Remote Sensing of Environment 169 (2015) 270–279

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Estimation of foliar chlorophyll and nitrogen content in an ombrotrophic bog from hyperspectral data: Scaling from leaf to image

M. Kalacska *, M. Lalonde, T.R. Moore

Department of Geography and Global Environmental & Climate Change Centre, McGill University, 805 Sherbrooke Street West, Montréal, QC H3A 0B9, Canada

ARTICLE INFO

Article history:
Received 24 December 2014
Received in revised form 25 July 2015
Accepted 13 August 2015
Available online xxxx

Keywords:
Peatland
Airborne hyperspectral
Foliar chlorophyll
Nitrogen
CASI
Ombrotrophic bog

ABSTRACT

The relationship between spectral reflectance and foliar chlorophyll (Chl) and nitrogen (N) was examined for 19 species over a six-month growing period at Mer Bleue, an ombrotrophic bog located near Ottawa, Ontario, Canada. The goal of this study was to model total Chl and N concentration at the landscape-scale from remotely sensed data utilizing a model insensitive to plant functional type (PFT), species and season. To date the relationship between spectral reflectance and foliar properties is poorly understood in peatlands owing to the scarcity of studies examining the spectral variability between mosses and vascular plants. A model that comprised a continuous wavelet transform coupled with a neural network was constructed to predict Chl and N content from selected wavelet features (coefficients) at both leaf and airborne image scales. The model was compared to thirteen common spectral indices used to determine vegetation properties in forest environments. The heterogeneity of the vascular plant/moss cover over small spatial scales (<1 m) and the spectral complexity of the vegetation cover, precluded a regression model to be derived from the spectral indices for all species across seasons; the best model for all species combined was $R^2 = 0.3$. The final continuous wavelet model resulted in a noticeable improvement with R^2 values ranging from 0.8 to 0.9 (for both Chl and N content). We scaled up our predictive model from the leaf/capitulum level data to 40 cm spatial resolution 72-band airborne imagery (CASI-2 429.6–968.8 nm) to create surfaces of Chl and N content for the study area.

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1. Introduction

Northern peatlands cover only about 3% of the global land surface, but they store approximately one-third of the global soil carbon pool (Loisel et al., 2014). Peatlands remove atmospheric CO_2 through sequestration and subsequent peat accumulation, and despite also releasing methane, peatlands have been shown to contribute to net radiative cooling over the past 10,000 years (Frolking & Roulet, 2007). Due to cold, nutrient-limited, waterlogged, anoxic soils, northern peatlands have slow rates of plant production and decomposition (Akumu & McLaughlin, 2014; Kurz et al., 2013; Wu & Roulet, 2014). In this wetland type the production of plant matter exceeds decomposition resulting in an accumulation of organic material (i.e. peat). However, as climate change scenarios predict more intensive warming effects at high latitudes, increased plant production is expected along with faster decomposition rates of organic matter stored in peatlands (Loisel et al., 2014). Simulation models of carbon dynamics showed that northern peatlands (bogs and fens) could undergo significant changes to their carbon cycling under various climate change scenarios where they become either reduced sinks or may switch to become sources (Wu & Roulet, 2014).

Foliar pigments (e.g. chlorophyll (Chl)) and nitrogen (N) play an important role in controlling carbon exchange and plant productivity; both have been successfully estimated from remotely sensed data at the leaf and ecosystem levels in forests, where there is a limited range of tissue types (leaves and needles) (e.g. Martin, Plourde, Ollinger, Smith, & McNeil, 2008; Ollinger & Smith, 2005; Ollinger et al., 2002; Smith et al., 2002). In contrast, peatlands have a broader range of plant functional types (PFT), which vary from trees and shrubs (leaves and needles) through sedges to mosses. Martin et al. (2008) conclude that further development in predictive models of foliar N estimates is necessary by inclusion of a wider range of ecosystems beyond forest types. Yet, comparatively few remote sensing studies have been conducted in peatlands. Furthermore, little is known about the nitrogen budget in northern peatlands (Loisel et al., 2014).

