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Arctic shrub effects on NDVI, summer albedo and soil shading

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ABSTRACT

The influence of Arctic vegetation on albedo, latent and sensible heat fluxes, and active layer thickness is a crucial link between boundary layer climate and permafrost in the context of climate change. Shrubs have been observed to lower the albedo as compared to lichen or graminoid-tundra. Despite its importance, the quantification of the effect of shrubification on summer albedo has not been addressed in much detail. We manipulated shrub density and height in an Arctic dwarf birch (*Betula nana*) shrub canopy to test the effect on shortwave radiative fluxes and on the normalized difference vegetation index (NDVI), a proxy for vegetation productivity used in satellite-based studies. Additionally, we parametrised and validated the 3D radiative transfer model DART to simulate the amount of solar radiation reflected and transmitted by an Arctic shrub canopy. We compared results of model runs of different complexities to measured data from North-East Siberia. We achieved comparably good results with simple turbid medium approaches, including both leaf and branch optical property media, and detailed object based model parameterisations. It was important to explicitly parameterise branches as they accounted for up to 71% of the total canopy absorption and thus contributed significantly to soil shading. Increasing leaf biomass resulted in a significant increase of the NDVI, decrease of transmitted photosynthetically active radiation, and repartitioning of the absorption of shortwave radiation by the canopy components. However, experimental and modelling results show that canopy broadband nadir reflectance and albedo are not significantly decreasing with increasing shrub biomass. We conclude that the leaf to branch ratio, canopy background, and vegetation type replaced by shrubs need to be considered when predicting feedbacks of shrubification to summer albedo, permafrost thaw, and climate warming.

1. Introduction

Arctic ecosystems have been exposed to air temperature increases of almost double the global mean in the 20th century (Chapin et al., 2000; Cowtan & Way, 2014; Serreze et al., 2000; Solomon et al., 2007). Further increases in air temperature and precipitation, as projected for the north-eastern Siberian tundra (Solomon et al., 2007), may cause further shifts in the vegetation distribution in the Arctic (Pearson et al., 2013). Currently observed changes include northward movement of trees and shrubs, which increasingly dominate large areas of tundra (e.g. Miller & Smith, 2012; Myers-Smith et al., 2011; Sturm, Racine, & Tape, 2001; Tape, Sturm, & Racine, 2006). Productivity estimates based on remote sensing, dendroecological, and plot data show an increasing trend with temperature, while the sensitivity of this effect is mediated by soil moisture, with productivity in wet areas responding stronger to temperature increase than in dry areas (Berner, Beck, Bunn, & Goetz, 2013; Blok, Sass-Klaassen, et al., 2011; Elmendorf et al., 2012; Forbes, Fauria, & Zetterberg, 2010; Huemmrich et al., 2010; Kim et al., 2014).

Shrub cover and distribution are not only affected by climate, but also control important components of the surface energy balance. Main observed and expected feedbacks of increasing shrub cover include a reduction of the albedo, an increase in evapotranspiration, and a local decrease in the permafrost active layer due to soil shading (Pearson et al., 2013). Shrub cover reduces the surface albedo during the growing season (Beringer, Chapin, Thompson, & McGuire, 2005; Bonfils et al., 2012; Sturm, Douglas, Racine, & Liston, 2005), but the effect is most pronounced during critical snow accumulation and snowmelt periods (Loranty, Goetz, & Beck, 2011; Sturm et al., 2005). The additional shortwave radiation absorbed by the canopy is partly partitioned into latent and sensible heat fluxes which are likely to increase with increasing shrub height and density (Beringer et al., 2005; Bonfils et al., 2012). Increasing shrub cover increases surface roughness and thus the coupling between the atmosphere and the surface (Beringer et al., 2005). These fluxes are also modulated by other system properties including soil moisture and the presence of mosses (Blok, Heijmans, et al., 2011).

Additionally, shrubs affect the amount of shortwave radiation transmitted to the soil surface, an important component of the soil

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surface energy balance (Eugster et al., 2000). While shrubs increased the winter soil temperature, summer soil temperature was reduced through shading (Myers-Smith & Hik, 2013). At least at the local scale, shrub shading may offset air temperature warming and reduce active layer thickness (Blok et al., 2010; Jorgenson et al., 2010). These changes in the energy balance resulting from shrub expansion may in turn facilitate further shrub growth (Chapin et al., 2005; Swann, Fung, Levis, Bonan, & Doney, 2010).

The quantification of the effect of shrubification on summer albedo has not been addressed in much detail, apart from observations across a latitudinal gradient. It is hard to relate satellite based albedo data to shrub abundance in the Arctic as the spatial resolution of operational satellite-derived albedo products is 0.5 km to 1 km. As such, we are currently unable to effectively assess shrub cover and abundance at this scale. We therefore performed an experimental and radiative transfer modelling study to disentangle the effect of shrub density and height on reflected and transmitted shortwave radiation fluxes and NDVI, the proxy most often used to estimate long-term productivity at large spatial scale (e.g. Bhatt et al., 2010; Hope, Pence, & Stow, 2004). Radiative transfer modelling can help to quantify reflected and transmitted shortwave radiation, including subdaily and seasonal variation (Widlowski et al., 2011). It can be used to validate simpler approaches which are often used in large-scale modelling (Pinty et al., 2006). Two studies on Arctic shrubs quantify the absorption of solar radiation of woody elements before leaf-out (Bewley, Pomeroy, & Essery, 2007; Reid, Essery, Rutter, & King, 2014), but, to our knowledge, no study so far has simulated the full radiative budget of Arctic dwarf shrub leaves and branches including spectral reflectance of the canopy and transmitted radiation.

