Tall Shrub Species Distribution in the Arctic: Patterns, Drivers, and Limits

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1. Background

The **expansion of deciduous tall shrubs** into the Arctic tundra may fundamentally modify land-atmosphere interactions, with potentially broad **impacts on plant and animal biodiversity, energy balance, and the biogeochemical cycling** of carbon, water, and nutrients.

However, the processes and mechanisms that control tall shrub distribution and expansion, as well as **their variation across key species** remain poorly understood.

Here we attempt to address three questions:

(1) What are the **patterns and primary drivers** of deciduous tall shrub distribution in low-Arctic tundra?

(2) How does **environmental niche** differ between two key tall shrub genera **– Alnus and Salix**?

(3) What limits the **potential of deciduous tall shrub expansion** in low-Arctic tundra?

2. Study Area and Data

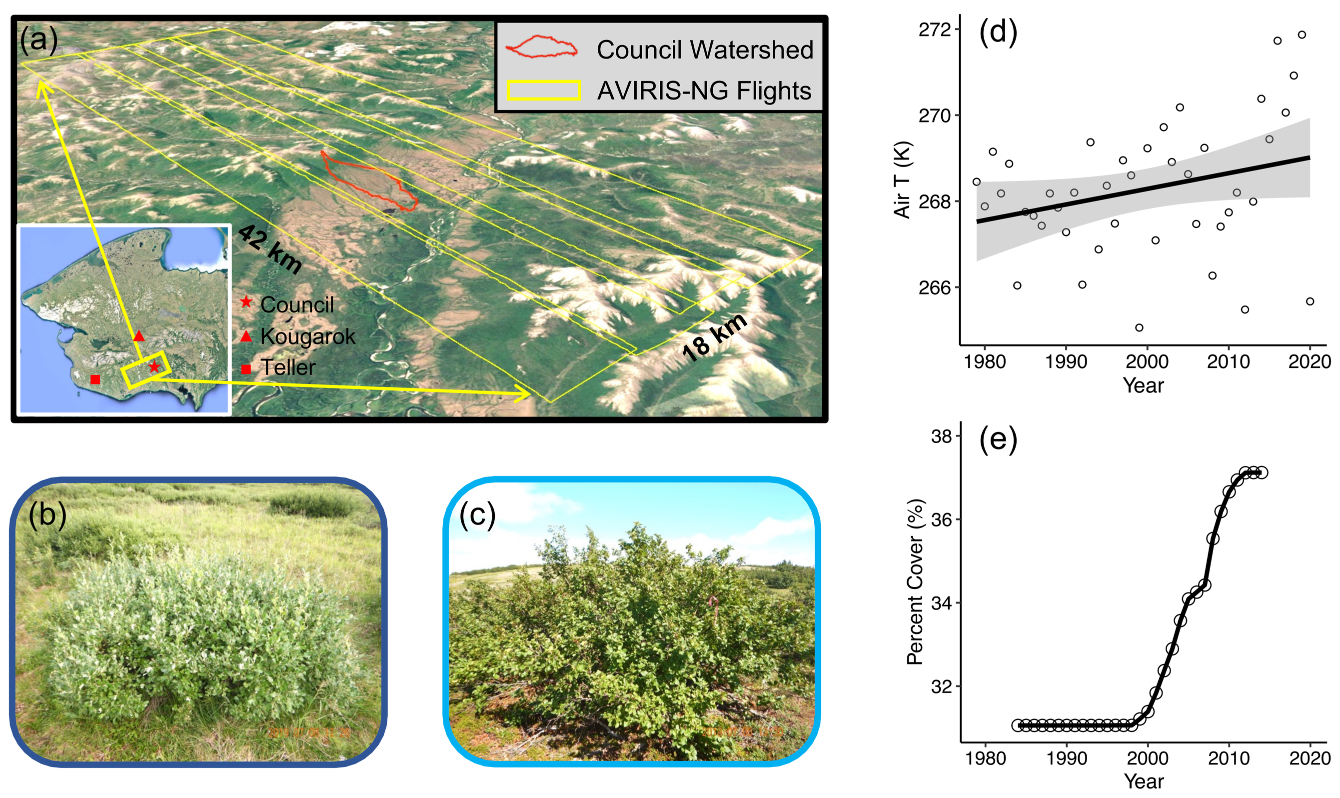


Fig. 1: (a) Study area on the Seward Peninsula; (b) and (c) Field photos of representative *Salix* species (*Salix* glauca) and *Alnus* species (*Alnus* viridis); (d) Historical air temperature change at Council since 1980; (e) Total deciduous tall shrub cover change within the studied region since 1984.

A combination of **multi-scale remote sensing** (unoccupied aerial system [UAS], airborne, and satellite), model outputs, and in-situ **physiological measurements (i.e., gas exchange)** was used to:

1. Map the **fractional cover (fCover)** of *Alnus* and *Salix* from Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG).
2. Link shrub fCover with climate, topography, and soil data to **investigate the patterns, drivers, and limits** of deciduous tall shrub distribution.
3. Explore the **biological causes** of the different *Alnus*/*Salix* distributions.

