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Shrub Cover on the North Slope of Alaska: a circa 2000 Baseline Map

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Abstract

In situ observations show increases in shrub cover in different arctic regions in recent decades and have been cited to explain the increases in arctic vegetation productivity revealed by satellite remote sensing. A widespread increase in shrub cover, particularly tall shrub cover, is likely to profoundly alter the tundra biome because of its influence on biogeochemical cycling and feedbacks to climate. To monitor changes in shrub cover, aid field studies, and inform ecosystem models, we mapped shrub cover across the North Slope of Alaska. First, images from the IKONOS and SPOT satellite sensors were used to detect tall (>1 m) and short shrub presence at high resolution (<5 m grid cells) in different parts of the domain. The resulting maps were then used to train a Random Forest regression algorithm that mapped total and tall shrub cover, expressed as a percent of the total surface area, at 30 m resolution from a mosaic of Landsat scenes. The final shrub cover maps correspond well with field measurements ($r^2 = 0.7$, root mean square error = 17%, $N = 24$) and compared well with the existing vegetation type maps of the study area and a gridded temperature data set not used in the map generation.

Introduction

The most prominent documented change in arctic vegetation during recent climate warming has been derived from satellite observations indicating that regions have become more productive over the past two to three decades (Goetz et al., 2005; Jia et al., 2006; Stow et al., 2007). This so-called ‘greening’ has been attributed to the expansion of dwarf birch (*Betula nana*), alder (*Alnus viridis* ssp. *fruticosa*), and willow (*Salix* spp.), which are all deciduous and hereafter are simply referred to as shrubs (Sturm et al., 2001; Goetz et al., 2007; Post et al., 2009; Forbes et al., 2010). Direct links between satellite and shrub observations have, however, only rarely been established (Forbes et al., 2010). In arctic Alaska repeat aerial photography provides evidence of a widespread increase in tall shrub cover, estimated at 1.2% per decade since 1950 (Tape et al., 2006). Because shrubs are already present in most tundra areas at low density, continued warming could lead to more rapid growth and areal expansion (Epstein et al., 2004; Chapin et al., 2005). Recent work has established that warming and shrub growth, as documented by growth-ring widths, are indeed positively correlated (Hallinger et al., 2010). Moreover, shrub-dominated areas have the highest above-ground biomass of all arctic plant communities, and it increases rapidly not only with warming but also nutrient mobilization (Mack et al., 2004; Wahren et al., 2005). Shrub expansion from warming could have profound effects on arctic ecosystems (Wookey et al., 2009), triggering changes in species diversity (Bret-Harte et al., 2001; Walker et al., 2006), soil biogeochemistry (Weintraub and Schimel, 2005), trace gas exchange between land and atmosphere (Cornelissen et al., 2007), and energy budgets (Sturm et al., 2005a). These changes in key ecosystem processes, particularly if occurring over large expanses of the Arctic as the satellite observations indicate, are thus likely to result in significant feedbacks to climate

(Chapin et al., 2005). Tall shrub branches that protrude from the snow pack in winter, for example, reduce winter albedo and thus result in energy-related positive feedbacks to climate (Euskirchen et al., 2009)

A more local positive feedback loop has been described, whereby climate-induced shrub expansion alters a series of biological processes that ultimately lead to further shrub expansion (Sturm et al., 2005b). The greater stature of shrubs, relative to most of the tundra flora, causes them to trap snow, increasing snow depth. This deeper, more aerated snow layer insulates the soil in winter resulting in warmer winter soil temperatures and a deeper active layer during the growing season (Sturm et al., 2005b; Elberling, 2007). Additionally, the dark branches of the taller shrubs generate a sensible heat flux that accelerates snowmelt and can thus lengthen the growing season (Pomeroy et al., 2006). These two processes promote the mineralization of N and further shrub growth (Schimel et al., 2004; Goetz et al., 2011). In ecosystems where tall shrubs dominate, nutrient availability in the soil is also higher because of higher quality litter, suggesting that shrub expansion is more likely to occur in the vicinity of tall shrubs (Buckeridge et al., 2010; Chu and Grogan, 2010). This relationship has been observed using repeat photography (Tape et al., 2006).

Because of the importance of shrub stature, information on the distribution of shrubs and their relative heights is needed to understand the changing ecosystem dynamics and ecosystem feedbacks to climate associated with tundra shrub expansion. Satellite remote sensing provides a potentially powerful tool to efficiently monitor and understand the dynamics of change in the arctic tundra landscape (Hall et al., 2002; Beck et al., 2006; Hall et al., 2006; Goetz et al., 2007). Through remote sensing, vegetation cover can be mapped over large areas, thus complementing and informing observational (Sturm et al., 2001; Tape et al., 2006),

