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Original Research Article

The applicability of empirical vegetation indices for determining leaf chlorophyll content over different leaf and canopy structures

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ABSTRACT

Retrieving leaf chlorophyll content at a range of spatio-temporal scales is central to monitoring vegetation productivity, identifying physiological stress and managing biological resources. However, estimating leaf chlorophyll over broad spatial extents using ground-based traditional methods is time and resource heavy. Satellite-derived spectral vegetation indices (VIs) are commonly used to estimate leaf chlorophyll content, however they are often developed and tested on broadleaf species. Relatively little research has assessed VIs for different leaf structures, particularly needle leaves which represent a large component of boreal forest and significant global ecosystems. This study tested the performance of 47 published VIs for estimating foliar chlorophyll content from different leaf and canopy structures (broadleaf and needle). Coniferous and deciduous sites were selected in Ontario, Canada, representing different dominant vegetation species (*Picea mariana* and *Acer saccharum*) and a variety of canopy structures. Leaf reflectance data was collected using an ASD Fieldspec Pro spectroradiometer (400–2500 nm) for over 300 leaf samples. Canopy reflectance data was acquired from the medium resolution imaging spectrometer (MERIS). At the canopy level, with both leaf types combined, the DD-index showed the strongest relationship with leaf chlorophyll ($R^2 = 0.78$; RMSE = 3.56 μg/cm^2), despite differences in leaf structure. For needleleaf trees alone the relationship with the top VI was weaker ($D_{[red]}$, $R^2 = 0.71$; RMSE = 2.32 μg/cm^2). A sensitivity study using simulated VIs from physically-modelled leaf (PROSPECT) and canopy (4-Scale) reflectance was performed in order to further investigate these results and assess the impacts of different background types and leaf area index on the VIs' performance. At the leaf level, the MNDVI8 index showed a strong linearity to changing chlorophyll and negligible difference to leaf structure/type. At canopy level, the best performing VIs were relatively consistent where LAI ≥ 4, but responded strongly to differences in background at low canopy coverage (LAI = 2). This research provides comprehensive assessments for the use of spectral indices in retrieval of spatially-continuous leaf chlorophyll content at the leaf (MTCI: $R^2 = 0.72$; $p < 0.001$) and canopy (DD: $R^2 = 0.78$; $p < 0.001$) level for resource management over different spatial and temporal scales.

1. Introduction

The amount of solar radiation absorbed by a leaf is largely a function of the foliar concentrations of photosynthetic pigments, with Chlorophyll *a* and *b* playing a crucial role in the conversion of solar radiation into stored chemical energy through photosynthesis. Consequently, low chlorophyll concentrations can directly limit photosynthetic potential and hence primary production (Richardson et al., 2002). This pivotal role of chlorophyll in photosynthesis and net primary productivity is therefore a driving force for obtaining spatially-continuous chlorophyll content inputs at a variety of spatial and temporal scales to regional and global carbon models (Inoue, 2003). Foliar chlorophyll is strongly related to leaf nitrogen content (Daughtry et al., 2000) and acts as a bio-indicator of plant physiological condition; highlighting regions of plant disturbance and stress (Gitelson et al., 2003; Sampson et al., 2003). Understanding differences in the physiological response of leaf chlorophyll to changing biotic and abiotic factors between and within species is also important to resource management (Richardson et al., 2002). The accurate retrieval chlorophyll content at different spatiotemporal scales is crucial for the effective monitoring and understanding a number of ecosystem responses. Remote sensing plays a unique role in the ability to provide spatially-continuous data at fine temporal intervals and across broad spatial extents.

Leaf reflectance is controlled by the presence of foliar constituents such as chlorophyll, nitrogen, carotenoids, and water (Ustin et al., 2004). In visible wavelengths, chlorophyll absorbs

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strongly in red and blue spectral regions, with maximum absorbance between 660 and 680 nm and maximum reflectance in green wavelengths (560 nm). Internal leaf structure also affects the amount of incident radiation absorbed, scattered and reflected through the upper epidermis, due to refractive discontinuities between intercellular air spaces and cell walls (Blackburn, 2006). Broadleaves have a thin epidermal layer, long palisade cells and more air spaces surrounding spongy mesophyll cells, whereas cylindrical needle leaves have an undifferentiated, densely packed mesophyll and thick cell walls (Ollinger, 2011). Research has suggested that NIR reflectance is controlled by the ratio of mesophyll cell surface to intercellular air spaces (Serrano, 2008). As such, differences in needleleaf and broadleaf reflectance spectra could exist even with the same chlorophyll content; making chlorophyll content estimation across plant functional types complex. At the canopy level, reflectance is also governed by leaf architecture, leaf area index (LAI), clumping, leaf angle distribution, tree density, non-photosynthetic canopy elements (Croft et al., 2013; Demarez and Gastellu-Etchegorry, 2000; Simic et al., 2011), along with solar/viewing geometry, ground cover and understory vegetation (Broge and Leblanc, 2001). Conifer canopies reflect less NIR radiation than broadleaf canopies, which is a function of the optical properties of the leaves, non-photosynthetic elements and leaf angle distribution. Vertical leaves promote a deeper penetration of incident radiation within the canopy, where multiple scattering within the crown allows for a higher probability of photon absorption (Ollinger, 2011). It is also therefore possible that reflectance factors from two forest canopies are different even if the spectral reflectance of the constituent leaves is the same (Blackburn, 1998).