A number of studies utilizing remotely sensed imagery have focused on peatland classification (e.g. Cole, McMorrow, & Evans, 2014a,b; Middleton et al., 2012), PFT characterization (e.g. Akumu & McLaughlin, 2014; Harris, Charnock, & Lucas, 2015), and biophysical models (Kross, Seaquist, Roulet, Fernandes, & Sonnentag, 2013; Watts et al., 2014) in order to infer biotope abundances, carbon stocks, floristic gradients and exchange rates respectively. Limited studies have also examined the sensitivity of spectral vegetation indices (SVIs) to CO_2 flux (Letendre, Poulin, & Rochefort, 2008), chlorophyll fluorescence (Van Gaalen, Flanagan, & Peddle, 2007) and individual species pigment

* Corresponding author.
E-mail address: margaret.kalacska@mcgill.ca (M. Kalacska).

http://dx.doi.org/10.1016/j.rse.2015.08.012
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contents (Nichol & Grace, 2010). A fundamental complication for remote sensing studies conducted in peatlands arises from the spatial variability in species composition (both vascular and mosses) at small spatial scales (<1 m). Therefore, models constructed to retrieve foliar properties on a species by species basis cannot be applied at the landscape-scale where individual pixels are mixtures of a number of different species. In addition, the phenology of the various species is highly variable across the growing season. Cole et al. (2014b) found that the optimal timeframe for remote observation and inference of peatland vegetation is species dependent owing to phenological differences. This poses logistical challenges to landscape-scale inferences of peatland characteristics, such as the retrieval of pigment concentrations, because multi-temporal hyperspectral imagery at fine scales (<1 m) is presently available from airborne platforms, which can be difficult to obtain as a time series.

The goal of this study was to model total chlorophyll (Chl_{tot}) and N concentration at the landscape-scale in a peatland from remotely sensed data. More specifically, we sought to derive a model insensitive to PFT, species and season, and fundamentally to scale up our predictive model from the leaf/capitulum level to airborne imagery.

2. Methods

2.1. Study area

The study was conducted at Mer Bleue, an ombrotrophic bog located near Ottawa, Ontario, Canada (45.41 N; 75.52 W). The surface has a hummock–lawn–hollow micro-topography, with a mean relief difference of 25 cm between hummocks and hollows (Lafleur, Hember, Admiral, & Roulet, 2005). *Sphagnum capillifolium* dominates hummocks, *S. magellanicum* dominates lawns, *S. angustifolium* and *S. fallax* co-dominate hollows and *Polytricum strictum* occurs throughout. The sparse tree cover comprised *Betula populifolia*, *Larix laricina*, *Picea mariana* and *Pinus strobus*. The shrub cover includes both evergreen (*Chamaedaphne calyculata*, *Kalmia angustifolia* and *Rhododendron groenlandicum*) and deciduous species (*Vaccinium myrtilloides*). Deciduous herbs, such as *Eriophorum vaginatum* and *Maianthemum trifolium* are also fairly common. Within the marginal lagg areas of the bog, deciduous herbs such as *Typha latifolia*, *Calla palustris* and *Eleocharis smallii* can be found with *S. majus* in the beaver pond and *S. fallax* at the edges.

2.2. Field spectra

Ten leaves (vascular) or capitula (mosses) were sampled monthly from May to October 2009 for *B. populifolia*, *L. laricina*, *C. calyculata*, *K. angustifolia* and *R. groenlandicum*, *E. vaginatum* and *S. capillifolium*, *S. magellanicum*, *S. angustifolium*, *S. fallax* and *P. strictum*. Samples of *V. myrtilloides*, *M. trifolium* and *T. latifolia* were collected monthly from June to October, *P. mariana* and *P. strobes* needles were sampled in May, July and October, and *C. palustris* and *E. smallii* were sampled monthly from June to September resulting in a total of 890 spectra collected from 19 species over a six-month period. Each leaf and capitulum was sampled from different individuals. The samples were excised from the plants and stored in a plastic bag to prevent desiccation prior to spectral measurements (Foley, Rivard, Sanchez-Azofeifa, & Calvo, 2006).

