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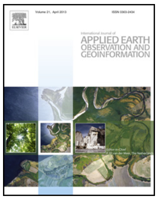

Modelling high arctic percent vegetation cover using field digital images and high resolution satellite data

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ABSTRACT

In this study, digital images collected at a study site in the Canadian High Arctic were processed and classified to examine the spatial-temporal patterns of percent vegetation cover (PVC). To obtain the PVC of different plant functional groups (i.e., forbs, graminoids/sedges and mosses), field near infrared-green-blue (NGB) digital images were classified using an object-based image analysis (OBIA) approach. The PVC analyses comparing different vegetation types confirmed: (i) the polar semi-desert exhibited the lowest PVC with a large proportion of bare soil/rock cover; (ii) the mesic tundra cover consisted of approximately 60% mosses; and (iii) the wet sedge consisted almost exclusively of graminoids and sedges. As expected, the PVC and green normalized difference vegetation index (GNDVI; $(R_{NIR} - R_{Green})/(R_{NIR} + R_{Green})$), derived from field NGB digital images, increased during the summer growing season for each vegetation type: i.e., ~5% (0.01) for polar semi-desert; ~10% (0.04) for mesic tundra; and ~12% (0.03) for wet sedge respectively. PVC derived from field images was found to be strongly correlated with WorldView-2 derived normalized difference spectral indices (NDSI; $(R_x - R_y)/(R_x + R_y)$), where R_x is the reflectance of the red edge (724.1 nm) or near infrared (832.9 nm and 949.3 nm) bands; R_y is the reflectance of the yellow (607.7 nm) or red (658.8 nm) bands with R^2's ranging from 0.74 to 0.81. NDSIs that incorporated the yellow band (607.7 nm) performed slightly better than the NDSIs without, indicating that this band may be more useful for investigating Arctic vegetation that often includes large proportions of senescent vegetation throughout the growing season.

1. Introduction

Percent vegetation cover (PVC), also known as the fraction of green vegetation, is defined as the percentage of the ground surface covered by green vegetation (Purevdorj et al., 1998). PVC is an important biophysical variable and a key indicator of ecosystem health and productivity. Long-term records of PVC have been used to examine Arctic vegetation dynamics (e.g., shrub expansion) (Frost and Epstein, 2014; Sturm et al., 2001; Tape et al., 2012). PVC is also an important factor that controls the surface energy balance; e.g., increased shrub cover results in a decrease in albedo and an increase in evapotranspiration and surface roughness, which greatly affects the surface energy balance (Chapin et al., 2005; Juszak et al., 2014; Pearson et al., 2013; Bonfils et al., 2012). Further, PVC has been found to be closely related to other important biophysical variables such as leaf area index (LAI) (Chen et al., 2009), biomass (Chen et al., 2009; Hudson and Henry, 2009), carbon flux (Huemmrich et al., 2010; Sharp et al., 2013; Sweet et al., 2014), fraction of absorbed photosynthetically active radiation (FAPAR) (Gamon et al., 2013; Huemmrich et al., 2010) and vegetation indices (VIs) (Atkinson and Treitz, 2013; Hope et al., 1993; Kushida et al., 2009; Laidler et al., 2008). In many climate and land-surface models, PVC and LAI are input for modelling the amount of photosynthetic biomass (Brovkin et al., 2013; Case et al., 2014; Gutman and Ignatov, 1998; Zeng et al., 2000).

Among the conventional field techniques for measuring PVC, the point-frame method is the most widely adopted for low vegetation communities (Bonham, 2013; Molau and Mølgaard, 1996). Here, a rectangular quadrat (e.g., 1 m × 1 m) consisting of a gridded network of intersecting strings/wires (e.g., at 10 cm = 100 grid points) is placed above the vegetated surface. At each grid, a pin is lowered until it comes into contact with green vegetation, whereby the plant species and the distance between the contact and grid are recorded. The total PVC is then derived from the total number of contacts with green plants divided by the total number of grid points (i.e., 100). Compared with the visual estimate method (Barbour et al., 1980; Bonham, 2013; Chen et al., 2010), this method is considered to be objective and as a result has been adopted by

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many as the standard protocol for measuring PVC of Arctic vegetation (Atkinson and Treitz, 2013; Elmendorf et al., 2012; Hope et al., 1993; Laidler et al., 2008; Molau and Mølgaard, 1996; Sharp et al., 2013; Sweet et al., 2014; Wahren et al., 2005). However, this method is time-consuming and laborious (Chen et al., 2010). Further, a dense grid is required to obtain more accurate estimates of PVC, thereby requiring additional time and resources to complete (Chen et al., 2010).

Recently, true colour (i.e., RGB) digital images, collected for field plots, have proven to be useful and effective for estimating PVC in various landscapes such as grasslands (Purevdorj et al., 1998; Seefeldt and Booth, 2006), croplands (Gitelson, 2013), semi-arid/arid environments (Laliberte, 2010; Laliberte et al., 2007; Zhang et al., 2012) and Arctic tundra (Chen et al., 2010). By applying various thresholds/rules to pixels' RGB values, green vegetation can be distinguished from other covers such as senescent vegetation and bare soil/rock (Gitelson et al., 2002; Liu et al., 2012; Purevdorj et al., 1998; White et al., 2000). Classification techniques, such as *k*-means and maximum likelihood, have also been used to extract PVC from digital images (Mirik and Ansley, 2012; Vanha-Majamaa et al., 2000; Zhou and Robson, 2001). Since these methods consider the reflectance characteristics of cover types, they are most suited to generating broad categories, such as green (i.e., photosynthetic) versus non-green (i.e., non-photosynthetic) vegetation. When differentiating different plant species or functional groups with similar reflectance characteristics, the geometric information of vegetation can be incorporated into the classification (Chen et al., 2010; Laliberte, 2010; Laliberte et al., 2007; Luscier et al., 2006). For instance, Chen et al. (2010) segmented digital images into polygons/objects and used the length/width ratio of polygons to differentiate grasses from forbs since the length/width ratio of grasses is larger than that of forbs. Luscier et al. (2006) also used objects' length/width ratios and RGB colours as the *k*-NN classification features for differentiating forbs, grasses and shrubs.