We present results of modelling and experimental work on the effect of dwarf birch leaf and branch area on the radiative balance. Unlike most studies on the effect of vegetation on the energy balance of the Arctic (e.g. Beringer et al., 2005; Chapin et al., 2005; Loranty et al., 2011), we did not compare different ecosystems but quantified the effects of varying biomass within one vegetation type. We ran the 3D radiative transfer model DART (Gastellu-Etchegorry, Demarez, Pinel, & Zagolski, 1996; Grau & Gastellu-Etchegorry, 2013) for shrub vegetation of different densities. The model was initialised with field data which included detailed information on vegetation structure and leaf and branch optical properties. We validated the model with canopy reflected and transmitted radiation measurements on natural canopies and vegetation with experimentally reduced density. We compared results from models with different levels of complexity to assess the importance of detailed shrub representation on shortwave radiation results.

2. Methods

2.1. Field site

The Kytalyk field site is located in the Indigirka lowlands, North-East Siberia (70.83°N, 147.49°E, Fig. 1, a). The mean annual air temperature is −10.5 °C with a range of −32.5 °C in January and 10.4 °C in July (van der Molen et al., 2007). The mean annual precipitation is 220 mm (Parmentier et al., 2011). Kytalyk is in the continuous permafrost zone with an average active-layer thickness (ALT) of 42 cm. Dry areas show a reduced ALT of 12 cm to 28 cm, while the ALT in wetter areas ranges from 22 cm to 50 cm (Mi et al., 2013).

The Circumpolar Arctic Vegetation Map classifies the vegetation at the study site as tussock-sedge, dwarf-shrub, moss tundra (Walker et al., 2005). Dwarf birch (*Betula nana*) is the main shrub type (Fig. 1, d). Shrubs and sedges are arranged alternately in small patches associated with microtopography and moisture on the scale of a few metres in the area of a drained thaw lake bed (Fig. 1, b and c).

2.2. Field experiment and measurements

We conducted a field campaign in June and July 2012 and measured input and validation data to parameterise a radiative transfer model for dwarf birch canopies. We performed a manipulation experiment to

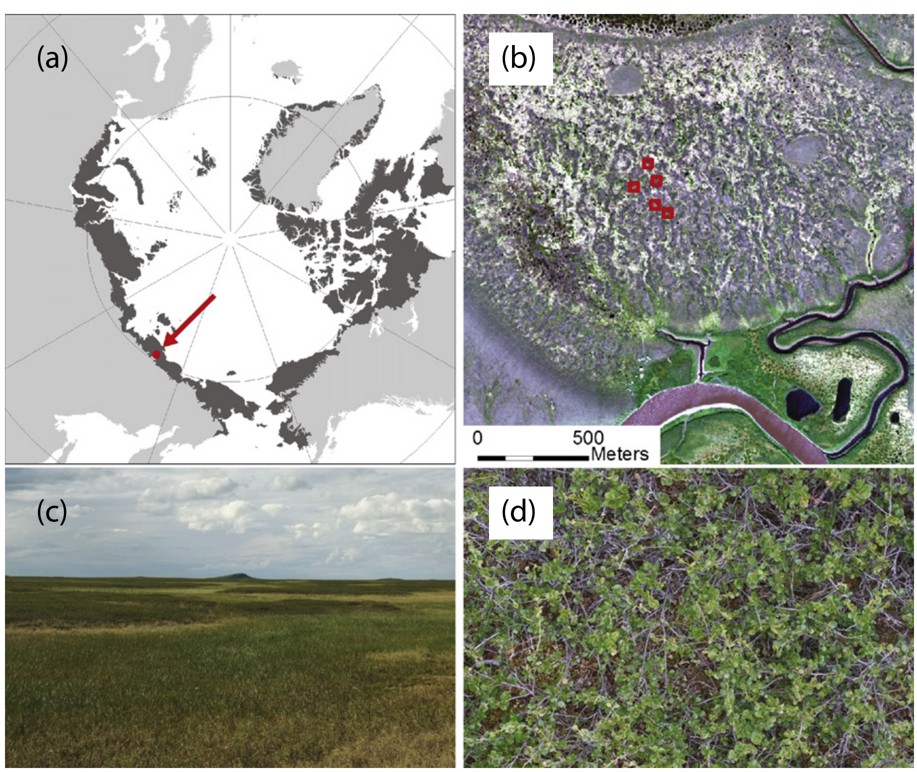

Fig. 1. Overview of the stations location in north-east Siberia and the extent of Arctic tundra (a, dark grey, data from Walker et al. (2005)), satellite image (GeoEye-1) of the site with the location of the five plots (b, red squares), tundra landscape (c) and dwarf birch vegetation (d, detail of about 60 · 90 cm).