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Biomass allometry for alder, dwarf birch, and willow in boreal forest and tundra ecosystems of far northeastern Siberia and north-central Alaska

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ABSTRACT

Shrubs play an important ecological role in the Arctic system, and there is evidence from many Arctic regions of deciduous shrubs increasing in size and expanding into previously forb or graminoid-dominated ecosystems. There is thus a pressing need to accurately quantify regional and temporal variation in shrub biomass in Arctic regions, yet allometric equations needed for deriving biomass estimates from field surveys are rare. We developed 66 allometric equations relating basal diameter (BD) to various aboveground plant characteristics for three tall, deciduous shrub genera growing in boreal and tundra ecoregions in far northeastern Siberia (Yakutia) and north-central Alaska. We related BD to plant height and stem, branch, new growth (leaves + new twigs), and total aboveground biomass for alder (*Alnus viridis* subsp. *crispa* and *Alnus fruticosa*), dwarf birch (*Betula nana* subsp. *exilis* and *divaricata*), and willow (*Salix* spp.). The equations were based on measurements of 358 shrubs harvested at 33 sites. Plant height ($r^2 = 0.48–0.95$), total aboveground biomass ($r^2 = 0.46–0.99$), and component biomass ($r^2 = 0.13–0.99$) were significantly ($P < 0.01$) related to shrub BD. Alder and willow populations exhibited differences in allometric relationships across ecoregions, but this was not the case for dwarf birch. The allometric relationships we developed provide a tool for researchers and land managers seeking to better quantify and monitor the form and function of shrubs across the Arctic landscape.

1. Introduction

Shrubs – multi-stemmed woody plants – are widely distributed throughout the Arctic (Walker et al., 2005). These plants provide important forage for wildlife (White and Trudell, 1980; Sæther and Andersen, 1990) and influence many aspects of ecosystem function, including nutrient cycling (Sturm et al., 2005; Tape et al., 2006; DeMarco et al., 2011) surface energy balance (Chapin et al., 2005; Loranty et al., 2011), permafrost thaw and stability (Blok et al., 2010; Lawrence and Swenson, 2011), and carbon storage (Shaver and Chapin, 1991; Epstein et al., 2012). Arctic shrubs are highly responsive to environmental change (Chapin et al., 1995; Bret-Harte et al., 2002) and there is mounting evidence derived from satellite imagery, repeat-photography, dendrochronology and long-term monitoring showing increased size and abundance of tall deciduous shrubs in many Arctic regions, including parts of Alaska, Canada, Scandinavia and Russia (Sturm et al., 2005; Tape et al., 2006; Berner et al., 2011; Myers-Smith et al., 2011; Frost et al., 2014; Frost and Epstein, 2014). Increased shrub cover has been linked to regional warming (Forbes et al., 2010; Macias-Fauria et al., 2012; Berner et al., 2013), as well as to disturbances (Racine et al., 2004; Frost et al., 2013; Jones et al., 2013) and other processes (e.g. herbivory and anthropogenic activities, Myers-Smith et al., 2011). Shrub expansion and increased height might lead to larger aboveground carbon pools; yet modeling efforts suggest that these changes in shrub populations could act as a net positive feedback to regional warming by increasing energy absorbed by the land surface, enhancing evapotranspiration (Lawrence and Swenson, 2011; Bonfils et al., 2012; Pearson et al.,

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2013), and exacerbating permafrost thaw (Lawrence and Swenson, 2011; Bonfils et al., 2012). Although details remain unresolved (Loranty and Goetz, 2012), snow-shrub interactions will likely plan an important role in shaping the seasonality and magnitude of feedbacks on the climate system (Sturm et al., 2005; Lawrence and Swenson, 2011; Bonfils et al., 2012).

Given the ongoing changes in Arctic shrub populations and the importance of shrubs for wildlife, surface biophysics, and ecosystem carbon balance, there is a need to quantify variations in shrub biomass and height across regions, ecosystems, and time in an accurate, repeatable, and rapid manner. Although destructive harvests are generally the most accurate method, this approach is time-consuming and not suitable for long-term monitoring. Many alternative methods, therefore, have been developed for estimating shrub aboveground biomass (Chojnacky and Milton, 2008) such as point-intercept sampling (Shaver and Chapin, 1991) and a combination of percent cover and plant height (Chen et al., 2009). In an evaluation of techniques for estimating shrub biomass pools, Chojnacky and Milton (2008) noted that the most robust, albeit relatively time-consuming, approach involves measuring stem basal diameter (BD) of individual shrubs in a known area and then applying allometric equations to convert stem BD to biomass. Allometric equations are, however, often unavailable for species or regions of interest, particularly in Arctic regions.

The objective of this study was to develop allometric equations relating shrub BD to height (H) and stem, branch, new growth, and total aboveground biomass (AGB) for three deciduous shrub genera or species found widely throughout the Arctic. In particular, we focused on alder (*Alnus* spp.), dwarf birch (*Betula* spp.) and tall willow species (*Salix* spp.) growing at boreal and tundra sites in far northeastern Siberia (Yakutia) and north-central Alaska. We then examined variation in allometric relationships among ecoregions for each species or generic group to determine whether generalized equations could be applied to estimate biomass regardless of ecoregion. As an illustration of the influence of applying equations from other ecoregions, we estimated willow AGB pools for boreal and tundra sites in Yakutia by combining site inventories with equations for willow developed both within and outside each of the two ecoregions. The shrub allometry presented herein should serve as a resource for researchers and land managers needing to quantify shrub biomass pools across space or time in select Arctic regions.

