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Examining spectral reflectance features related to Arctic percent vegetation cover: Implications for hyperspectral remote sensing of Arctic tundra

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ABSTRACT

In this study, we investigated the utility of hyperspectral remote sensing data for estimating green percent vegetation cover (PVC) for a study site in the Canadian High Arctic. A field experiment was conducted on Sabine Peninsula (76°27′ N, 108°33′ W), Melville Island, Nunavut, Canada to collect field spectra and PVC for five vegetation types, i.e., polar semi-desert (PD), dry mesic tundra (DMT), mesic tundra (MT), wet mesic tundra (WMT) and wet sedge/moss (WSM). Based on field spectra, two types of 2-band hyperspectral (i.e., Hyperion) and multispectral (i.e., WorldView-3) vegetation indices (VIs) were derived using all possible band combinations. Optimal spectral bands were identified based on their correlations with green PVC. In addition, VIs designed for other landscapes were examined for their ability to estimate green PVC in an Arctic environment. The results indicate that PVC and spectral features for Arctic vegetation types were related to moisture content: (1) vegetation types with dry to intermediate soil moisture (e.g., PD, DMT and MT) possessed large amounts of bare soil and exhibited spectral properties similar to bare soil; and (2) vegetation types with high moisture content (e.g., WMT and WSM) exhibited spectra similar to senescent vegetation given the substantial proportion of senescent vegetation in these vegetation types. The optimal Hyperion spectral bands for estimating green PVC were located at the absorption features observed in Arctic vegetation spectra, including 681.20 nm (leaf pigment absorption); 721.90 nm and 732.07 nm (along the red-edge slope); 1174.77 nm and 1184.87 nm (leaf water absorption); and 1447.14 nm, 1457.23 nm, 2072.65 nm and 2102.94 nm (leaf cellulose and lignin absorption). Narrowband VIs exhibited a stronger correlation with green PVC than broadband VIs due to the finer spectral features sampled by hyperspectral data. Further, VIs designed to estimate leaf pigment and dry matter content (e.g., lignin and cellulose) showed strong correlations with green PVC.

1. Introduction

It has been estimated that temperatures in the Arctic will exceed global mean warming by 40% (IPCC, 2013). Hence, it is not surprising that some of the strongest signals of climate change have already been observed at high latitudes (Barber et al., 2008). This amplified warming will have widespread and diverse impacts on Arctic vegetation types (Myers-Smith et al., 2011; Post et al., 2009; Walker et al., 2006); i.e., plant growth will increase (Myneni et al., 1997) and differentially affect species abundance, thereby changing community boundaries, species composition and overall ecosystem processes (Wookey et al., 2009). In addition to air (and soil) temperature, there are a number of factors that serve as controls on vegetation growth in the High Arctic, including soil moisture (Atkinson and Treitz, 2013; Laidler et al., 2008), available nutrients (Shaver and Chapin, 1980; van Wijk et al., 2005), topography (Evans et al., 1989), soil type (Walker et al., 2011) and permafrost disturbance (Rudy et al., 2013). The spatial variability of these environmental controls contribute to a diverse and heterogeneous vegetation cover.

Long-term measurements of percent vegetation cover (PVC) and species abundance are required to monitor the impact of a warming climate on Arctic vegetation (Atkinson and Treitz, 2013; Davidson et al., 2016; Elmendorf et al., 2012; Hudson and Henry, 2010; Stewart et al., 2016; Stow et al., 2004; Tape et al., 2012). The point-frame technique represents the traditional field method for collecting PVC data (Atkinson and Treitz, 2013; Elmendorf et al., 2012; Hudson and Henry, 2010; Molau and Mølgaard, 1996). Although this technique provides quantitative data on plant species richness, canopy height and PVC, it is extremely time-consuming since the plant identification of all

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vegetation layers is required (Chen et al., 2010). As a result, this field-based technique is difficult to implement and extrapolate over large areas.