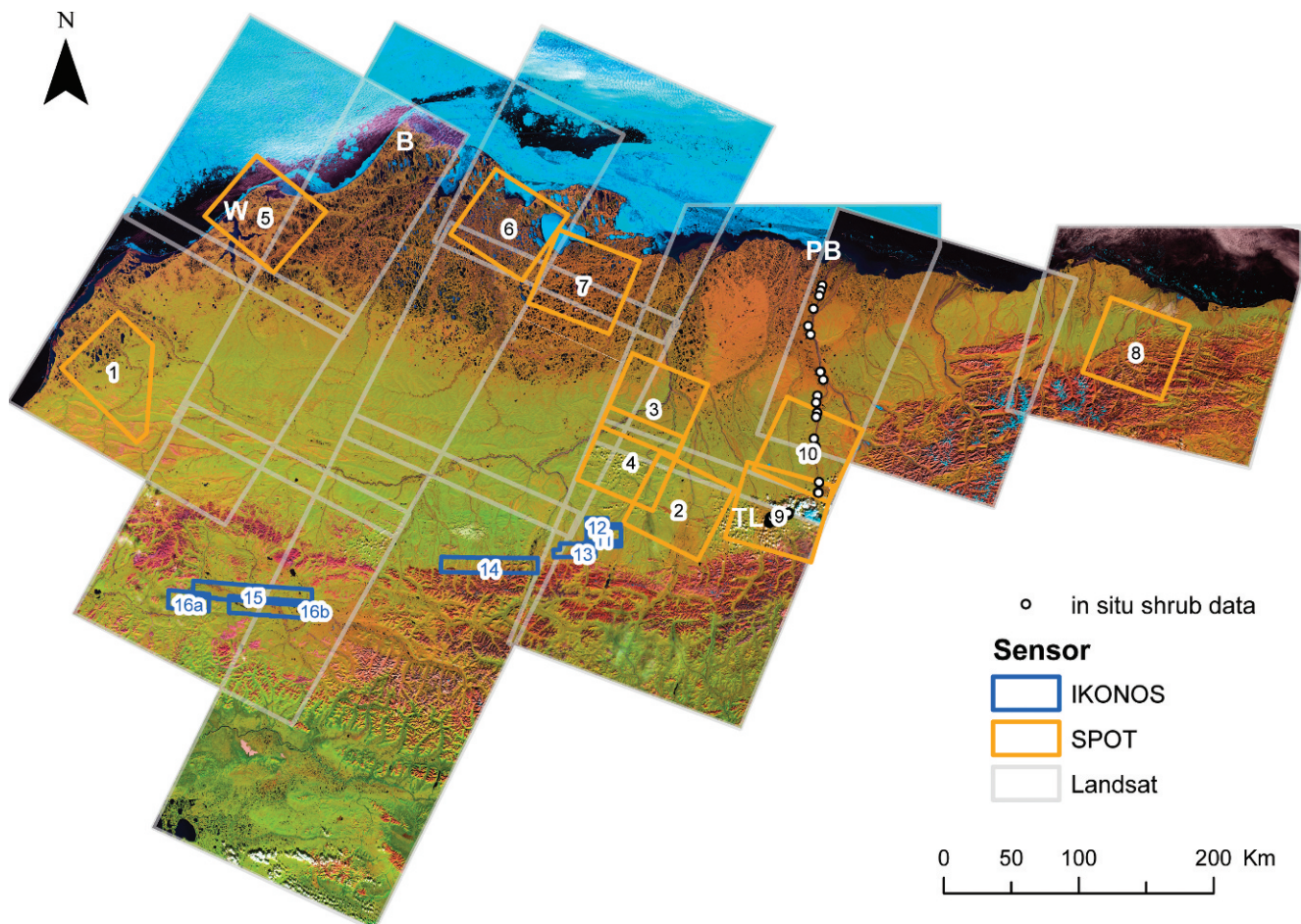


FIGURE 1. Overview of remote sensing data over the North Slope of Alaska and field sites used here. Landsat scenes provide the backdrop and are composited to RGB using bands 5, 4, and 3, respectively. Approximate locations are indicated for Wainwright (W), Barrow (B), Prudhoe Bay (PB), and Toolik Lake (TL).

experimental (Chapin et al., 1995; Bret-Harte et al., 2001; Mack et al., 2004), and modeling studies (Stieglitz et al., 2000; Chapin et al., 2005; Epstein et al., 2007) of ecological feedbacks associated with shrub cover. However, monitoring landscape-scale change in the Arctic using remote sensing requires trade-offs between the spatial and temporal aspects of the observational data sets. High-resolution airborne imagery and satellite data have been used to detect change locally in arctic landscapes by comparing images acquired years apart (Silapaswan et al., 2001; Sturm et al., 2001). Because these data are difficult to acquire, frequently they are not ideal for quantifying change over regional or greater spatial extents. Combining the attributes of regional medium-resolution satellite data and local high-resolution data overcomes some limitations imposed by other approaches as we demonstrate here.

Maps of tundra vegetation types are currently available for the Pan-Arctic (Walker et al., 2002), national (Gould et al., 2002), regional (Nilsen et al., 1999b; Jorgenson and Heiner, 2003), and very local extents (Nilsen et al., 1999a; Alaska Geobotany Center, accessed 2010). These maps depict classes of vegetation at different scales based on species composition or dominance, ecosystems, or physiognomic units based on plant growth forms. In contrast to common vegetation maps which represent vegetation as discrete classes, “continuous field maps” (DeFries et al., 1995; Hansen et al., 1996; Beck et al., 2005) represent the density of cover as percentage values. As a result, continuous field maps are well suited to detect gradual changes, such as the increasing shrub density documented at fine spatial scales. Our objective was thus

to create baseline maps of total and tall (>1 m) shrub cover for the North Slope of Alaska by combining fine- (<5 m) and medium-resolution (~30 m) remote sensing data. The resulting maps, derived from IKONOS, SPOT, and Landsat imagery, depict the proportional cover of shrubs as a percent of the total surface area at 30 m spatial resolution.

