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Airborne laser scanning and spectral remote sensing give a bird's eye perspective on arctic tundra breeding habitat at multiple spatial scales

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ABSTRACT

The effects of climate change are more acute in the Arctic than any other region, and as such, arctic tundra wildlife habitats are changing in ways that are not yet well understood. Remote sensing tools are capable of assessing dynamics in wildlife-habitat associations over a wide range of spatial scales and in a variety of ecosystems. As already well-established in other ecosystems, Light Detection and Ranging (LiDaR) technology has the potential to greatly expand our understanding of tundra wildlife-habitat associations because unlike the most commonly used spectral vegetation index - the Normalized Difference Vegetation Index (NDVI) - LiDaR directly quantifies three-dimensional (3-D) vegetation structure. Only recently has airborne laser scanning (ALS) technology evolved to having vertical resolution and point densities high enough to quantify small differences in vegetation structure, such as characterize arctic tundra ecosystems. Our objective was to employ ALS metrics, airborne spectral data (for NDVI), and Landsat 7 ETM+ data (for snow cover) to determine the relative importance of a suite of ecological characteristics - considered at multiple spatial scales - on habitat use and reproductive success of two of the most common migratory songbird species breeding in northern Alaska. Our most important findings are that (1) combining ALS metrics, but not NDVI, with Landsat derived snow cover data provided useful information, revealing that while Gambel's white-crowned sparrows use breeding territories in areas with high canopy volume and large snow-free areas, Lapland longspurs will establish territories in areas with low canopy volume, small patches of snow-free tundra, and minimal surface wetness and; (2) while habitat characteristics were important determinants of habitat use for both species at the territory scale, those in the immediate vicinity of nest-sites were not important. Contrary to expectation, we also found that the reproductive success of both species was unaffected by variation in our hypothesized metrics of shelter and food availability (canopy volume, standard deviation of micro-terrain height) at both the nest-site or territory scales. Our study is the first arctic demonstration of how ALS yields novel insights into wildlife-habitat associations, suggesting it has great potential in other ecosystems with similarly small - yet often ecologically important - ranges in 3-D vegetation structure.

1. Introduction

1.1. Remote sensing of arctic tundra wildlife habitat

The effects of climate change are more acute in the Arctic than any other region (Callaghan et al., 2004). Considering the myriad current and expected future changes in vegetation cover (Pearson et al., 2013; Zhang et al., 2013) and phenology (Zeng, Jia, and Epstein, 2011), snow cover dynamics (Derksen and Brown, 2012; Stone et al., 2002), and seasonality in environmental conditions (Bintanja and van der Linden, 2013; Chapman and Walsh, 1993; Overland et al., 2004; Serreze et al., 2000); the spatial and temporal characteristics of current wildlife habitats are also expected to change considerably (Boelman et al., 2014; Ehrich et al., 2012; Henden et al., 2011; Post et al., 2009; Zöckler and Lysenko, 2000). While some species are likely to benefit or adapt to these changes, others will shift their geographic range or be extirpated (Boelman et al., 2014; Wingfield et al., 2016). In order to better predict how a particular species will respond to changing tundra conditions, it is necessary to determine the relative importance of ecological characteristics that define its habitat (Bowler and Benton, 2005; Clobert et al., 2009; Cote et al., 2010; Wingfield et al., 2016;

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Parmesan and Yohe, 2003; Parmesan, 2007). Although field surveys are often an essential first step towards understanding wildlife-habitat associations, for practical reasons they are typically limited in their spatial scope. However, combining animal surveys with remote sensing and predictive modeling techniques can not only broaden the spatial applicability of field-derived findings, but can also enable examination of the importance of key ecological characteristics at multiple spatial scales (Hurlbert and Haskell, 2003; Swatantran et al., 2012; Turner et al., 2003), and is particularly useful for studies of remote and inaccessible regions – such as most of the Arctic.

Although various types of spectral, RADAR (RAdio Detection And Ranging) and LiDaR based remote sensing products have been employed (Bergen et al., 2009; Swatantran et al., 2012; Turner et al., 2003; Vierling et al., 2008; Wood et al., 2013), the Normalized Difference Vegetation Index (NDVI, Rouse et al., 1974) is by far the most commonly used in wildlife ecology (as reviewed in Hurlbert and Haskell, 2003; and Pettorelli et al., 2011). For example, arctic studies employing NDVI have been used to examine ungulate-vegetation interactions (Griffith et al., 2002; Bremset-Hansen et al., 2009; Couturier et al., 2009; Virtanen et al., 2013) and avian ecology (Pedersen et al., 2007; Shariatinajafabadi et al., 2014; Tombre et al., 2008). The success of NDVI can be in large part attributed to the fact that because it is a good proxy for spatial and temporal dynamics in primary productivity in many contexts, it often correlates with abundance and distribution patterns of animals (as reviewed in Hurlbert and Haskell, 2003; and Pettorelli et al., 2011). While these studies have provided valuable insight, it is likely that inherent measurement limitations of the vegetation index itself fail to elucidate some of the most important wildlife-vegetation associations on the tundra. For example, although the majority of tundra ecosystems are currently dominated by short stature sedge, shrub, moss and lichen cover (Leaf Area Index (LAI) < 1), tall deciduous shrub dominated communities (LAI ≤ 2) are becoming taller, denser, and more ubiquitous in many arctic regions (Elmendorf et al., 2012; Myers-Smith et al., 2011, 2015). As this shift in vegetation cover continues, LAI-NDVI relationships are likely to become less informative in tundra because NDVI tends to be insensitive to variation in green leaf area for canopies in which LAI exceeds values between 2 and 6, depending on the type of vegetation being measured (Chen et al., 2004; Hatfield et al., 1985). Thus, animal responses to increasing shrub dominance may go undetected or misinterpreted. In addition, due to the non-linear contribution of various plant tissue types (i.e. live green tissue, standing litter, stem) to canopy reflectance properties, it has proven challenging to accurately apply the NDVI as a remote proxy for tundra vegetation cover characteristics without use of rarely available a priori knowledge of the vegetation community type dominant within a given pixel (Boelman et al., 2005; Street et al., 2007). Further, NDVI measurements in the tundra will be confounded by temporal variations in rapidly changing vegetation phenology and standing water – which will dilute the NDVI signal, making repeat passive remote sensing measurements difficult to interpret unless taken under identical conditions in space and time (i.e., Gamon et al., 2013). Perhaps the most critical limitation from a wildlife habitat perspective however, is that the NDVI does not directly provide information on the tundra's inherently small yet ecologically important (Boelman et al., 2014; Ehrich et al., 2012; Henden et al., 2011; Sweet et al., 2015), range in vegetation 3-D structure (Boelman et al., 2011; Vierling et al., 1997).