Satellite remote sensing provides an opportunity to monitor Arctic vegetation at a variety of spatial and temporal scales (Stow et al., 2004). While there have been studies examining biophysical variables at high latitudes, they have been predominantly limited to coarse (i.e., 1–8 km^2) (Jia et al., 2009; Myneni et al., 1997; Raynolds et al., 2012; Walker et al., 2005; Zeng et al., 2011) and to a lesser extent, intermediate spatial resolutions (Fraser et al., 2011; Johansen and Tømmervik, 2014; Ju and Masek, 2016; Nitze and Grosse, 2016; Olthof et al., 2009). In these studies, the broadband Normalized Difference Vegetation Index (NDVI) has been applied to characterize Arctic biophysical variables such as green PVC, biomass and carbon flux (Atkinson and Treitz, 2013; Epstein et al., 2004; Hope et al., 1993; Laidler et al., 2008; Stow et al., 2004; Tagesson et al., 2012). However, this relationship is complicated for Arctic tundra by the optical properties of non-vascular plants/organisms (e.g., mosses, lichens, cyanobacteria), non-photosynthetic components of vegetation (vascular and non-vascular) (e.g., woody stems, leaf litter, senescent vegetation), leaf and plant architecture/structure/organization, illumination conditions and sensor viewing geometry, and soil/substrate reflectance (and organic content) (Asner, 1998; Curran, 1989; Feret et al., 2008; Juszak et al., 2014; Stow et al., 2004).

Compared to multispectral (i.e., broadband) remote sensing, hyperspectral (i.e., narrowband) remote sensing provides numerous spectral bands which have demonstrated great utility in Arctic research. For instance, satellite/airborne hyperspectral data are capable of capturing subtle changes in mineral absorption features and mapping Arctic lithologic units (Bedini, 2009; Gleeson et al., 2010; Harris et al., 2005; Leverington, 2010). With regard to hyperspectral remote sensing of Arctic vegetation, most studies have been based on field spectra (Bratsch et al., 2016; Buchhorn et al., 2013; Davidson et al., 2016; Hope et al., 1993; Huemmrich et al., 2013; Kushida et al., 2009, 2015; Laidler et al., 2008; Riedel et al., 2005a, 2005b; Ulrich et al., 2009). These studies can be grouped into two broad categories: (1) vegetation classification; and (2) biophysical variable estimation.

Studies of hyperspectral classification of Arctic vegetation have largely focused on characterizing spectral features of the tundra and investigating spectral separability among different vegetation types (Buchhorn et al., 2013; Davidson et al., 2016; Huemmrich et al., 2013; Ulrich et al., 2009). Generally, Arctic vegetation spectra were found to be a mixed signal of vascular plants (green or non-green), non-vascular plants (e.g., lichens and mosses) and soil background (dry or wet) (Ulrich et al., 2009). For some vegetation types with dry to intermediate soil moisture, spectral features common to green vegetation, such as the green reflectance peak (around 550 nm), steep red-edge slope (690–720 nm) and the high near-infrared reflectance plateau (720–1300 nm) were not observed (Bratsch et al., 2016; Buchhorn et al., 2013; Davidson et al., 2016; Ulrich et al., 2009). Classification results from these studies have suggested that hyperspectral data may be useful for Arctic vegetation mapping (Bratsch et al., 2016; Buchhorn et al., 2013; Davidson et al., 2016). By using the sparse partial least squares regression, Bratsch et al. (2016) identified several optimal hyperspectral bands for classifying four Alaskan Arctic vegetation types. These optimal spectral bands were located at important spectral features (e.g., pigment absorptions at blue and red bands, red-edge slopes and near-infrared bands) and could achieve a high classification accuracy (>80%). One recent research by Davidson et al. (2016) has also highlighted these spectral bands. In addition, Davidson et al. (2016) found that classification accuracy could be improved by incorporating vegetation indices (VIs) into classification.