Materials and Methods

REMOTE SENSING DATA

Two sources of high resolution remote sensing data were used (Fig. 1): 16 images from two different series of satellites were located discontinuously across the North Slope of Alaska and used to create local maps of short and tall shrub presence or absence at high resolution (1–5 m). A third set of 11 Landsat images with 30 m resolution was used to provide complete coverage of the North Slope of Alaska and map shrub cover on a continuous scale (0–100%) using the higher resolution maps as reference data.

SPOT AND IKONOS SCENES

Ten images were acquired from the high resolution sensors onboard the SPOT 5 satellite that was launched in 2002, and six scenes were acquired from the imaging sensor onboard the IKONOS satellite launched in 1999 (Table 1). The scenes were

TABLE 1

Overview of SPOT and IKONOS satellite images used for short and tall shrub presence/absence mapping and Landsat images used for percent shrub cover mapping. SPOT images at 2.5 and 5 m resolution were produced through the sharpening of 10 m multispectral data with 2.5 m and 5 m panchromatic data, respectively, by SPOT Image Corporation.

Image no.	Satellite	Spatial resolution (m)	Acquisition date
1	SPOT	2.5	2008-07-07
2	SPOT	2.5	2008-07-06
3	SPOT	2.5	2008-07-12
4	SPOT	2.5	2008-07-12
5	SPOT	2.5	2009-07-02
6	SPOT	2.5	2009-07-19
7	SPOT	2.5	2009-08-01
8	SPOT	2.5	2009-07-17
9	SPOT	5	2005-07-28
10	SPOT	5	2005-06-25
11	IKONOS	1	2006-07-24
12	IKONOS	1	2006-07-24
13	IKONOS	1	2006-08-09
14	IKONOS	1	2007-07-05
15	IKONOS	1	2007-08-08
16	IKONOS	1	2007-08-08
A	Landsat	30	2000-07-12
B	Landsat	30	2000-07-12
C	Landsat	30	2001-07-01
D	Landsat	30	1999-07-28
E	Landsat	30	2001-07-03
F	Landsat	30	1999-07-14
G	Landsat	30	1999-08-31
H	Landsat	30	2001-07-14
I	Landsat	30	2002-08-02
J	Landsat	30	2001-06-30
K	Landsat	30	2001-08-28

selected from the summer months to provide a representative sample of landscapes across the North Slope of Alaska with minimal cloud cover (Fig. 1). The SPOT scenes contained 3 spectral bands (green, red, and near-infrared), and the IKONOS scenes 4 spectral bands (blue, green, red, and near-infrared). All SPOT and IKONOS scenes were acquired during July and August in the period 2005–2009.

LANDSAT SCENES

Eleven images acquired by the Enhanced Thematic Mapper aboard the Landsat 7 satellite launched in 1999 were used to provide complete coverage of the North Slope of Alaska at 30 m spatial resolution in 6 spectral bands (blue, green, red, two near-infrared bands, and a mid-infrared band). The images were acquired between 1999 and 2002 in the months of July and August, with the exception of one, which dated from 30 June 2001 (Table 1).

The data were georeferenced and corrected for topographic distortions, and the radiance values in each of the different Landsat scenes and bands were calibrated to one another after clouds and cloud shadows were manually masked. The intercalibration relied on linear regressions, with the intercept fixed at zero, between coincident reflectance values, as registered in areas where multiple scenes overlapped. Using these linear regressions, radiance values recorded in adjacent scenes were transformed. The order of scene processing was determined to maximize the area of overlap between intercalibrated scene pairs. This method has been

shown to standardize spectral data across different satellite images (Hall et al., 1991). Nevertheless, we expect that residual variations in atmospheric conditions and vegetation phenology within scenes may prevent absolute spectral consistency of the final scene mosaic.

The Landsat radiance data displayed shadows due to sun-surface geometry in the steepest areas of the Brooks Range. To avoid these features causing artifacts in the final shrub maps, areas of high topographical slope ($>35^\circ$) and low radiance (maximum radiance in Landsat bands 1–3 $< \text{DN}65$) were excluded from the final tall shrub maps. The shadow effect was not present in the North Slope portion of the map because of the reduced topographic relief north of the Brooks Range.

SHRUB MAPPING

Statistical models were used to predict shrub presence through classification of the high resolution SPOT and IKONOS images and to predict shrub cover through regression of the coarser Landsat images with training data from the shrub presence layers (Fig. 2). The statistical models were based on ensembles of decision trees used for classification and regression, commonly known as Random Forests (Breiman, 2001). Each decision tree in the ensemble used a random sample of the training data and splits of the trees were chosen from subsets of the available predictor variables, randomly selected at each node. In the calibration of individual trees, a subset of the training data, called the out-of-bag sample, was withheld to estimate the classification error. In this study, each Random Forest model consisted of 500 decision trees, which contained at least 1 or 5 observations at each terminal node, for classification and regression models, respectively.

The SPOT and IKONOS scenes were classified into 5 classes (short shrubs, tall shrubs, water, cloud or cloud shadow, and ‘other land cover’) using a Random Forest classification model on a scene-by-scene basis (Fig. 2). Where available, geotagged oblique photographs taken *in situ* between 2004 and 2010 were used to identify reference areas in the satellite scenes to train the classification algorithm. From these 5-class maps, binary maps depicting short shrub presence and tall shrub presence were created. The 16 high-resolution binary presence-absence maps were then spatially aggregated to a grid depicting total and tall shrub percent cover within each Landsat 30 m resolution grid cell.