1.2. LiDaR for arctic tundra wildlife studies

Light Detection and Ranging (LiDaR) sensors have the potential to greatly expand our understanding of tundra wildlife-habitat associations because LiDaR directly quantifies the three-dimensional (3-D) structure of vegetation (Lefsky et al., 2002; Zolkos et al., 2013). As such, LiDaR technology is increasingly being used in ecosystems with high structural complexity (i.e. forests) for wildlife habitat characterization and mapping (Hill et al., 2004; Hyde et al., 2005, 2006; Hinsley et al., 2002; Hinsley et al., 2006; Boelman et al., 2007; Goetz et al., 2007; Goetz et al., 2010; Goetz et al., 2014; Clawges et al., 2008; Vierling et al., 2008; Bergen et al., 2009; Vogeler et al., 2014; Zellweger et al., 2014; Davies and Asner, 2014), as well as studies of wildlife behavior (Trainor et al., 2013; Melin et al., 2013; Loarie et al., 2013). To date however, the use of LiDaR technology in ecological studies in low stature ecosystems (i.e. <2 m tall) - such as characterizes the arctic tundra - is extremely limited (Greaves et al., 2015, in review; Streutker and Glenn, 2006). This is due to technological limitations in vertical resolution and point density of LiDaR systems that were previously too coarse to quantify small differences in vegetation structure (Zolkos et al., 2013). It is therefore not surprising that, to our knowledge, LiDaR technology has never been used in wildlife ecology in arctic tundra. Given that the physical structure of tundra vegetation is changing quickly as deciduous shrubs become increasingly tall, dense and abundant (Boelman et al., 2011; Myers-Smith et al., 2011, 2015) and the forest-tundra ecotone expands northward, current advances in LiDaR technology are likely to prove critical to uncovering tundra wildlife-vegetation interactions.

LiDaR technology has proven particularly insightful to the field of avian ecology (see recent reviews by Hill et al., 2004; Muller and Vierling, 2014; Davies and Asner, 2014) because birds are often highly sensitive to the 3-D structure of vegetation cover (e.g. Lesak et al., 2011; Macarthur and Macarthur, 1961). Given that every year, billions of songbirds migrate to breed in the Arctic (Pielou, 1994), LiDaR is likely to be equally informative in the study of arctic-breeding species that exhibit high species specificity in terms of the 3-D structural characteristics of the vegetation communities in which they prefer to nest. In a recent study, Boelman et al. (2014) used field-surveys to determine how vegetation community composition and height were associated with nest-site preferences in two arctic-breeding songbird species, but were subsequently limited in their ability to accurately predict habitat availability at the regional scale. This was partially attributed to the fact that the 3-D structural properties of mapped vegetation cover types are only coarsely known, while it was the fine-scale variations in vegetation structure - that can now be resolved using airborne laser scanning (ALS) (Greaves et al., 2015, in review) - that were determined to be very important to the birds. In addition to vegetation properties, ground-nesting songbirds generally select breeding habitats based on other ecological factors that can be assessed using state of the art ALS technology, including areas where certain micro-topographical characteristics prevail or where surface water does not accumulate during the breeding season (Norment, 1993; Oakeson, 1954; Rodrigues, 1994). Further, many studies have found that the additional inclusion of remotely sensed datasets derived from other sensor types often provide ecological information that is complementary to LiDaR, thus providing more comprehensive characterization of wildlife habitats compared to LiDaR alone (e.g. Davies and Asner, 2014; Holmgren et al., 2008; Nijland et al., 2015; Orka et al., 2013; Zald et al., 2016).

1.3. Objectives and hypotheses

Our goal was to use airborne laser scanning (ALS), as well as spectral reflectance data from both an airborne sensor and the Landsat 7 ETM+ sensor, to determine the relative importance of key ecological characteristics considered at multiple spatial scales, on habitat use and reproductive success of two of the most common migratory songbird species breeding in northern Alaska. Using a suite of spectral reflectance products and ALS derived metrics, we addressed three major objectives: (1) to determine the influence