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Landsat-based snow persistence map for northwest Alaska

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ABSTRACT

Landsat imagery for northwest Alaska from 1 February to 31 August, 1985–2011 was used to map snow persistence at high spatial resolution. We analyzed 11,645 scenes covering 505,800 km^2, including five Arctic National Park units and the range of the Western Arctic caribou herd (85 Landsat path/rows). A cloud mask was created using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS). Terrain shadows were calculated from ASTER G-DEM2 and solar incidence angle. The presence of snow cover was determined using separate Snowmap algorithms for non-shadowed and shadowed pixels. Resulting snow cover data were reformatted into 562 30 × 30 km tiles, with an average sample size per pixel of 216 cloud-free observations. A binary classification tree was used to successfully determine the day of the year that best marked the change from snow to snow-free conditions for 99.8% of the study area. An internal consistency check evaluating the occurrence of snow-free data earlier than that day or snow data later than that day, showed that 98.7% of the land pixels were consistently classified ≥90% of the time. Comparison with MODIS end of snow season data showed an average difference of 4.2 days. The snow persistence map was strongly correlated with the few SNOTEL stations in the study area ($r^2 = 0.856$). Broadly, most snowmelt over the study area occurs from late April through early June, with timing delayed farther north and at higher elevations. Many local-scale snow patterns are evident in the detailed, 30-m product. The snow persistence map was co-registered to Landsat land cover mapping, creating a powerful, publicly available resource for ecosystem and land use analyses (https://irma.nps.gov/App/Reference/Profile/2203863).

1. Introduction

Snow persistence and snow depth patterns affect important aspects of northern ecosystems. Snow cover protects plants from desiccation, wind abrasion, and herbivory (Tape, Lord, Marshall, & Ruess, 2010; Walker, Billings, & De Molenaar, 2001). Approximately 30 cm of snow provides the hiemal threshold needed to insulate the surface from daily fluctuations in air temperature, creating the subnivean environment in which invertebrates and small mammals survive through the winter (Aitchison, 2001). Snow insulates plants and the soil, and can facilitate shrub growth and expansion (Sturm et al., 2001). In return, vegetation protruding above snow has been shown to decrease albedo, speeding up spring snowmelt (Cohen et al., 2013). Snowbed plant communities often include unique species assemblages, have delayed phenology, and melt from late-lying snowbeds can help support stream flow during dry summers (Walker et al., 2001). Deep snow areas also provide drifts for dens of large animals such as wolverines and bears (McKelvey et al., 2011). Conversely, many wildlife species use shallow-snow and snow-free areas that are exposed early in the season for grazing and nesting (e.g., Hupp et al., 2001).

Caribou (*Rangifer tarandus*) are an iconic species of the Arctic. Snow influences caribou winter distribution and habitat availability by impacting the energy required for traveling and foraging for food. Snow depth patterns on the landscape also affect the distribution of preferred forage species. Access to lichens is particularly important for caribou when the land is snow-covered (approx. October–April in our study area), as lichens form a major part of their winter diet (Boertje, 1984). Lichens are most common and abundant on sites with moderate snow cover (Flock, 1978). Areas that are wind-scoured during winter are often snow-free or melt in very early spring. These sites may have many species of lichens growing on rocks but they do not produce abundant biomass and are generally not preferred caribou forage (Flock, 1978). Very deep snow makes winter travel and foraging more difficult for caribou (Fancy & White, 1985). Sites with shallow snow provide protection for vegetation, including lichens, easier travel and minimal costs for digging for winter forage. These sites tend to melt earlier than average in the spring, making a snow-persistence map an ideal tool for examining caribou habitat.

Maps of snow characteristics are valuable tools for monitoring changes caused by widespread warming and increased precipitation

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in the Arctic. North America has experienced decreases in snow cover and snow depth since the 1950s, with northwest Alaska showing no change in fall onset of snow cover, but a decrease of four days in the snow melt date between the 1972/1973 and 2008/2009 snow seasons (Callaghan et al., 2011). Physical modeling techniques (e.g. Liston & Hiemstra, 2011; Liston & Sturm, 2002) have been used to simulate global and regional snow characteristics. Remote sensing methods have been used to map snow cover since the 1960s (Dozier, 1989; Matson, 1991). While Landsat data provided needed spatial resolution (30-m pixels) (Rosenthal & Dozier, 1996), the 16-day imaging interval is too coarse to portray snow dynamics. Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) data come from satellites with more frequent passes (1–2 days globally, more frequent at high latitudes), but have coarser spatial resolution (≥250-m pixels). The MODIS snow products, built on the work done with Landsat (Brozdik, Armstrong, & Savoie, 2007; Hall, Riggs, Salomonson, DiGirolamo, & Bayr, 2002; Sirguey, Mathieu, Arnaud, Khan, & Chanussot, 2007) provide information on snow cover at daily to monthly timescales, and at spatial resolutions as fine as 500 m. However, much of the variability in snow cover occurs at much finer spatial scales, particularly for mountain and tundra snowpacks (Liston & Sturm, 2002; Sturm, Holmgren, & Liston, 1995). Some work has been done using Landsat snow cover patterns to downscale MODIS fractional snow cover data (Selkowitz, 2011).