From each aggregated map of total or tall shrub cover, we randomly selected 1000 samples to train a Random Forest regression model that predicted total and tall shrub cover from Landsat radiance values and elevation. The elevation data were derived from a digital elevation model provided by the U.S. Geological Survey at 60 m horizontal resolution. We converted these to 30 m resolution using cubic spline interpolation to match the Landsat resolution. After total and tall shrub cover were predicted in all Landsat scenes, the resulting shrub cover maps were inter-calibrated following the linear-regression method used for radiance calibration. The regions that coincided with IKONOS or SPOT scenes were used as a reference, since they were used to develop the regression models. Finally, the maps were mosaicked to provide North Slope-wide maps of total and tall shrub cover.

FIELD ASSESSMENT AND COMPARISON WITH EXISTING VEGETATION MAPS

In the summer of 2008, total and tall shrub cover were estimated *in situ* at 24 plots of 900 m² as the consensus of visual estimates made by three observers. The plots coincided with

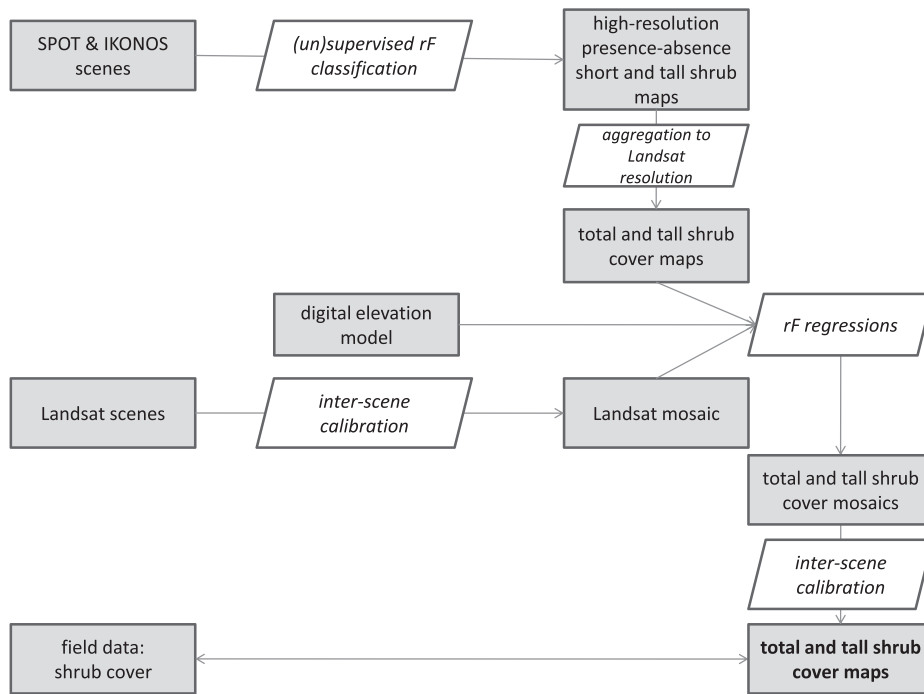


FIGURE 2. Flow chart of data sets (gray shaded) and processing steps (italics).

Landsat grid cells along the Dalton Highway between the Arctic Ocean and the Brooks Range (see Fig. 1) and observed values ranged from 0 to 90% for both tall and total shrub cover.

Shrub cover values from the derived maps were compared to two existing vegetation classifications of Arctic Alaska: (1) The geobotanical vegetation units of the Alaskan section of the Circumpolar Arctic Vegetation Map (CAVM; Walker et al., 2002), and (2) the eight physiognomic tundra classes of the Ecosystems of Northern Alaska map (ENAK; Jorgenson and Heiner, 2003).

The CAVM was originally produced at 1:7.5 M scale from remote sensing data, elevation models, surface and bedrock geology maps, and regional vegetation maps. A false color-infrared image composited at 1 km resolution from Advanced Very High Resolution Radiometer (AVHRR) data acquired between April and October of 1993 and 1995 provided the baseline for regional experts from arctic countries to draw polygons, following a common classification system (Walker et al., 2002). Here, the barren and mountain classes of the CAVM were merged and wetlands of different bioclimatic subzones were differentiated. The bioclimatic subzones, (A) Herb subzone, (B) Prostrate dwarf-shrub subzone, (C) Hemiprostrate dwarf-shrub zone, (D) Erect dwarf-shrub subzone, and the (E) Low-shrub subzone, represent a gradient of increasing summer temperature with subzone C lying roughly between the 5 and 7 °C mean July temperature isopleths, and subzones D and E extending southward to the 9 and 12 °C mean July temperature isopleths, respectively.

Input data to develop the ENAK included Landsat Multi-spectral Scanner images classified at 100 m resolution, a digital elevation model and gridded land cover maps of varying spatial resolution for, amongst others, the Northwest Areas (at 28 m), Gates of the Arctic National Park and Preserve (at 30 m), and the Arctic Refuge (50 m). As a result, the ENAK map varies in spatial resolution from 28 m to 100 m depending on the availability of input data.

COMPARISON WITH CLIMATE

Monthly temperature grids for the period 1960–2008 were acquired from Scenarios Network for Alaska Planning (SNAP; <<http://www.snap.uaf.edu/downloads/alaska-climate-datasets>>). These data were derived from Climate Research Unit (CRU) data sets downscaled to 2 km grid cells. For our application, grid cells of monthly temperature data were grouped into 1 °C bins and used to describe the correlation between shrub cover and macroclimate across the study domain.

