

Nadir and Bidirectional Surface Measurements of Arctic Tundra: Site Differentiation and Vegetation Phenology Early in the Growing Season

Lee A. Vierling

Department of Environmental, Population, and Organismic Biology, University of Colorado
Boulder, CO 80309-0334

tel: (303) 492-5130, FAX: (303) 492-5070, email: leev@hypatia.colorado.edu

Donald W. Deering

Biospheric Sciences Branch, NASA/Goddard Space Flight Center
Mail Code 923, Greenbelt, MD 20771. email: ddeering@ltpmail.gsfc.nasa.gov

Thomas F. Eck

Hughes/STX, NASA/Goddard Space Flight Center
Mail Code 923, Greenbelt, MD 20771. email: teck@ltpmail.gsfc.nasa.gov

Abstract -- Ground-based nadir and bidirectional radiometric measurements were collected on the North Slope of Alaska in early June to determine their utility in differentiating arctic tundra vegetation community types and examining differences in vegetation community structure and phenology. Three common arctic vegetation types were sampled: lowland wet sedge, tussock tundra essentially devoid of woody vegetation, and tussock tundra with dwarf woody shrub vegetation. Nadir measurements alone allowed spectral differentiation between the wet sedge site and the two tussock tundra sites, but did not allow clear discrimination between the two tussock tundra sites. Bidirectional reflectance measurements, however, permitted good discrimination between the two tussock tundra sites. This outcome is largely due to the fact that normalized difference vegetation index (NDVI) values derived from measurements taken at large view zenith angles were sensitive to the woody plant foliage that extends above the hummocky tussock tundra surface early in the growing season.

INTRODUCTION

Arctic latitudes are expected to undergo pronounced warming with continued increases of global atmospheric greenhouse gases [1]. Such warming will likely influence arctic ecosystems because permafrost, the dominant control on tundra ecosystem processes, is highly sensitive to temperature fluctuation [1, 2]. Shifts in arctic tundra ecosystem processes are likely to be expressed through changing vegetation phenology and species composition. For example, Chapin et al. [2] report that increases in deciduous shrub cover have accompanied arctic warming over the last decade.

Remote sensing may provide a viable means for estimating and monitoring large-scale shifts in tundra species composition [3]. Several investigators have recently conducted ecological remote sensing studies at arctic latitudes [4-12]. Of these studies, only Whiting et al. [12] considered and incorporated bidirectional reflectance measurements of the tundra canopy. However, no previous study characterizes the bidirectional reflectance of arctic tundra in detail.

Here, we report field bidirectional measurements of arctic tundra collected on the North Slope of Alaska. We specifically address the following research questions: 1) How may bidirectional reflectance measurements aid in differentiating arctic tundra vegetation community types in northern Alaska?, and 2) What aspects of arctic tundra vegetation structure and phenology are revealed in the early growing season when supplementing nadir views with multiple-view radiometric measurements?

SITE DESCRIPTION

Radiometric characteristics of arctic tundra were measured at three sites on Alaska's North Slope between June 5-13, 1995. The three sites are situated roughly on a north-south transect along the Dalton Highway and represent three different types of tundra vegetation. The northernmost site (69°38'N, 148°40'W, elev. 96 m) is located in a wet coastal lowland zone dominated by sedges. The second site (69°25'N, 148°42'W, elev. 332 m) lies on the northern flank of the Brooks Range foothills and is comprised of tussock tundra vegetation that is essentially devoid of woody deciduous shrub vegetation. At this site, sedges dominate the tussocks while evergreen species and mosses comprise the majority of the inter-tussock areas. Similar tussock tundra occurs at the third, southernmost site (69°11'N, 148°50'W, elev. 529 m), but the landscape at this site also contains a significant cover of low-growing woody deciduous shrub species.