Investigating the relationship between PVC and VIs is important for up-scaling field-measured PVC to satellite scales. Generally, strong correlations have been reported in related studies: e.g., Hope et al. (1993), Laidler et al. (2008), Kushida et al. (2009) and Atkinson and Treitz (2013). Hope et al.'s (1993) results indicated that vegetation communities with different soil moisture conditions and vegetation composition may have different regression relationships with normalized difference vegetation index (NDVI). Laidler et al. (2008) found that the correlation between NDVI and PVC derived from high-resolution satellite images (i.e., 4 m IKONOS) was greater than those derived from medium-resolution images (i.e., 30 m Landsat). This may be due to the enhanced capacity to stratify heterogeneous Arctic land surfaces into relatively homogeneous areas using high-resolution satellite data, thereby strengthening the correlation between NDVI and biophysical variables (Hope et al., 1993; Laidler et al., 2008). Atkinson and Treitz (2013) examined the linear PVC-NDVI relationship along latitudinal gradients. The statistical tests indicated that there was no significant difference between the regression slopes for two disparate sites, while the intercepts were significantly different, i.e., the regression equations for the two sites were parallel. This parallelism suggests that NDVI can be used as an indicator for monitoring the changes in PVC since the response of NDVI to PVC appears to be equal at different sites; however, some caution needs to be exercised in applying the regression equation of one site to estimate the PVC of another site due to the different intercepts observed (Atkinson and Treitz, 2013). Other VIs such as the soil adjusted vegetation index (SAVI) (Huete, 1988) and modified SAVI (MSAVI) (Qi et al., 1994) were developed to minimize the influence of soil brightness on NDVI for low PVC. These have also been tested in the Arctic but do not appear to improve the PVC-VI correlation when compared to NDVI (Laidler et al., 2008; Kushida et al., 2009).

Although image-based classification is an effective way to derive PVC, to our knowledge, it has not been widely tested in Arctic environments, particularly in the High Arctic. Further, due to the time consuming nature of the point-frame method for conducting landscape or watershed-scale studies, most studies focus on measuring the PVC at the peak of growing season rather than examining seasonal vegetation change. Hence, the goal of this research is to model PVC for a High Arctic study site using field digital images collected throughout the growing season and high spatial resolution satellite images. The specific objectives are:

1) to characterize the seasonal changes in PVC and NDVI for a study site in the Canadian High Arctic using field near infrared-green-blue (NGB) digital images; and
2) to 'scale up' PVC to satellite scales using the PVC derived from field NGB images and high-resolution satellite images.

2. Study area

The Cape Bounty Arctic Watershed Observatory (CBAWO) (75.4°N, 109.5°E) is located on the southern coast of Melville Island, Nunavut, Canada and covers approximately 150 km^2 (Fig. 1). The terrain of this area is undulating with gradual slopes (above sea level elevation: 5 m to 125 m). The study site is underlain by sedimentary rocks of the Devonian Weatherall and Hecla Bay formations (Hodgson et al., 1984). Climatically, the growing season is short (i.e., late June to early August) (Environment and Climate Change Canada) and cool with low stratus cloud and fog being common during the growing season (Atkinson and Treitz, 2013). The mean monthly July temperature in 2014 was 3.7 °C and the total precipitation for July was 70.2 mm.

Walker et al. (2005) describe the vegetation in this area as graminoid, prostrate dwarf shrub, forb tundra. Previous studies at the CBAWO have classified vegetation types into three broad communities based on topographic and soil moisture conditions: polar semi-desert (PD), mesic tundra (MT) and wet sedge tundra (WS) (Atkinson and Treitz, 2013; Edlund, 1993). The PD generally occurs on drained uplands and consists of willow (e.g., *Salix arctic* Pall.), forbs (e.g., *Dryas intergrifolia* Vahl., *Papaver cornwallisense* D. Love, *Saxifraga oppositifolia* L., *Saxifraga hyperborean* R. Br., *Saxifraga tricuspidata* Rothb.), rushes (e.g., *Luzula confusa* Lindeberg., *Luzula confusa* Spreng.), grasses (e.g., *Dupontia fisheri* R. Br., *Phippsia algida* Sol. R. Br., *Poa abbreviata* R. Br.), mosses and lichens with large patches of bare soil and rock. The MT tends to occur on intermediate moisture sites and exhibits a thick moss layer with patches of exposed bare soil and rock. The WS possess a thick mat of grasses (e.g., *Alopecurus alpinus*, *Phippsia algida*), sedges (e.g., *Carex aquatilis* var. *stans*, *Eriophorum triste*, *E. scheuchzeri*) and mosses, occurring in low-lying areas alongside waterways or downslope of permanent snow fields.

3. Methods

3.1. Field sampling

In July 2014, a field campaign was undertaken at three sites at the CBAWO to examine vegetation properties (i.e., PVC and VIs). Each sampling site was 300 m × 300 m (i.e., identified as squares in Fig. 1, panel b). Within each site, several 6 m × 6 m plots (designed to correspond to 3 by 3 pixel windows of WorldView-2 data), were located using a stratified random sampling procedure described as follows.

First, the Worldview-2 image data, acquired on July 12th, 2012, were classified into five vegetation communities for each sampling site using the *k*-means algorithm (Fig. 1, panel c). These five vege-