Results

MAPS OF TOTAL AND TALL SHRUB COVER

The regression model predicting semi-continuous total and tall shrub cover from Landsat imagery agreed reasonably well with the shrub cover estimated from SPOT and IKONOS and aggregated to Landsat resolution. About 68% and 43% of the variance in total and tall shrub cover, respectively, was explained by the models, based on the out-of-bag samples. Shrub presence was predicted in 86% of the mapped area, with 78% of the mapped area having a cover of $\geq 10\%$ and 54% having a cover of $\geq 50\%$. The maps show shrubs are nearly ubiquitously present on the North Slope of Alaska, occurring in all but the wettest areas, with the low-lying wetland areas on the coastal plain of the North Slope having the lowest shrub cover (Fig. 3).

Tall shrub presence was predicted in 29% of the mapped area, with 18% having a cover of $\geq 10\%$ and 3% having a cover of $\geq 50\%$. The map indicates a general east-west gradient of increasing shrub cover, and tall shrub cover in particular on the North Slope of Alaska. Further north on the North Slope, tall shrubs become more restricted to favorable topographical conditions such as stream channels and floodplains. In addition, tall shrub cover $> 5\%$ was rarely observed when total shrub cover was $\leq 60\%$ (Fig. 4).

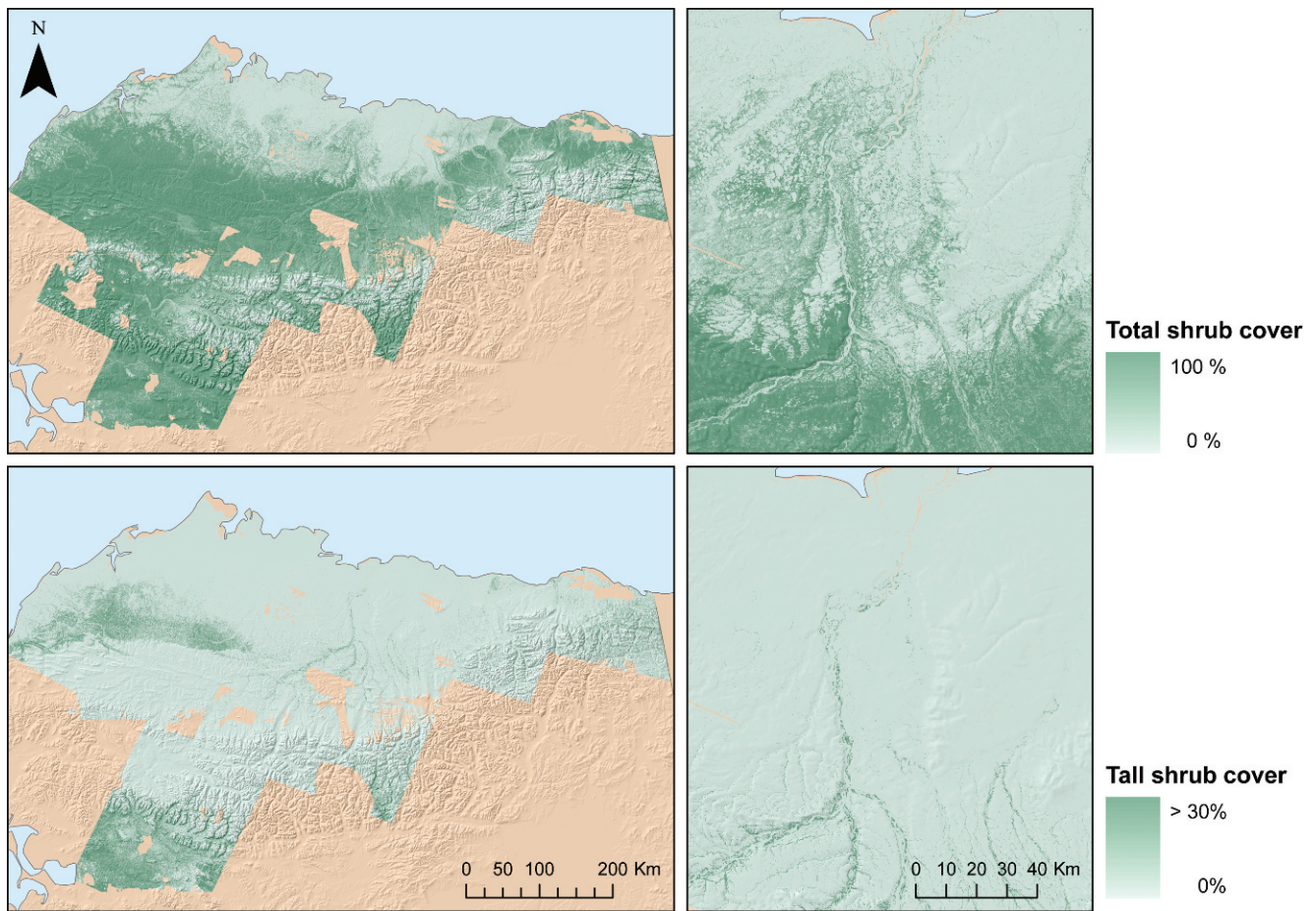


FIGURE 3. Total (upper panels) and tall (lower panels) shrub cover on a background of elevation. Left-hand panels show the entire mapped area, which includes the North Slope and part of the Brooks Range. Right-hand panels show the maps centered on the lower section of the Colville River.