The phenological state of the vegetation differed among sites at the time of field sampling. At the wet sedge site, the vegetation was highly senescent with virtually no photosynthetically active tissue contained in the canopy. The two tussock tundra canopies both contained a mix of standing dead (mostly sedges) and green vegetation (*Sphagnum* moss and evergreen shrubs), with the woody tussock tundra site exhibiting additional greenness due to emergent deciduous shrub foliage. Due to time and resource limitations, we did not conduct comprehensive biomass harvests to quantify the biomass fractions (green and senescent) at each site.

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INSTRUMENTATION AND METHODS

Two field radiometers served as the primary instrumentation in this study. The first was the Portable Apparatus for Rapid Acquisition of Bidirectional Observations of the Land and Atmosphere (PARABOLA), a unique three-channel radiometer capable of measuring radiance over almost the complete (4π) sphere [13]. The PARABOLA's three channels reside in the red (650-670 nm), near infrared (810-840 nm), and shortwave infrared (1620-1690 nm) spectral regions, respectively. The second primary instrument was the Personal Spectrometer II (PS-II; Analytical Spectral Devices, Boulder, CO), a commercially available diode-array field spectroradiometer capable of rapidly gathering contiguous, narrowband (4 nm) spectral data ranging from 350-1050 nm.

A flat, near-horizontal (slope $<5^\circ$) sampling area was selected for measurements at each site. A tripod/boom platform supported the PARABOLA during sampling, allowing data acquisitions from ~ 4.0 m above the tundra surface. Before and after each set of data acquisitions, the PARABOLA was leveled at ~ 0.3 m above a painted, calibrated barium sulfate reference panel to gather spectral incident radiance data.

Nadir spectra were acquired at each site by walking line transects with the PS-II spectrometer and sampling at points spaced 3 m apart from a height of ~ 1.4 m. Reference spectra of the same barium sulfate panel used with the PARABOLA were taken before and after each transect plot sample sequence.

We attempted to acquire PARABOLA and PS-II readings at solar zenith angles (Θ_s) of 48° , 60° , and 75° for each site. NDVI values for the three sample sites were calculated according to Θ_s using both radiance and reflectance [$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED})$]. PS-II NDVIs were calculated after averaging the radiometric values that corresponded to the bandwidths of the PARABOLA red and near-infrared channels to allow robust comparisons between the NDVIs derived from each instrument.

RESULTS AND DISCUSSION

The average nadir spectrum of the wet sedge site is easily differentiable from those of the two tussock tundra sites upon visual analysis (Fig.1). The spectral difference between the two tussock tundra sites, however, is not readily apparent. Statistical analysis reveals that, in all but the red region, the mean spectra of the two tussock tundra sites spectra fall within 1 standard deviation (σ) of each other. Calculated NDVI values similarly depict the site phenological differences (Table 1). The wet sedge NDVI value was considerably lower than those of the tussock sites. However, while the mean NDVI of the woody tussock tundra site was higher than that of the non-woody tussock site, the ranges ($\pm 1\sigma$) of the tussock site NDVIs exhibited significant overlap at nadir. Hence, the tussock tundra sites are not clearly differentiable using nadir measurements.

PARABOLA measurements, like the nadir PS-II spectra, show that the highly senesced wet sedge site possesses a

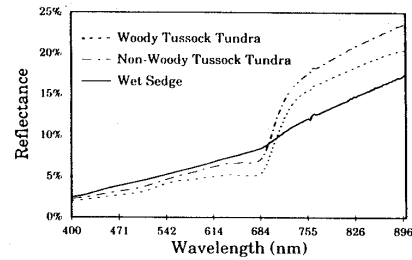


Fig. 1. Average nadir PS-II spectra of three vegetation types at $\theta_s = 61^\circ - 66^\circ$.