Leaf/capitulum-level reflectance was measured within one hour of collection using an ASD FieldSpec hand-held spectrometer (Analytical Spectral Devices Inc, Boulder, CO) spanning the 325 to 1075 nm range. The spectrometer was fitted with a plant probe, which contains an internal halogen light source (10 mm spot size) and a leaf clip to hold samples in place, exclude ambient light, and ensure constant lighting and viewing geometry. Apparent sample reflectance was calculated as the ratio between each sample spectrum and a white reference spectrum of Spectralon™.

Plot level spectra were collected at twenty-six field plots at a height of 1 m above the surface of the bog using a 25° FOV bare fiber, within two hours of solar noon on clear days resulting in an effective circular target area of 44 cm diameter. Plot coordinates were recorded with a Garmin 60CSx GPS with a spatial accuracy of 3 m. Eight of the field plots fell within the airborne imagery (described below). Measurements were made on August 12th, two days prior to the airborne image acquisition. The species composition of the plots was recorded whereby each 1936 cm^2 (44 × 44 cm) plot was subset into 34 subplots in which the dominant species was logged. A standard rarefaction curve using species presence/absence data was calculated using EstimateS version 9.1.0 (Colwell, 2013).

2.3. Foliar chlorophyll and nitrogen content

Foliar Chl was extracted from a subset of five leaves/capitula of each species from each monthly collection (same leaves that were measured with the spectroradiometer) with a dimethyl sulphoxide (DMSO) extraction (Hiscox & Isrealstram, 1979). Samples from vascular plants where the units of Chl_{tot} were measured in mg cm^{-2} were converted to be consistent across all species (i.e. mg g^{-1}). A separate ten leaves/capitula per species (total across all months) were oven-dried at 60 °C for 12 h, ground into powder and N concentration (mg g^{-1}) was determined on an elemental analyzer (Leco CNS 2000, Leco Corporation, St. Joseph, Michigan, USA).

2.4. Airborne imagery

A Compact Airborne Spectrographic Imager 2 (CASI-2) hyperspectral image was acquired over the study area on August 14, 2009 by the National Research Council of Canada's, Flight Research Laboratory, Twin Otter aircraft (NRC-FRL). The CASI-2 is a pushbroom system with up to 512 spatial pixels across the flight line covering a FOV of 37.8°. However, for this application we chose the 'extended spectral' mode, which resulted in 406 spatial pixels (sum by 4) (FOV 28.9°). The image was collected at an altitude of 412 m AGL, at 90 knots with an integration time of 32 ms (212.9 m flight line width). With those parameters the imagery resulted in 72 bands ranging from 429.6 to 968.8 nm with a FWHM ranging from 3.7 to 3.8 nm and a pixel size of 38.8 cm (across track) and an along track spacing of 1.48 m. A second flight line with the same band configuration was collected over the NRC-FRL campus (15 km from Mer Bleue) for calibration and data quality assessment purposes.

The first step in the preprocessing consisted of converting the raw digital numbers to radiance (μW m^{-2} nm^{-1} sr^{-1}) via in-lab generated radiometric correction coefficients followed by a smile correction. These data were calibrated to reflectance with the FLAASH (Fast Line of Sight Atmospheric Analysis of Spectral Hypercubes) atmospheric correction module in ENVI 4.8 resulting in ground reflectance (Anderson et al., 1999). The Mid-Latitude Summer atmospheric model was chosen along with the rural aerosol model for the atmospheric correction. The first three and last three bands (poor responsivity bands) were removed resulting in a spectral range of 451–946 nm (66 bands).

To assess the quality of the atmospheric correction, in-situ spectra of a concrete tile from the airport hangar apron collected coincident with the acquisition of the NRC-FRL line (SVC HR-1024 spectrometer (Spectra Vista Corporation, Poughkeepsie, NY, USA)), were compared to the reflectance of the same tile in the image. Comparison of the reflectance from the concrete tile collected in-situ and the atmospherically corrected image resulted in an agreement within 3.0–6.5% across the wavelength range.

Geocorrection was undertaken using programs developed by ITRES Research Ltd, the sensor manufacturer, implemented by NRC-FRL, resulting in a resampled spatial resolution of 40 cm. The positional accuracy of the geocorrection of both lines was assessed through comparison to a 20 cm spatial resolution color orthophoto. The RMSE was determined to be 1.77 m for the Mer Bleue study area image and 1.63 m for the NRC-FRL campus image. Because the two flight lines

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