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Detecting continuous lichen abundance for mapping winter caribou forage at landscape spatial scales

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ABSTRACT

Spatial variation of available food resources can be difficult to accurately quantify for wide ranging organisms at landscape scales. Lichens with usnic acid, a yellowish pigment, constitute a large portion of caribou winter diet across much of their range. We take a new approach of modeling lichen abundances by capitalizing on unique spectral characteristics of usnic acid lichens. We utilize a recently completed ground reference vegetation data set extending over 12,000 km^2 in Denali National Park and Preserve, Alaska to model the abundance of usnic lichen and other forage vegetation groups. Spectral signatures were obtained for more than 700 vegetation monitoring plots in Denali from Landsat 7 ETM+ imagery. We fit models of the absolute percent cover of vegetation groups corresponding to caribou diet items, with a focus on lichens. We used non-parametric multiplicative regression to capture the non-linear relationships between vegetation cover and spectral and environmental data. Different groupings of lichen cover were tried as response variables in addition to usnic lichens to see if other lichen color groups were more detectable. The best fitting lichen model was for usnic acid lichens, which explained 37% of the variation using only three predictors (elevation, bands 1 and 7). Elevation had a non-linear, double-humped shaped relationship to usnic lichen abundance while bands 1 and 7 were positively correlated with usnic lichen cover. These results support previous spectroradiometric ground measurements that indicated usnic lichens were distinctive at those wavelengths. Other vegetation groups had models that explained between 31% and 51% of the variation in cover. Maps of estimated abundance of usnic lichens and other vegetation groups covering the northern half of Denali were generated using our models. These maps enable the study of the role of food resources as a continuous resource in winter habitat selection by caribou, rather than assuming food as a coarser, categorical or thematic variable assigned to discrete areas of the landscape as has been done in most previous studies.

1. Introduction

It is difficult to conduct detailed habitat studies of highly mobile terrestrial species whose individuals range over large areas in a single year. To do so, relevant habitat characteristics must be measured over a wide spatial extent at sufficient resolution to be biologically meaningful. Caribou (*Rangifer tarandus*) are excellent study organisms in this respect. They are also of central importance for subsistence for many human populations across the northern latitudes, both as wild game and domestic livestock. Caribou have large home ranges, in some cases migrating over thousands of miles in a single year (Russell et al., 1993). Caribou respond to many habitat factors but we focused on one, the abundance of winter food resources at landscape spatial scales. Caribou need more energy in the winter due to cold temperatures and difficulty of travel and foraging in snow. Wintering areas therefore often have higher forage abundance (e.g., Johnson et al., 2000). Most caribou subspecies are similar in that their winter diet is composed mostly of lichens, often in the genus *Cladonia*, a terrestrial fruticose macrolichen common across the high northern latitudes (Heggberget et al., 1992; Joly et al., 2007; Russell et al., 1993). Increased soil temperatures in northern latitudes are thought to have caused a decrease in lichen cover caused by tree and shrub expansion (ACIA, 2005; Cornelissen et al., 2001). We need new tools for measuring large-scale woody plant encroachment into lichen-rich areas that are critical to caribou diet during the winter. Such tools would allow us to detect possible changes in forage resources as well as gain a better understanding of caribou ecology. This paper presents a method to make continuous vegetation maps for caribou to meet this need.

Some lichens are distinguishable from other elements of the vegetation using remote sensing data, including use of Normalized

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Difference Vegetation Index (NDVI) (Stow et al., 1993). Many lichen species, including *Cladonia*, are lighter colored and reflect more light in blue to yellow wavelengths than green vegetation, helping to distinguish them from other vegetation (Petzold & Goward, 1988). *Cladonia* species eaten by caribou also commonly contain usnic acid, a pale yellow pigment that is spectrally distinct and has been suggested as a potentially useful characteristic in remote sensing (Petzold & Goward, 1988; Rees et al., 2004). However, no study has focused on the continuous mapping of usnic lichens using remotely sensed data.

Previous studies of caribou habitat incorporated food items by mapping them using remote sensing alone or in combination with other methods (Bechtel et al., 2002; Gilichinsky et al., 2011; Nordberg & Allard, 2002; Petzold & Goward, 1988; Théau et al., 2005). Caribou select food resources at multiple scales (Johnson et al., 2004; Mayor et al., 2009) but most previous studies of caribou habitat that include forage used thematic maps (e.g., categories of % lichen) rather than continuous measures of forage. This approach may be too coarse-grained to detect multiple spatial scales at which caribou are selecting habitat based on food resources if these themes mask important variation in forage. We seek to produce continuous estimates of food resources to enable study of caribou forage resources across multiple spatial scales.

