experiment to test the response of TGI to leaf chlorophyll content and to compare the results with other vegetation and chlorophyll indices.

2. Methods

2.1. Study site and experimental design

On 29 April 1999, maize (*Zea mays* L) was planted in an irrigated 64-ha field (40°45′39″N, 98°43′35″W) near Shelton, Nebraska, USA (Fig. 1). The east–west rows were spaced 0.76 m apart and the average plant density for the field was 8.3 m^{-2}. The dominant soil types were a Hord silt loam (fine-silty, mixed, mesic, Pachic Haplustoll) and a Blendon loam (coarse-loamy, mixed, superactive, mesic, Pachic Haplustoll). At planting, 20 kg N ha^{-1} (as liquid ammonium polyphosphate) was applied along each planted row at a soil depth of 5–10 cm.

Twenty plots (75 m × 90 m) with different levels of applied nitrogen fertilizer were established along the center of the field in a randomized complete block design with four replications (Fig. 2). On 5 June 1999, sidedress fertilizer of 0, 50, 100, 150 or 200 kg N ha^{-1} (as anhydrous ammonia) was applied to one plot in each block. During the sidedress fertilization, a mistake was made in programming the variable rate applicator; two applicator passes in the odd numbered plots received the treatment from the even-numbered plot directly north (Fig. 2). Two plots were left bare on the east and west edges of the field to serve as calibration targets.