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High-resolution mapping of aboveground shrub biomass in Arctic tundra using airborne lidar and imagery

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ABSTRACT

Accurate monitoring of climate-driven expansion of low-stature shrubs in Arctic tundra requires high-resolution maps of shrub biomass that can accurately quantify the current baseline over relevant spatial and temporal extents. In this study, our goal was to use airborne lidar and imagery to build accurate high-resolution shrub biomass maps for an important research landscape in the American Arctic. In a leave-one-out cross-validation analysis, optimized lidar-derived canopy volume was a good single predictor of harvested shrub biomass ($R^2 = 0.62$; RMSD = 219 g m^{-2}; slope = 1.08). However, model accuracy was improved by incorporating additional lidar-derived canopy metrics and airborne spectral metrics in a Random Forest regression approach (pseudo $R^2 = 0.71$; RMSD = 197 g m^{-2}; slope = 1.02). The best Random Forest model was used to map shrub biomass at 0.80 m resolution across three lidar collection footprints (~12.5 km^2 total) near Toolik Field Station on Alaska's North Slope. We characterized model uncertainty by creating corresponding maps of the coefficient of variation in Random Forest shrub biomass estimates. We also explore potential benefits of incorporating lidar-derived topographic metrics, and consider tradeoffs inherent in employing different data sources for high-resolution vegetation mapping efforts. This study yielded maps that provide valuable, high-resolution spatial estimates of aboveground shrub biomass and canopy volume in a rapidly changing tundra ecosystem.

1. Introduction

Accelerating climate warming in Arctic regions appears to be stimulating an increase in abundance, size, and range of deciduous tundra shrubs—mostly willow (*Salix* spp.), birch (*Betula* spp.) and alder (*Alnus* spp.) (Myers-Smith et al., 2011, 2015; Naito and Cairns, 2015; Tape et al., 2006). This shift in tundra vegetation communities is expected to impact wildlife habitat and trophic interactions (Boelman et al., 2014; Rich et al., 2013), alter carbon and nutrient storage and cycling (Mack et al., 2004; Schimel et al., 2004), influence hydrology and permafrost dynamics (Blok et al., 2010; Lawrence and Swenson, 2011), and may contribute to additional warming (Chapin et al., 2005; Loranty and Goetz, 2012). To permit accurate accounting of these ecological changes, and to facilitate modeling and prediction of landscape trajectories as climate continues to warm, researchers and managers require spatial models (maps) of tundra vegetation structure and biomass. However, the fine spatial heterogeneity and low stature of tundra vegetation communities present a daunting challenge for conventional methods of mapping aboveground vegetation biomass.

Owing to the considerable extent of the Arctic tundra biome, maps of tundra vegetation attributes often cover large areas at coarse resolution (e.g. the Circumpolar Arctic Vegetation Map [CAVM]; Walker et al., 2005). Moderate resolution (20+ m pixel) vegetation maps exist for some tundra regions: in Alaska, for example, the North Slope, and especially the Dalton Highway corridor stretching from Prudhoe Bay to the Brooks Range, is one of the best-studied and best-mapped regions of the American Arctic. Multiple efforts have been made in that region to characterize coarse- and moderate-scale land cover (Ducks Unlimited, 2013; Muller et al., 1999; Raynolds et al., 2005; Walker and Maier, 2007; Walker et al., 2005; www.arcticatlas.org) and total aboveground biomass (Raynolds et al., 2012; Shippert et al., 1995; Simms and Ward, 2013; Walker et al., 2005), but there have been relatively few attempts to describe existing shrub characteristics in better detail or higher resolution.

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The shortage of high-resolution maps (<20 m pixel) represents a significant data gap, since these maps are necessary for characterizing spatial heterogeneity of tundra vegetation (Lantz et al., 2010; Naito and Cairns, 2015; Raynolds et al., 2008), calibrating and validating coarser maps (Stow et al., 2004), and estimating related fine-scale ecological function such as wildlife habitat suitability (Boelman et al., 2014). These considerations are especially important in tundra ecosystems, where vegetation communities can be heterogeneous at extremely fine spatial scales (e.g. <1 m; Walker et al., 1994), rendering moderate-resolution maps inadequate (Lantz et al., 2010; Stow et al., 2004). Additionally, although shrubs are the tallest common vegetation on the treeless tundra landscape, their height rarely exceeds 2 m except in deeply thawed riparian areas; generally, tundra shrubs are <1 m in height and occur in slow-growing, irregular patches or dispersed among other tundra vegetation. Such low-stature, heterogeneous vegetation is especially difficult to identify and quantify using coarse- and moderate-resolution passive satellite-based remote-sensing approaches.