2. Methods

2.1. Study area

Over three summers (2011–2013) we harvested 358 plants spread across 27 sites in north-central Alaska and six sites in Yakutia in far northeastern Siberia (Table 1, Fig. 1). In Alaska, sampling occurred near Fairbanks in the boreal zone, as detailed in Alexander et al. (2012), and near the Toolik Field Station in a tundra ecosystem (Pizano et al., 2014). In Yakutia, sampling occurred near Cherskii in the boreal zone and Ambarchik in tundra, both located in the northern portion of the Kolyma River watershed.

Deciduous shrubs are widespread and often phylogenetically similar in these four ecoregions (Petrovsky and Zaslavskaya, 1981; Krestov, 2003; Troeva et al., 2010). Many species of willow (e.g. *Salix alaxensis*, *Salix glauca*, and *Salix pulchra*) occur in these ecoregions and occupy a range of habitat types (e.g. upland, riparian and tundra). Both Alaskan green alder (*Alnus viridis* subsp. *crispa*) and Siberian alder (*Alnus fruticosa*), sometimes considered a subspecies of *A. viridis*, similarly occur over a variety of upland and lowland landscape positions. Arctic dwarf birch (*Betula nana* subsp. *exilis*) are found widely across northeastern Asia and northern North America, complementing *Betula glandulosa* in boreal Alaska and *B. nana* subsp. *divaricata* in boreal Yakutia.

2.2. Shrub collection, processing, and inventory

Samples used in this analysis were harvested as part of three independent projects; therefore, sampling strategies and processing methods were similar but not completely identical. In Yakutia and boreal Alaska, we sampled shrubs across a range of size classes and landscape positions, excluding riparian zones. We harvested plants so long as they did not exhibit severe damage (e.g. extensive browse or large broken stems). On the Alaskan tundra, willow were harvested at random intervals along transects in and around thermokarst features. In all cases we clipped each shrub at the soil surface and then measured the stem BD using calipers. In the event that the base of the stem did not appear circular, we measured BD twice at perpendicular angles and then averaged the measurements. *B. nana* often assumes a multi-stemmed growth form in which stems fuse beneath the soil surface. We considered each individual stem protruding from the soil as a unit of observation (i.e. not the entire plant). For a subset of shrubs, we measured standing height using a stadia rod or tape measure prior to clipping.

After harvesting, we partitioned the plants into tissues (stem, branches, new growth), subsampled if necessary, and then oven-dried the material at 60 °C until it reached a constant mass. Stems and branches included both wood and bark. Alder (*A. viridis* subsp. *crispa* and *A. fruticosa*) were identified to the species-level, as were most tall willow from the Alaskan tundra (*S. alaxensis*, *S. glauca*, and *S. pulchra*) and Yakutian tundra (*S. pulchra*); however, we did not classify tall willow harvested in other ecoregions beyond genus. We did not differentiate between dwarf birch subspecies

Table 1
Summary of shrub samples collected in Alaska (USA) and Yakutia (Russia) for allometric analysis. The ranges in basal diameter (BD), stem length (L), and aboveground biomass (AGB) are provided for each genera (*Alnus*, *Betula*, and *Salix*) and ecoregion.

Genus	Ecoregion	General proximity	Year sampled	N sites	N stems	Range			Species
						BD (cm)	L (cm)	AGB (g)	
Alder	Boreal Alaska	Fairbanks	2011	11	32	0.26–5.3	2–450	0.60–2510.27	*A. viridis* subsp. *crispa*
	Boreal Yakutia	Cherskii	2012	2	22	0.18–9.52	3–475	0.05–9867.55	*A. fruticosa*
	Total			13	54	0.18–9.52	2–475	0.05–9867.55	
Birch	Boreal Yakutia	Cherskii	2012	3	25	0.09–2.53	8–152	0.04–521.79	*B. nana* subsp. *exilis* *B. nana* subsp. *divaricata*
	Tundra Yakutia	Ambarchik	2013	2	27	0.25–0.75	20–54	0.88–8.42	*B. nana* subsp. *exilis*
	Total			5	52	0.09–2.53	8–152	0.04–521.79	
Willow	Boreal Alaska	Fairbanks	2011	13	39	0.11–3.9	4–390	0.08–1361.52	*Salix* spp.
	Boreal Yakutia	Cherskii	2012	3	28	0.1–6.3	3–593	0.03–4819.84	*Salix* spp.
	Tundra Alaska	Toolik	2011	2	30	0.2–3.17	4–225	0.48–563.51	*S. alaxensis*, *S. glauca*, *S. pulchra*
	Tundra Yakutia	Ambarchik	2013	9	155	0.11–4.7	6–282	0.44–1409.67	*S. pulchra*
	Total			27	252	0.1–6.3	3–593	0.026–4819.84	