In this study, we used a combination of image interpretation and statistical modeling to describe patterns of snow persistence on the landscape at 30-m spatial resolution to help characterize winter and spring caribou habitat conditions related to snow depth across northwest Alaska. To accomplish this we compiled and analyzed an extensive time series of over 10,000 Landsat images (1985–2011) that covered the study area. We used the results of this analysis to map the typical date when areas became snow-free across the range.

2. Methods

2.1. Study area

The study area covers the northwest portion of Alaska, including portions of the North Slope, Brooks Range, Yukon Basin, Seward Peninsula and Yukon–Kuskokwim Delta, with a focus on the range of the Western Arctic caribou herd (Fig. 1). The study area encompasses the winter range, calving grounds, summer range, migratory areas, and outer range (areas on the periphery of the herd's range that get occasional use). The status, distribution, movements and trends in the condition of caribou are monitored as part of the US National Park Service's Arctic Network Inventory and Monitoring Program. Data on snow cover within the range of the Western Arctic caribou herd are important to understanding movement patterns and timing of caribou migrations. There are five Arctic National Park Service units (Gates of the Arctic National Park and Preserve, Noatak National Preserve, Kobuk Valley National Park, Cape Krusenstern National Monument, and Bering Land Bridge National Preserve), three National Wildlife Refuges (Selawik, Kanuti and Koyukuk) and the National Petroleum Reserve—Alaska in northwestern Alaska that are wholly contained by the study area. The extent of the area for which Landsat data were downloaded and analyzed was somewhat larger than the Western Arctic caribou herd's range to accommodate possible range expansion and to include the full extent of some conservation units, for a total area of 505,800 km^2 (Fig. 2).

2.2. Landsat image acquisition

A total of 89 path/row locations (footprints of individual satellite scenes as defined by the Landsat Worldwide Reference System-2 (WRS-2)) covered the study area (Fig. 3). Four of these were excluded because they were mostly ocean and contained no land that was not also included in the adjacent row. All browse images available by September 2011 for Landsat 4-TM, Landsat 5-TM, and Landsat 7-ETM+ for the remaining 85 WRS-2 path/rows were downloaded, along with the associated metadata text records. The browse images were georeferenced by creating a GIS-readable world file from the information in the metadata file using a custom Python script. Each Landsat path/row was reviewed manually and browse images which contained useful information about ground conditions over at least 10% of the scene were identified.

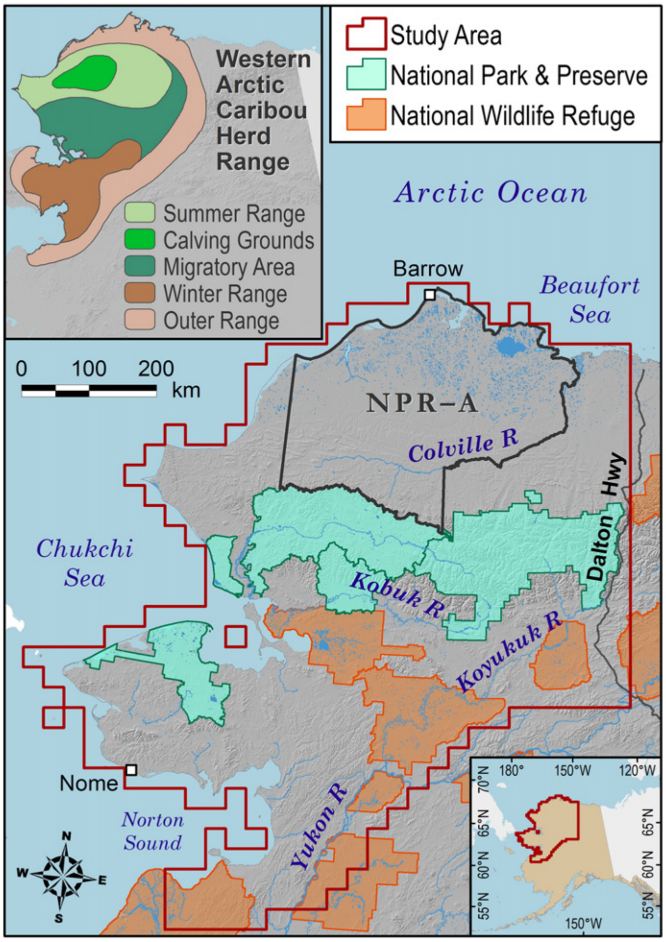

Fig. 1. Study area overview, Western Arctic caribou herd range, northwest Alaska.

A total of 11,811 scenes of interest were selected, and the list was submitted to the U.S. Geological Survey (USGS) Earth Explorer website (http://earthexplorer.usgs.gov) for processing. Some of the scenes (166) could not be processed, though the USGS indicates that it is possible that these may be processed in the future (11,645 scenes downloaded).

The number of images from each path/row was fairly uniform (Fig. 4), with well over 100 scenes with useable imagery for each path/row except some path/rows at the edge of the study area, which were often mostly ocean and sea ice. Few Landsat scenes are collected for path/rows that are mostly ocean, since the satellites are focused on land-surface studies. There are more scenes available towards the east of the study area. There were fewer scenes available towards the north because the daylight acquisition window is reduced with latitude.

While there were some Landsat TM scenes from as early as September 1984, the number of early season (February–May) images was very limited prior to the launch of Landsat 7 in late 1999. The current analysis was heavily weighted by data available in the 2000 to 2011 period (97% of February–May scenes and 90% of June scenes were from the 2000–2011 period) (Supplement Table S1).