Table 1: Environmental and biological drivers explored in this study.

Data Type	Time Period	Resolution	Included Variables	Unit
Climate	1975 - 2013	60 m	Potential Evapotranspiration (ET0)	mm
			Apparent Evapotranspiration (AET)	mm
			Deficit (ET0-AET)	mm
			Radiation	w/m²
			Precipitation	mm
			Snow Water Equivalent	mm
			Maximum Temperature (Tmax)	K
			Minimum Temperature (Tmin)	K
Topography	NA	32 m	Elevation	m
			Slope	degree
			Topographic Wetness Index (TWI)	N/A
Soil	1975 - 2013	500 m	Active Layer Depth (ALD)	m
			Annual Ground Temperature (AGT)	K
Leaf Traits	2019	In-situ	Stomatal slope / leaf water use efficiency (WUE)	N/A

3. Patterns of Tall Shrub Distribution

Imaging spectroscopy from AVIRIS-NG enables an accurate differentiation of *Alnus* and *Salix* fCover, with RMSEs <14% when validated against high resolution UAS data.

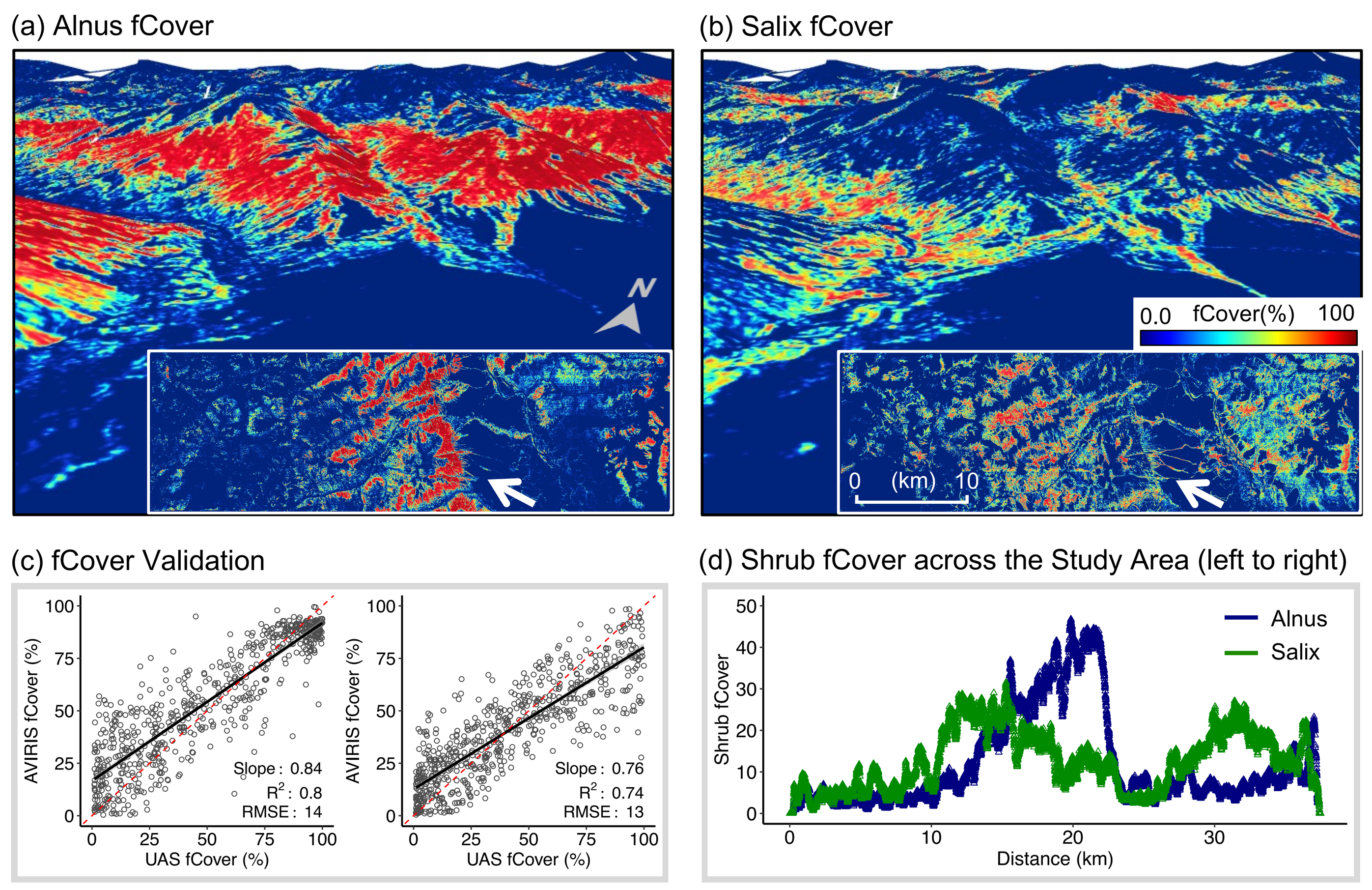
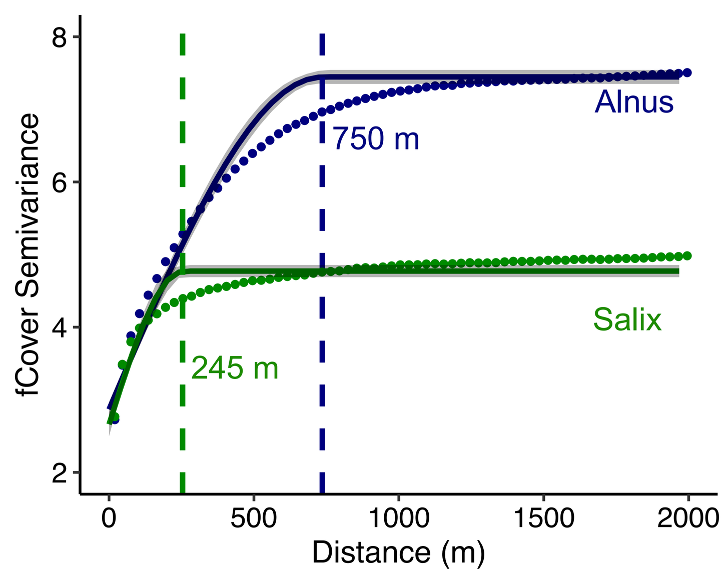


