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Estimating and mapping chlorophyll content for a heterogeneous grassland: Comparing prediction power of a suite of vegetation indices across scales between years

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ABSTRACT

This study investigates the performance of existing vegetation indices for retrieving chlorophyll content for a semi-arid mixed grass prairie ecosystem across scales using *in situ* data collected in 2012 and 2013. A 144 published broadband (21) and narrowband (123) vegetation indices are evaluated to estimate chlorophyll content. Results indicate that narrowband indices utilize reflectance data from one or more wavelengths in the red-edge region (~690–750 nm) perform better. Broadband indices are found to be as effective as narrowband indices for chlorophyll content estimation at both leaf and canopy scales. The empirical relationships are generally stronger at the canopy than the leaf scale, attributable to the fact that leaf samples are collected during the peak growing season when chlorophyll in plant species are uniform. SPOT-5 and CASI-550 derived chlorophyll maps result in map accuracies of 63.56% and 78.88% respectively. The assessment of vegetation chlorophylls at the canopy level, especially using remote sensing imagery is important for providing information pertaining to ecosystem health such as the physiological status, productivity, or phenology of vegetation.

1. Introduction

Vegetation pigments are integrally related to the physiological function and health of vegetation and are thus of great importance in the biosphere. Vegetation chlorophyll is also an indicator of net primary production (Curran et al., 1990; Filella et al., 1995; Blackburn, 2007), stress physiology (Gitelson and Merzlyak, 1994a, 1994b; Peñuelas and Filella, 1998; Merzlyak et al., 1999; Netto et al., 2005), and an indirect measure of nutrient status (Filella et al., 1995; Moran et al., 2000). Methods for predicting and estimating vegetation chlorophyll are based on light-vegetation interactions that have been in development for several decades and quantified using remote sensing (Card et al., 1988; Peterson et al., 1988; Curran, 1989). The empirical-statistical approach is most often used to estimate chlorophyll content because of its simplicity and computational efficiency, requiring minimal input information to establish a relationship between remote sensing data (i.e., vegetation index (VI) derived from reflectance spectra) and ground data (i.e., leaf chlorophyll).

VIs developed and formulated for the estimation of chlorophyll have been based on reflectance or transmittance measurements and empirically correlated to chlorophyll (Blackburn, 1998a; Datt, 1999a; Maccioni et al., 2001; Vogelmann et al., 1993). Three primary types of VIs for chlorophyll estimation include simple ratio (SR), normalized difference (ND), and red-edge. SR and ND indices typically comprise of a reflectance value from a reference wavelength in the near infrared (NIR) region (750–950 nm) that accounts for vegetation structure, and a reflectance from an index wavelength in the red to near red-edge region (660–720 nm) that is sensitive to chlorophyll (Sims and Gamon, 2002). Red-edge indices are based on the reflectance from the inflection point in the red-edge region between 680 and 780 nm, which is the position of the wavelength that marks the transition between the low reflectance in the red to the high reflectance in the NIR (Gates et al., 1965; Collins, 1978; Horler et al., 1983; Buschmann and Nagel, 1993). Similar to red-edge indices, derivative indices (e.g., Boochs et al., 1990; Penuelas et al., 1994) are calculated using wavelengths in the red-edge region at the slope of the reflectance spectra, typically in the first derivative. They have been suggested to correct for variations caused by leaf surface scattering, bidirectional reflectance distribution function (BRDF) effects, and background noise (Vogelmann et al., 1993).

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The spectral and spatial resolution of conventional multispectral space-borne image data is often inadequate to accurately assess chlorophyll. In recent decades, advances in hyperspectral sensors have enabled the development of narrowband greenness VIs, which has become the most suitable avenue for the study of chlorophyll. These narrowband greenness indices can effectively distinguish discrete vegetation biochemical properties such as chlorophylls as they exploit certain narrow wavelength bands corresponding to its peak absorption in the red to near red-edge region. Numerous VIs have been developed to exploit these wavelength bands, especially those based on SR (e.g., Gitelson and Merzlyak, 1996a; Datt, 1998) and ND (e.g., Gitelson et al., 1996b; Blackburn, 1998a). Greenness VIs based on more complex algorithms and band combinations include the modified chlorophyll absorption ratio index (MCARI; Daughtry et al., 2000) which was further developed as the transformed chlorophyll absorption ratio index (TCARI; Haboudane et al., 2002). MCARI and TCARI were combined with the optimized soil-adjusted vegetation index (OSAVI) to create an integrated index, MCARI/OSAVI and TCARI/OSAVI (Daughtry et al., 2000; Haboudane et al., 2002, 2008) to further reduce background noises and enhance sensitivity to chlorophyll.

Similar to the narrowband greenness indices are ones specifically formulated for carotenoid/anthocyanin estimation and stress detection. Since chlorophylls are the primary pigments responsible for photosynthesis, carotenoid and anthocyanin pigments are essential leaf structural components and complementary to the photosynthetic process (Davies, 2004; Blackburn, 2007). Accordingly, narrowband indices formulated for carotenoids (e.g., Blackburn, 1998a) and to a lesser extent, anthocyanins (e.g., Gitelson et al., 2001) may serve as an indirect measure of chlorophyll. Similarly, indices formulated for stress detection (e.g., Carter, 1994) can be directly linked to chlorophyll content as the variation in total chlorophyll/carotenoid ratio is related to plant stress physiology. Chlorophylls tend to decline more rapidly than carotenoids under environmental stress (e.g., drought) and during leaf senescence; hence as concentrations of carotenoids increases, chlorophylls generally decrease (Gitelson and Merzlyak, 1994a, 1994b; Peñuelas and Filella, 1998; Merzlyak et al., 1999).