MAP ASSESSMENT AND COMPARISON WITH EXISTING MAPS

Comparisons with field observations showed good agreement between mapped and observed total shrub cover ($r^2 = 0.72$, root mean square error ($RMSE$) = 19%, $N = 24$; Fig. 5a), but somewhat poorer agreement between mapped and observed tall shrub cover ($r^2 = 0.63$, $RMSE = 23\%$, $N = 24$; Fig. 5b). Despite relying on separate regression models, predictions of total shrub cover and tall shrub cover were consistent with each other. Contradictions between the two maps that indicate errors, i.e. areas where total shrub cover wrongly exceeded tall shrub cover, were very rare (2% of the total area). In cases where predicted tall shrub cover exceeded predicted total shrub cover it was by a relatively small margin (mean = 14%, s.d. = 20%) i.e. within the uncertainty of the predictions. For the final maps, tall as well as total shrub cover in these areas were set to the mean of the originally predicted tall and total shrub cover.

COMPARISON WITH EXISTING MAPS

Average shrub cover in the CAVM classes represented in the study area range from 11% in the wetlands of bioclimatic subzone C to 73% in the low-shrub tundra (Fig. 6a). The wetlands show a clear gradient of shrub cover which follows the bioclimatic zones (Fig. 6a). Wetlands in climate zone C have an average shrub cover of only 11%, and have a near absence of tall shrubs (<1%) as do wetlands in climate zone D (<2%). Average total wetland shrub

cover increased from zone C to D (26%) to E (60%). Of all the classes, wetlands in climate zone E had the highest tall shrub cover (26%).

Among the ENAK classes, shrub cover was highest in the birch and willow dominated low shrub class (75%), and the shrubby tussock tundra (74%), followed by the alder dominated tall shrub (64%) and the tussock tundra (61%) classes (Fig. 6b). The barren and wet meadow classes had the lowest shrub cover at 15% and 21%, respectively. Tall shrub tundra had the highest tall shrub cover (11%), but similar values were recorded in both tussock tundra and the low shrub class (both 8%).

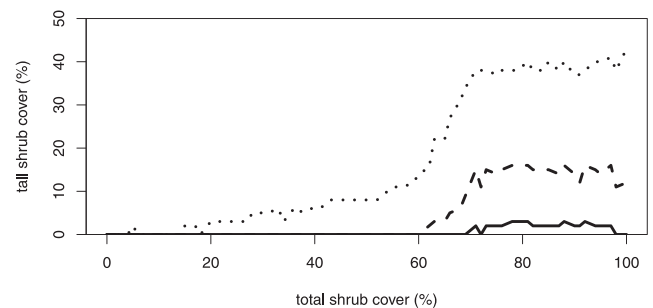


FIGURE 4. Median (solid line), 70% quantile (dashed line), and 90% quantile (dotted line) of tall shrub cover along a gradient of total shrub cover. Tall shrub cover values represent means calculated in 1% bins of total shrub cover.

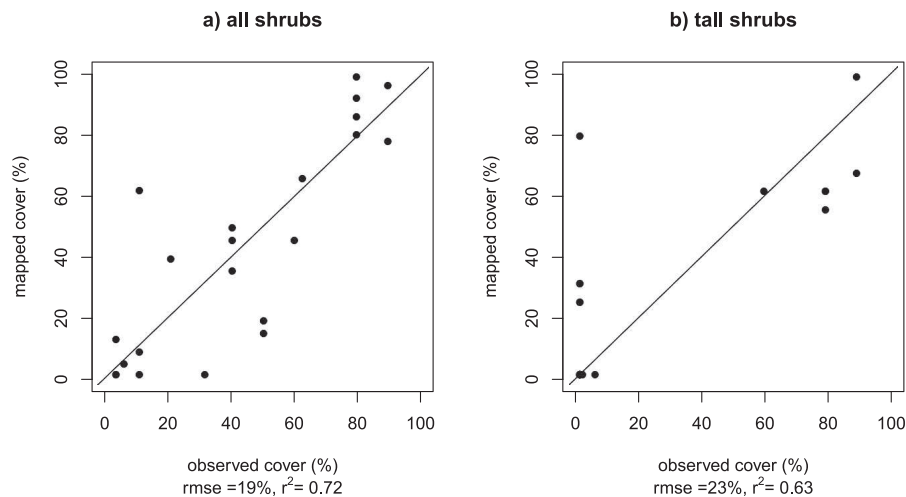


FIGURE 5. Mapped (a) total and (b) tall shrub cover versus *in situ* cover estimates (dots), and position of perfect agreement (line). rmse = root mean square error.

COMPARISON WITH CLIMATE GRADIENTS

Comparison with monthly temperatures suggests that the observed regional gradients in shrub cover in our map are directly related to temperature differences during the growing season (Fig. 7a). Regional temperature patterns correlate more consistently with total shrub cover than with tall shrub cover (maximum correlation [Kendall's τ] = 0.87 vs. 0.68). This is partly the result of a strong non-linear relationship between summer temperature and total shrub cover (Fig. 7b), with mean tall shrub cover being minimal (<10%) in areas with a mean July temperature below 9 °C.