With regards to biophysical estimation, most studies have focused on correlating narrowband VIs with field measured biophysical variables (Buchhorn et al., 2013; Huemmrich et al., 2013; Kushida et al., 2015; Laidler et al., 2008; Riedel et al., 2005a, 2005b; Stow et al., 2004. For instance, NDVI, enhanced VI (EVI) and soil-adjusted VI (SAVI) have been examined for their ability to estimate green PVC (Kushida et al., 2009; Laidler et al., 2008), biomass (Kushida et al., 2009, 2015; Riedel et al., 2005a, 2005b), and leaf area index (LAI) (Riedel et al., 2005a, 2005b; Williams, 2005; Williams et al., 2008). Huemmrich et al. (2013) used a 3-band hyperspectral VI as a proxy for the chlorophyll concentration of Arctic vegetation. Buchhorn et al. (2013) assessed the performance of the NDVI involving all possible two band combinations within the 420–1100 nm wavelength region for estimating shrub biomass and found that narrowband NDVI performed better than broadband NDVI. Recent studies have demonstrated that the absorption depth extracted from continuum-removed spectrum could be used to estimate Arctic biophysical variables with high accuracy (Bratsch et al., 2016; Buchhorn et al., 2013; Ulrich et al., 2009).

To our knowledge, hyperspectral remote sensing of Arctic vegetation has not been thoroughly explored. For instance, the spectral bands used in previous studies were limited to the visible – near infrared (VIS-NIR: 350–1300 nm) wavelength region (Buchhorn et al., 2013; Kushida et al., 2009). Studies that apply the shortwave infrared (SWIR: 1400–2500 nm) wavelengths for estimating Arctic biophysical variables are lacking. Further, spectral VIs designed for landscapes such as croplands, grasslands and forests have seldom been tested for their utility in sparsely vegetation High Arctic tundra vegetation with exposed soil/tills, large quantities of non-vascular plants (i.e., mosses, lichens) or large amounts of senescent vegetation (vascular and non-vascular).

As a result, the overall purpose of this research was to evaluate the performance of satellite hyperspectral data for estimating green PVC within the 450–2500 nm wavelength region. The first objective was to characterize the PVC and spectral properties of five vegetation types distributed along a moisture gradient for a study site in the Canadian High Arctic. The second objective was to identify the optimal spectral bands for estimating green PVC. Finally, the performance of broadband and narrowband VIs for predicting green PVC was evaluated.

2. Study area

The study area is located on the Sabine Peninsula, Melville Island, Nunavut, Canada (76°27′ N, 108°33′ W) (Fig. 1A–B). The mean monthly July temperature and precipitation are approximately 4.5 °C and 28.1 mm, respectively, based on 1981 to 2010 Canadian Climate Normals for Resolute Bay, Nunavut (http://climate.weather.gc.ca/climate_normals/index_e.html). Geologically, this site is located within the Sverdrup Basin and has four major geological units: Kanguk and Christopher shales, Hassel sandstone and an anhydrite dome (Harrison, 1990). Weathered bedrock generates a surficial material commonly observed in the Kanguk shale and anhydrite dome, and is too coarse to support vascular plants (Edlund, 1993; Harrison, 1990). Soil pH varies from weakly to moderately acidic (Kanguk) to weakly alkaline (Hassel and Christopher) to highly alkaline (anhydrite dome) (Harrison, 1990). The active layer depths for this area range from approximately 0.5–1.0 m (Collingwood et al., 2014).

The vegetation for this study area was grouped into five vegetation types: (1) polar semi-desert (PD); (2) dry mesic tundra (DMT); (3) mesic tundra (MT); (4) wet mesic tundra (WMT); and (5) wet sedge/moss (WSM) (Fig. 1C). The distribution of vegetation types is determined by topographic and soil moisture gradients (Edlund, 1993): the PD type is generally located on well-drained uplands; the WMT and WSM types generally occur in low-lying areas alongside waterways and in the proximity of permanent snowbanks; and the other vegetation types tend to occur on intermediate moisture sites.