Most empirical-statistical approaches have been used at the leaf scale between indices derived from leaf level reflectance spectra and a leaf pigment of interest, especially chlorophyll, for a wide range of species and ecosystems (Vogelmann et al., 1993; Blackburn, 1998a; Datt, 1999a; Maccioni et al., 2001). However, much difficulty remains for the spatial and temporal extrapolation of leaf level relationships to the canopy and larger scales (Zhang et al., 2008). This is a result of the differences in the photon-vegetation interactions at the leaf and canopy levels (Zarco-Tejada et al., 2000; Houborg et al., 2007; Zhang et al., 2008; Croft et al., 2014). Empirical relationships at the canopy or higher level are site, time and species specific, lacking robustness and portability when transferring them from one area, time, and species to another (Baret and Guyot, 1991; Houborg et al., 2007).

Further development has been focused on improving the generality and applicability of VIs for measuring vegetation chlorophyll content at larger scales. Scaling chlorophyll from the leaf to canopy scale has been performed using the direct extrapolation method (Peterson et al., 1988; Yoder and Pettigrew-Crosby, 1995; Zagolski et al., 1996), and canopy-integrated method (Gamon et al., 1993) by using LAI (Darvishzadeh et al., 2008; Ciganda et al., 2009), biomass (Yoder and Pettigrew-Crosby, 1995; Jago et al., 1999), or percent cover-based method (Wong and He, 2013) as a scaling parameter. Whereas the direct extrapolation and canopy-integrated methods consider a single species within a canopy, only the percent cover-based method considers multiple species within a canopy.

At present, most research that focused on estimating vegetation chlorophyll at the leaf and canopy scale has been for precision agriculture or forests and only limited attempts have been made for heterogeneous grassland ecosystems. A few recent grassland chlorophyll estimation works are reviewed here. Darvishzadeh et al. (2008) estimated leaf and canopy chlorophyll content for a heterogeneous Mediterranean grassland and determined that narrowband NDVI and the soil adjusted vegetation index 2 ($SAVI_2$) performed the best in comparison to methods using the red-edge inflection point. Rossini et al. (2012) estimated temporal grassland chlorophyll for a subalpine grassland using a suite of vegetation indices and found a high correlation of over 0.8 between leaf chlorophyll content and narrowband spectral indices. Furthermore, Wong and He (2013) tested the utility of SR, both the broadband [R, NIR] and narrowband [700, 750] versions for a heterogeneous tallgrass prairie and found the prediction power of the vegetation index SR is acceptable. From these studies, the authors only applied and tested a limited number of spectral indices. As a consequence, the utility of using other spectral indices is unknown for a grassland ecosystem.

The assessment of vegetation chlorophylls for grasslands at both leaf and canopy levels is necessary, as studies at these scales can provide important information pertaining to ecosystem health such as the physiological status, productivity, or phenology of vegetation. The objective of this study is thus to evaluate the performance of existing spectral indices for estimating vegetation chlorophyll content for a mixed grass prairie ecosystem. The specific aim was to assess the ability of spectral indices to predict vegetation chlorophyll content at the leaf level using leaf level measurements and at the canopy level using field based measurements and remote sensing images across species over time.

2. Methods

2.1. Study area

The study area was located in the West Block of the Grasslands National Park (GNP) (49°129′N, 107°249′W) in southwestern Saskatchewan, Canada (Fig. 1). This area is defined as a semi-arid, mixed grass prairie ecosystem which falls within the northern extent of the Great Plains (He, 2014). The park was established in 1988 to conserve and protect a portion of the remaining natural grasslands once so extensive in southwestern Saskatchewan. The climate in the study area is typical of a semi-arid environment; long, cold, and dry winters, short and hot summers, and low precipitation regimes (Parks Canada, 2011). Mean annual temperature is approximately 4.1 °C and ranges from −10.8 °C in January to 18.5 °C in July, while mean annual precipitation is approximately 352.5 mm based on the 1981–2010 climate normal (Environment Canada, 2014).

The soils are predominately brown Chernozemic clay to clay loam soils according to the Canadian System of Soil Classification (Saskatchewan Institute of Pedology, 1992). The dominant native grass species found in the study area were junegrass (*Koeleria gracilis*), needle-and-thread grass (*Stipa comata*), blue grama (*Bouteloua gracilis*), western wheatgrass (*Agropyron smithii*), and northern wheatgrass (*Agropyron dasystachym*). A non-native invasive grass species, crested wheatgrass (*Agropyron cristatum*) was also a dominant type found in the study area.

2.2. Overview of the methodology

The estimation of chlorophyll content at the leaf and canopy scales using the empirical-statistical approach involved relating chlorophyll content to VIs derived from lab, field, and image