Empirical spectral vegetation indices (VIs) are perhaps the most popular and straightforward means of retrieving chlorophyll content from reflectance factors. Spectral indices are formulated using ratios of wavelengths that are sensitive to a particular leaf pigment or to spectral regions where scattering is mainly driven by leaf internal structure or canopy structure (Blackburn, 2006). Recent research has focussed on improving the generality and applicability of spectral indices, through testing and modification over a range of species and physiological conditions, using empirical and simulated data (Blackburn, 2006). Most VIs are based on reflectance from wavelengths in the visible, NIR and around the red-edge, although some also contain exclusively visible wavelengths (Filella et al., 1995; Gitelson et al., 2002). Sims and Gamon (2002) analyzed nearly 400 leaf samples from 53 species, finding that leaf surface reflectance was an important factor in weak relationships between VIs and chlorophyll content. Le Maire et al. (2004) found that a modified simple ratio (mSR705) accounted for surface scattering on an experimental database (53 leaves) and a simulated database (>11,000 spectra), although the VI showed a dependence on leaf water content (Serrano, 2008). Whilst there has been considerable research devoted to deriving statistical relationships between leaf optical properties and chlorophyll content, they have often been developed and tested using a few closely related species, at the leaf scale and under controlled laboratory conditions (Blackburn, 1998; Gamon and Surfus, 1999; Gitelson et al., 2003; Le Maire et al., 2004). Fewer studies still have addressed the effect of leaf anatomical characteristics on leaf and canopy reflectance and chlorophyll content estimation (Serrano, 2008). It is important to assess the accuracy of VIs across different functional scales, leaf structures, and with additional canopy variables for their implementation within a reliable forest management programme. This is particularly relevant for trees with needle leaves, which have seen little focus or investigation in terms of using VIs to derive leaf chlorophyll content. Most studies relating empirical vegetation indices to chlorophyll content have focussed on broadleaves, at either the leaf or canopy scale, limiting their application and validation to specific plant functional types and observational scales.

This paper will assess the performance of VIs within and across leaf types and at different spatial sampling units (leaf and canopy), using empirical data and simulated data from radiative transfer models. The simulation of leaf and canopy data through physical models (PROSPECT; Jacquemoud and Baret, 1990 and 4-Scale; Chen and Leblanc, 1997) allows the testing of a greater range of chlorophyll values and canopy conditions, including the important influence of background composition and leaf area index. It also helps to validate and better understand the performance of VIs for the empirical dataset. A fundamental notion is to investigate how well these current techniques can be applied across species and leaf structures, in order to assess the contribution of other variables at leaf and canopy levels.

The specific aims of this research are to:

i. evaluate the accuracy of a comprehensive set of empirical indices for retrieving chlorophyll content from different leaf structures (broadleaf and needleleaf);
ii. assess the ability of empirical indices to predict leaf chlorophyll content at leaf-level from ground based measurements and canopy-level from remotely sensed data;
iii. determine the sensitivity of VIs to chlorophyll content across different LAI values and background contributions.

2. Methods

2.1. Field locations and data collection

Two field locations were selected representing broadleaf deciduous and needleleaf coniferous vegetation sites. Field sampling was conducted in 2004 in a mature broadleaf sugar maple (*Acer saccharum* M.) stand located in Haliburton Forest, Ontario Canada (45°14′16″ N, 78°32′18″ W). Haliburton forest falls within the Great-Lakes – St.-Lawrence region (Rowe, 1972), with an average annual precipitation of approximately 1050 mm and mean annual temperature of 5 °C (Gradowski and Thomas, 2006). The upland hardwood forests of Haliburton Forest are dominated by sugar maple but also contain beech (*Fagus grandifolia* Ehrh.), eastern hemlock (*Tsuga canadensis* (L.) Carr.), and yellow birch (*Betula alleghaniensis* Britt.) (Caspersen and Saprunoff, 2005). The site is underlain by shallow brunisols or juvenile podzols, (pH 4.2–5.1); mainly silty sands from Precambrian Shield granite or granite-gneiss deposits (Gradowski and Thomas, 2006). Ground-based measurements were carried out 8 times throughout the growing season from 27th May to 30th September, which are indicated in Table 1 by the day of year (DOY) within the site ID (see Zhang et al., 2007 for a more detailed description). Leaf samples were collected from the top of tree crowns within a 50 m × 20 m area, considered to be representative of the stand.

Eight sites in a coniferous forest located northwest of Sudbury, Ontario (46°49′13″ N to 47°12′9″ N and 81°22′2″ W to 81°54′30″ W) were sampled in the summer of 2003 and 2004 (Zhang et al., 2008a,b). The sites contain mature black spruce (*Picea mariana*) stands of different ages, crown closures and health condition, underlain by shallow soils on Canadian Shield bedrock. Leaf samples were taken from the top of tree canopies within a 20 m x 20 m area considered representative of the selected stands. Temperatures range from −40 °C to 30 °C and average summer rainfall is 71.3 mm, with snow-covered ground from December to March (Rayfield et al., 2005). Other local tree species include jack pine (*Pinus banksiana*) and Aspen (*Populus tremuloides* Michx). Table 1 details the study sites used in this research, including their