Maps that focus on characteristics of shrub canopies are especially uncommon. Active satellite-based data such as synthetic aperture radar (SAR) show promise for mapping shrub attributes at moderate resolution (Duguay et al., 2015), although so far such approaches are relatively rare. Selkowitz (2010) explored the potential strengths of different passive satellite data sources for moderate-resolution fractional shrub cover mapping over a swath of northern Alaska; Beck et al. (2011) used a selection of high-resolution commercial satellite imagery (IKONOS and SPOT, 1–5 m pixel) to train a model that estimated fractional cover of total and 'tall' (>1 m) shrubs at 30 m resolution across the entire North Slope of Alaska. While these moderate-resolution maps represent valuable baselines for understanding shrub cover over a large and ecologically important area, their resolution limits their applicability and poses challenges for verification in local areas. For example, in Beck et al. (2011), validation could only be performed against existing maps of similar or coarser resolution, and against relatively few (24) visual cover estimates by field observers, rather than against quantitative in situ measurements or higher resolution validated maps. Further, these maps (necessarily for their resolution) quantify percent shrub cover per area, a metric that obscures gradients in shrub structure and spatial patterns of distribution and constrains applications that depend on understanding these properties. Higher resolution maps are likely necessary to provide baselines against which incremental changes in heterogeneous shrub cover can be evaluated, especially in topographically complex landscapes (e.g. Naito and Cairns, 2015; Raynolds et al., 2008). Accurately identifying and monitoring vegetation changes, and understanding and quantifying landscape processes and function occurring at such fine scales requires high-resolution maps that can capture fine-grained heterogeneity and gradients in low-stature vegetation at a spatial scale relevant to the vegetation. Although such high-resolution maps would necessarily be limited in extent, coverage of even a few important landscapes would provide outsized informational value to researchers and managers working across the biome.

Challenges inherent in mapping heterogeneous low-stature vegetation highlight the importance of airborne and surface-based remote sensing approaches. Airborne lidar (light detection and ranging) has proven to be a powerful tool for quantifying structure-related attributes in ecosystems as diverse as forests (Dubayah and Drake, 2000; Hudak et al., 2012), Mediterranean woodlands (Estornell et al., 2012), salt marshes (Hladik et al., 2013), rangelands (Ritchie et al., 2001; Streutker and Glenn, 2006; Vierling et al., 2012), and agricultural fields (Eitel et al., 2014). Airborne lidar can be collected over small to moderate spatial extents and at a high spatial resolution (generally 1–30 data points per square meter). Lidar provides three-dimensional (3D) structural information that is difficult to quantify from passive optical data, making it especially relevant to the challenges of quantifying subtle variations in vegetation structure.

Although the high resolution and three-dimensionality of lidar make it a strong and flexible tool, using lidar to quantify vegetation metrics in low-stature ecosystems remains challenging. Methods for using lidar data to derive biomass estimates for shrubs (Estornell et al., 2011; Greaves et al., 2015; Olsoy et al., 2014) generally differ from methods established in forest systems, due to the severely abbreviated height range of shrub canopies. Low vegetation stature is often further exaggerated in lidar data, because airborne lidar tends to significantly underestimate vegetation heights in shrub systems. This may occur because of threshold limitations of the laser sensor, or because a laser pulse may miss the highest branch of a sparse shrub or fail to reach the ground through dense shrub canopies. These difficulties can make it impossible to accurately retrieve ground or canopy surfaces (and therefore canopy height) in areas of dense shrub cover. Depending on the density of the canopy and of the lidar data collection, the resulting error in vegetation height estimates can represent up to 50% of total shrub height (Streutker and Glenn, 2006).

Despite these difficulties, previous research with terrestrial (ground-based) lidar has shown that lidar-derived canopy volume can provide a good proxy for aboveground biomass in Arctic tundra (Greaves et al., 2015), as well as in dry sagebrush systems (Olsoy et al., 2014) and agricultural settings (Eitel et al., 2014). Quantifying canopy volume provides a direct, continuous metric of canopy structure that can encompass both horizontal and vertical components of vegetation, especially when measured at high spatial resolution. Given the problems inherent in using lidar to identify ground and canopy surfaces in shrub systems, lidar-derived shrub canopy volumes are unlikely to be correct in an absolute sense; however, they provide meaningful data when well calibrated against in situ vegetation sampling (Greaves et al., 2015; Olsoy et al., 2014). And although canopy volume is less commonly used than other airborne lidar metrics (but see e.g. Kim et al. (2009); Tao et al. (2014)), the previous success of volumetric approaches with terrestrial lidar suggests that such methods may also be successful with airborne lidar data. This may be particularly true in very low-stature ecosystems like Arctic tundra, where both terrestrial and airborne lidar data are acquired from above the canopy, making such datasets more similar to each other than they might be otherwise.

In this study, we investigate the potential for mapping shrub biomass estimates using lidar-derived canopy volume in a simple linear regression model. Such a parsimonious model would be less susceptible to overfitting of training data than a more complex model, and detecting changes across multiple datasets collected over time would be fairly straightforward (e.g. Jones et al. (2013))—especially because lidar datasets are somewhat more repeatable than aerial photography or even satellite data, which are more susceptible to variations caused by sun-sensor geometry and atmospheric effects (see Bater et al. (2011) for a discussion of lidar data stability over multiple data collections).

Although such a simple model is attractive, fusing lidar with spectral data has yielded improved estimates of vegetation biomass in a range of ecosystems (Zolkos et al., 2013); for example this approach has enhanced sagebrush mapping (Mundt, Streutker and Glenn, 2006), tree species classification (Dalponte et al., 2008), and quantification of tree structure (Hyde et al., 2006). This complementarity of lidar and spectral data is logical, since lidar measures the 3D structure of vegetation, while spectral data suggest its species and physiological state. For example, Reese et al. (2014) found that combining lidar and spectral data improved classification of alpine vegetation types, because spectral data improved differentiation among vegetation types that have similar vertical structure but different spectral properties, while lidar data improved differentiation among vegetation types with similar spectral properties but different vertical structure.

Combining lidar with high-resolution spectral data is an especially powerful technique for characterizing shrubs in low-stature ecosystems (Estornell et al., 2012; Mundt et al., 2006; Riaño et al., 2007), suggesting that the potential for improved mapping accuracy may outweigh a preference for a simple model. In the Arctic, high-resolution photography