Caribou habitat studies using spectral data fall into three categories: classification, inversion and regression. Classification finds groups of pixels with consistent spectral signatures and assigns a vegetation type to those areas based on reference vegetation data (Jensen, 2005). Classification is useful because it maximizes the purity of spectral signatures of each vegetation type by searching through homogenous pixel areas to gather a larger sample from which to calculate mean spectral characteristics. Inversion solves an equation for the observed reflectance across all bands in a pixel, assuming the spectroradiometric properties of pure pixels for each surface are known (e.g., Hoge & Lyon, 1996; Schlerf & Atzberger, 2006). A successful reflectance model estimates the quantity of each component surface contributing to the reflectance in each pixel. However, pure pixel characteristics for all vegetation types and surfaces in a scene are rarely known. Backscattering, which has been shown to significantly alter spectral signatures of lichens at different illumination angles (Kaasalainen & Rautiainen, 2005), further complicates reflectance modeling. Spectral signatures can be obtained by taking field measurements for all surfaces with field spectroradiometers. However, the potential number of surfaces with unique spectral characteristics and angles of illumination for each can be prohibitively large. We took the third approach, in which we regressed the abundance of vegetation cover groups against spectral and environmental data. Regression enables targeted modeling of spectrally heterogeneous surfaces without having to explicitly account for reflectance properties of other surfaces, as in inversion (Oltof & Fraser, 2007). Regressions can estimate continuous quantities of a target surface within a mixture of co-occurring surfaces, unlike classification, which produces categories of abundance for a target surface. Both of these attributes of regression made it preferable over inversion or classification since we sought to make models and maps of continuous cover for specific vegetation groups.

We seek to map the continuous abundance of major caribou diet categories, especially lichens, by using a large sample of vegetation plots as ground reference data to which we compare the spectral signatures of the same plots. The resulting models and maps will help scientists better quantify food resources for caribou, assess threats to caribou habitat and analyze habitat selection patterns across their range.

Our specific goals are to:

1) Create models to estimate the continuous cover of selected groups of lichens in relation to spectral and environmental data. Lichen groups were: total lichen, usnic lichens (usnic), light-colored lichens (light), usnic plus light colored lichens (usnlite) and dark colored lichens (dark).
2) Create models to estimate the continuous cover of other important caribou diet categories (coniferous and deciduous trees, shrubs and graminoids) using spectral and environmental data as predictors.
3) Estimate the continuous cover of each lichen and vegetation group in areas not directly measured by ground observation (generate maps).
4) Discuss the best predictors in each model and spatial patterns in each map in terms of known ecological and reflectance properties of each lichen and vegetation group.

2. Methods

2.1. Study area

Denali National Park and Preserve (henceforth "Denali"), located in central Alaska (Fig. 1A), covers slightly more than 2.4 million ha between 62° 18′ and 64° 04′ N and between 148° 48′ and 152° 52′ W. Our study area lies in the northern portion of the park covering 1.28 million ha. The Alaska Range, North America's highest mountains, bisects Denali along a northeast/southwest line. North of the Alaska Range is a predominantly continental climatic regime influenced by polar air masses. Vegetation in Denali varies from boreal forests and taiga at the lowest elevations (ca. 100 m), shrublands at middle elevations, and alpine tundra at higher elevations up to the rock and ice zone, which extends to the summit of Mt. McKinley (5934 m; Fig. 2). In Denali, ground dwelling lichens are most abundant in alpine tundra, windswept ridges or lowland open conifer forests but can occur in most habitats except for dense, broadleaf forests or alder thickets. Permafrost occurs sporadically in Denali, from discontinuous patches in mid-elevations to continuous polygons in lower elevations in poorly drained soil types.

2.2. Response data

Response variables were the percent cover of vegetation cover groups, based on data acquired from the National Park Service vegetation monitoring program (Roland et al., 2004). These vegetation cover groups corresponded to categories commonly used by caribou biologists to study diet, including shrubs, graminoids, lichens, deciduous and coniferous trees (Heggberget et al., 1992). Forbs were excluded because we focused on winter diet. We further divided lichens into color groups, partially based on Rees et al. (2004) including yellow colored lichens with usnic acid, such as *Cladonia arbuscula* (Table 1), light colored lichens, such as *Cladonia rangiferina* (Table S1), usnlite (yellow + light) and dark colored lichens, such as *Peltigera aphthosa* (Table S2a–c). We expected lighter colored lichens to be more detectable than dark lichens but also wanted to see if light lichens were spectrally similar enough to usnic lichens to be lumped with them. We therefore also tried the combination of usnic plus light-colored lichens (usnlite) as a response variable. Usnic lichens are yellow in color, light lichens white or gray colored and dark lichens are brown or black. The lichen color categories are mutually exclusive, except for usnlite lichens, which contain both yellow and light color lichens. Usnic lichens are listed in Table 1.

The vegetation monitoring sampling design used a 100 m grid overlaid on Denali based on a random starting position (see Roland et al., 2012). Plots were positioned on the original 100 m grid in groups of 25, called mini-grids (Fig. 1C). Each mini-grid was separated from the next by 20 km (Fig. 1B). Mini-grid spacing was decreased from 20 km to 10 km among-grid spacing in two areas of the park: 1) a 6 km buffer along the park road (which increases ease of access and decreases logistical costs); and 2) in the vicinity of the Toklat basin ecoregion (as a baseline for an area into which a road was being proposed at one time). Within each mini-grid, plots were positioned 500 m apart in each cardinal direction (e.g., every 5th 100 m point) (Fig. 1C). Each plot was a 16 m diameter circle