Discussion

HIGH-RESOLUTION VEGETATION MAPPING

The approach we used to map shrub cover across the North Slope of Alaska combined the benefits of fine resolution remote sensing (SPOT and IKONOS), which allowed detection of all but the smallest shrub patches (<1–5 m), with the regional cover provided by coarser resolution Landsat data. The resulting map of shrub cover spans about 250,000 km² at a 30 m spatial resolution. The shrub maps presented here are the first to depict cover across the North Slope on a continuous scale and, as such, provide a

baseline to track shrub changes independently of community composition and vegetation type classification. In addition, the maps can inform both local ecological studies and landscape-scale modeling efforts.

Collecting field data on vegetation in most arctic regions is difficult because of the remoteness of much of the landscape and the short growing season. By using fine resolution (1–5 m) satellite data sampled across the study domain we were able to detect shrub cover with relatively high confidence in areas that could not be easily visited in the field. Moreover, creating maps of arctic vegetation covering large areas from optical remote sensing data is challenging because the growing season is short and cloud cover is high, limiting the opportunities for satellite image acquisition. To inform ecological field studies, spatial data needs to be of sufficiently high resolution. Landsat data have been proven very useful for a wide variety of mapping activities (Tatem et al., 2008). However, because of Landsat's 16-day revisit cycle, imagery from three years were needed to provide full, nearly cloud-free coverage of the North Slope of Alaska. While only images acquired during the summer months were used, seasonal and yearly variation in vegetation phenology and illumination conditions caused substantial variation between the original Landsat scenes. Even though radiance values in the different Landsat scenes were

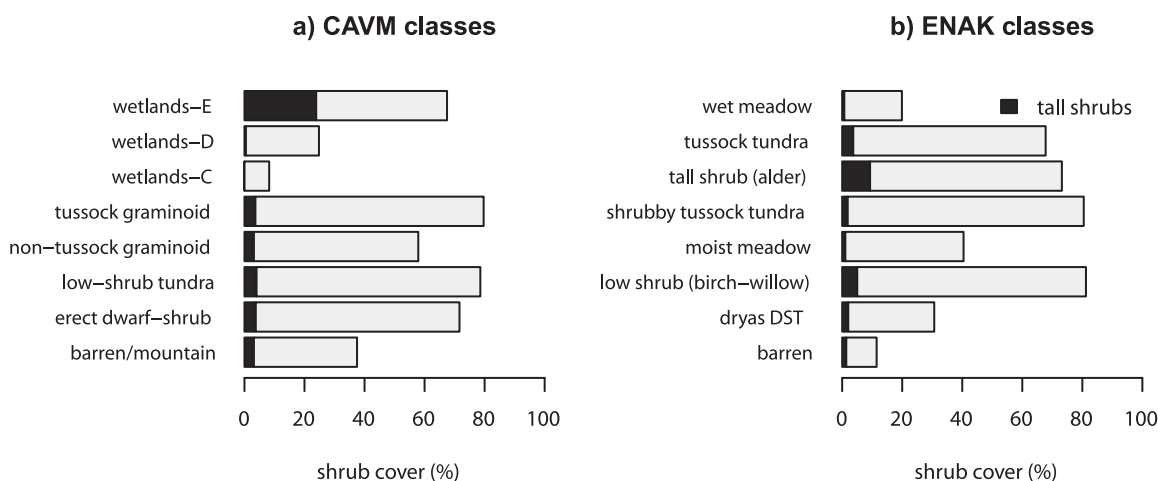


FIGURE 6. Shrub cover in tundra vegetation classes in northern Alaska, as defined in (a) the Circumpolar Arctic Vegetation Map (CAVM; Walker et al., 2002) and (b) the Ecosystems of Northern Alaska map, where DST stands for Dwarf Shrub Tundra (ENAK; Jorgenson and Heiner, 2003).

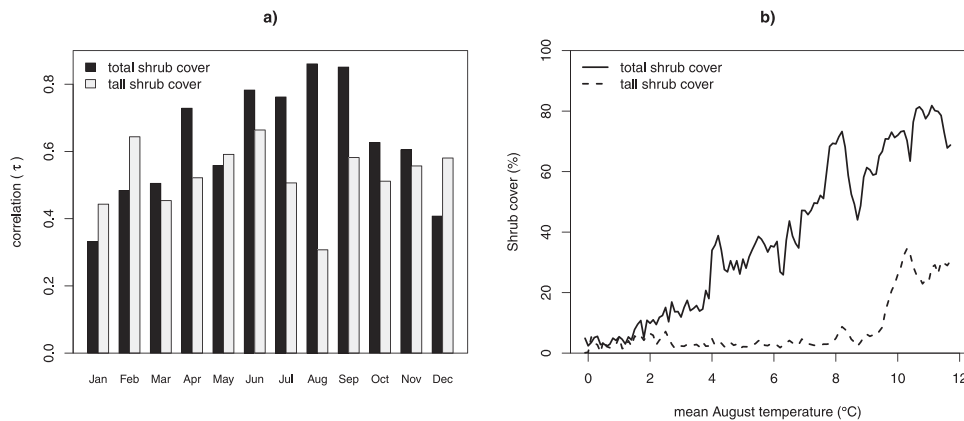


FIGURE 7. (a) Correlation between monthly mean temperature in the period 1960–2008 and mapped (tall) shrub cover, and (b) mean (tall) shrub cover in the mapped area along an August temperature gradient.

calibrated to one another, artifacts remain in the map at some intersections of adjacent Landsat scenes. Together with the paucity and limited spatial cover of field data available for validation, this indicates that the quantitative estimates of shrub cover provided by the maps have uncertainties that should be considered when tracking year-to-year changes in shrub cover. Our map provides the first comprehensive description of current spatial patterns in shrub cover and distribution over the full spatial extent of the North Slope of Alaska.