Table 1. Nadir NDVI values derived from PS-II reflectance measurements for three tundra vegetation types sampled at $\theta_s = 61^\circ - 66^\circ$.

site	θ_s	n (# of plots)	NDVI (mean)	NDVI (σ)
wet sedge	66°	20	0.31	0.03
non-woody tussock	62°	24	0.51	0.06
woody tussock	61°	12	0.56	0.04

significantly lower NDVI than the two tussock tundra sites over the full range of view angles (from 75° forwardscatter to 75° backscatter) in the solar principal plane. This relationship is seen regardless of Θ_s (Fig. 2). The NDVI values calculated from PARABOLA data for the two tussock tundra sites, however, reveal trends that are impossible to discern using nadir measurements alone. At large view zenith angles in both the forwardscatter and backscatter directions, the NDVI values of the two tussock tundra sites diverge considerably.

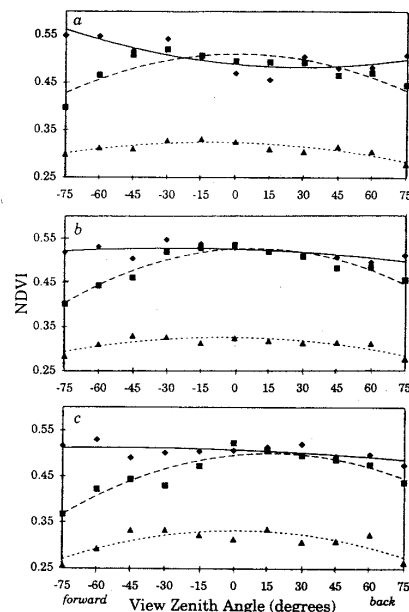


Fig. 2. NDVI values at three study sites with varying view zenith angle in the solar principal plane, derived from PARABOLA reflectance measurements. a. $\Theta_s = 47.3^\circ - 52.5^\circ$, b. $\Theta_s = 58.5^\circ - 61.2^\circ$ (values for wet sedge site represented as $\Theta_s = 60.0^\circ$ by averaging values from measurements at $\Theta_s = 55.3^\circ$ and 64.7°), c. $\Theta_s = 69.1^\circ - 75.0^\circ$. In each graph, the wet sedge site is depicted with triangles (finely dashed line), the non-woody tussock tundra with squares (coarsely dashed line), and the woody tussock tundra with diamonds (solid line). All curves represent second order polynomial fits to the data.

The sensitivity of the reflectance signal at high view angles to differences in shrub cover is likely due to the structure of tussock tundra vegetation. In the early spring, woody deciduous shrub stems extend above the hummocky surface of sedge-dominated tussocks. Thus, although the new deciduous shrub leaves are very small, with increasing view zenith angles they comprise a larger proportion of the green vegetation canopy early in the growing season because: 1) they are well-illuminated by the sun at large Θ_s , and 2) the other major component of the signal at large view angles, the tops of the sedge tussocks, are still dominated by standing dead biomass during initial woody deciduous shrub leaf flush. In contrast, at and near nadir the small deciduous shrub leaves comprise a much smaller fraction of the green biomass because the inter-tussock regions contain large amounts of green *Sphagnum* moss and evergreen species. As a result, NDVI at large view zenith angles early in the growing season may be more indicative of deciduous woody shrub biomass than overall canopy greenness.

CONCLUSIONS

From the results of this study, we conclude that early in the growing season on the North Slope of Alaska: 1) nadir-viewing radiometric measurements allowed spectral differentiation between a highly senesced wet sedge site and two tussock tundra sites with differing amounts of woody deciduous shrub cover, 2) bidirectional reflectance measurements provided the information necessary to differentiate all three sites due to a divergence of the NDVI at large view zenith angles between the two tussock tundra sites, and 3) bidirectional reflectance data is probably more sensitive to the amount of deciduous shrub cover than absolute green biomass in tussock tundra due to the hummocky structure of the vegetation. Thus, bidirectional reflectance measurements of arctic tundra may reveal small increases in deciduous shrub biomass that are expected to accompany shifts in arctic climate.

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