The fine resolution satellite scenes used for the detection of shrub patches and used for the calibration of the Landsat-based regression algorithm were acquired by the SPOT and IKONOS instruments between 2005 and 2009. As a result, a maximum mismatch of 9 years (median = 6 years), occurred between the acquisition of fine resolution data and coinciding Landsat data. Shorter temporal discrepancies occurred between the fine resolution satellite images and the oblique *in situ* photographs used to classify them. Although time series measurements of shrub cover on a landscape scale are sparse, repeat photography indicates that over this time period average increases in shrub cover have been incremental in Arctic Alaska (Tape et al., 2006). We have consequently assumed in our approach that the nested imagery acquired within a decade depicts comparable shrub cover. While small changes might have occurred over this time period, these are most likely within the error margin of the maps. Any disparities between imagery and validation could be more accurately elucidated retrospectively in local scale applications and associated assessments of the baseline map. We also note that occasionally significant overestimates of tall shrub cover occur in the map (Fig. 5b). These result from erroneous classification of low shrubs as tall shrubs during mapping and stem from our definition of tall shrubs as those plants that exceed 1 m of height. This threshold in the vertical structure of the shrubs does not always coincide with clear-cut spectral properties, limiting the ability of passive optical remote sensing data to distinguish between short and tall shrubs.

Whereas our primary objective was to generate a map of the circa 2000 shrub distribution on the North Slope of Alaska, the methods developed here have utility to other mapping applications. The specific algorithms developed for shrub cover mapping would, however, need to be calibrated to other regions using field or high resolution observations. The calibration of the Landsat radiance values, which in our case was relative to reference scenes (after Hall et al., 1991), was aimed at radiometric consistency rather than absolute radiometric accuracy, thus the regression tree parameterizations are not transferable to other Landsat scenes. In addition, the use of elevation information renders the shrub

mapping algorithm specific to the shrub-elevation relationship observed in our study domain. Both of these limitations illustrate the need for radiometrically consistent remote sensing data sets from Landsat and Landsat-like sensors to facilitate the monitoring of land cover change. Such efforts are currently underway (Roy et al., 2010) but require continuity of Landsat-like satellite missions.

BIOLOGICAL INTERPRETATION OF SHRUB COVER MAPS

The absence of tall shrubs in grid cells with less than 60% total shrub cover might be the result of locally observed positive feedbacks related to shrub growth (Sturm et al., 2005b; Elberling, 2007). Patches of high shrub cover trap more snow, thus increasing nutrient availability (Schimel et al., 2004) and promoting lateral and then vertical shrub expansion. A similar mechanism might explain the growth of low-stature shrubs that expand around previously established tall shrubs observed earlier (Tape et al., 2006).

The vegetation units depicted in the CAVM and ENAK maps varied significantly in their total and tall shrub cover estimates. Along the arctic bioclimatic subzones C, D, and E, the wetland communities of the CAVM show a strong association with our mapped estimates of shrub cover. Tall shrub cover was low in wetlands of both the C and D subzones, but highest of all CAVM classes in subzone E, which might contribute to the observed exponential increase in phytomass across these subzones (Raynolds et al., 2006). The relatively high shrub cover in the mountain/barren class might be due to the inclusion of relatively small shrub patches in the areas designated as mountains in the CAVM. These are possibly present due to the relatively coarse scale of the CAVM (Raynolds et al., 2008). Among the ENAK classes, the ‘tall shrub (alder)’ class had, logically, the highest tall shrub cover. However, average tall shrub cover in this class was low in absolute terms (11%).

At the 2 km scale of our climate data, the temperature-tall shrub correlation is lower than the temperature-all shrub correlation. Moreover, the relationship between tall shrub cover and August temperature was strongly non-linear. This was consistent with previous observations of broad scale tundra greening and temperature sensitivity (e.g. Bunn et al., 2005). At the northern end of their distribution, tall shrubs are more sensitive to micro-site conditions, as their distribution along river floodplains and ravines indicates. The micro-climate conditions that allow tall shrubs to occupy these areas are not well-represented in the moderate resolution climate data used here, and may thus limit the observed correlation with tall shrub cover.

Conclusion

As the effects of high latitude climate change become better documented, baseline studies are essential to monitor and anticipate future changes. Ideally such studies should be performed systematically, over large areas and in a repeatable manner (Post et al., 2009). The method we developed and report on here demonstrates how high resolution remote sensing observations, and the detail they provide, can be combined with the large area coverage provided by moderate resolution satellite imagery to create regional continuous maps. However, challenges remain in the automated generation of consistent data sets for future shrub cover monitoring. The continuous shrub cover maps that we produced will be submitted to the National Snow and Ice Data Center (NSIDC) archive. They can be used for monitoring ongoing change in arctic vegetation and are potentially useful to inform retrospective studies and help to elucidate earlier documented changes in arctic vegetation productivity (Goetz et al., 2011; Beck et al., 2011). Finally, these data sets not only provide valuable information across a large spatial domain, but are also at sufficiently fine spatial resolution to inform field-based ecological studies and models.

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