Fig. 2: (a) & (b) *Alnus* and *Salix* fCover derived from imaging spectroscopy data from AVIRIS-NG; (b) Validation of AVIRIS-NG derived *Alnus*/*Salix* fCover against "ground-truth" data derived from UAS; (d) Distribution of *Alnus* and *Salix* fCover across the entire surveyed region (from left to right).



Under favorable growth conditions, *Alnus* forms much larger communities (>750 m in radius) than *Salix* (>245 m in radius).

Fig. 3: Spatial autocorrelation of *Alnus* and *Salix* calculated from AVRIS-NG mapped fCover maps.

4. Niche Differentiation between *Alnus* and *Salix*

Niche differentiation between *Alnus* and *Salix* changed with community size, with **larger communities being more specialized in resource requirements than individual plants or small patches of *Alnus* and *Salix***.

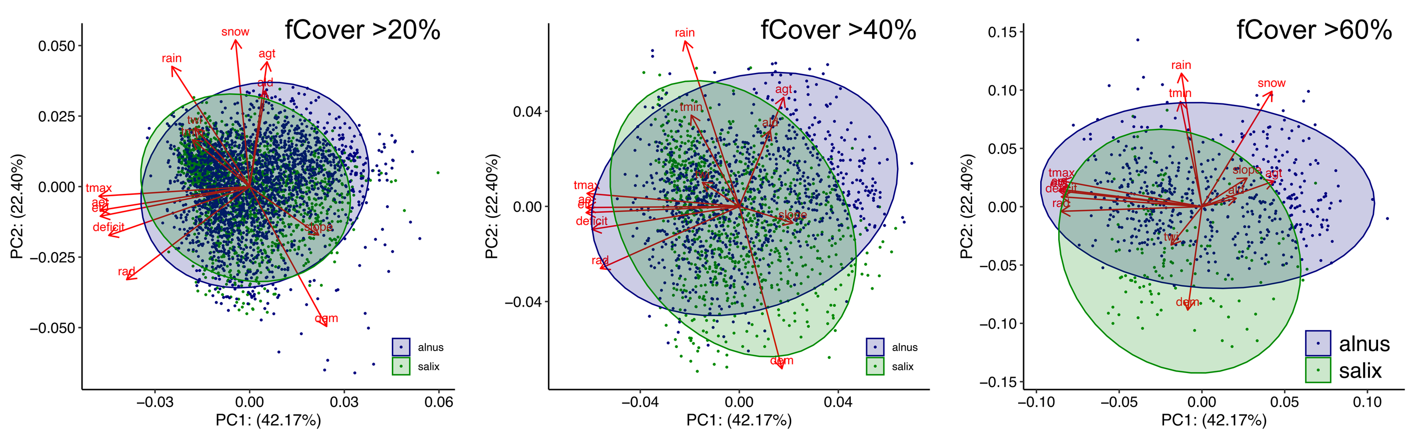


Fig. 4: Principal component analysis (PCA) on the three types of environmental drivers across example shrub fCover ranges. The figure showed principal component 1 (PC 1) vs principal component 2 (PC2) which account for ~64% of the total variance.

The geometric centers of *Alnus* and *Salix* in hypervolume environmental space split at a fCover of ~40%.

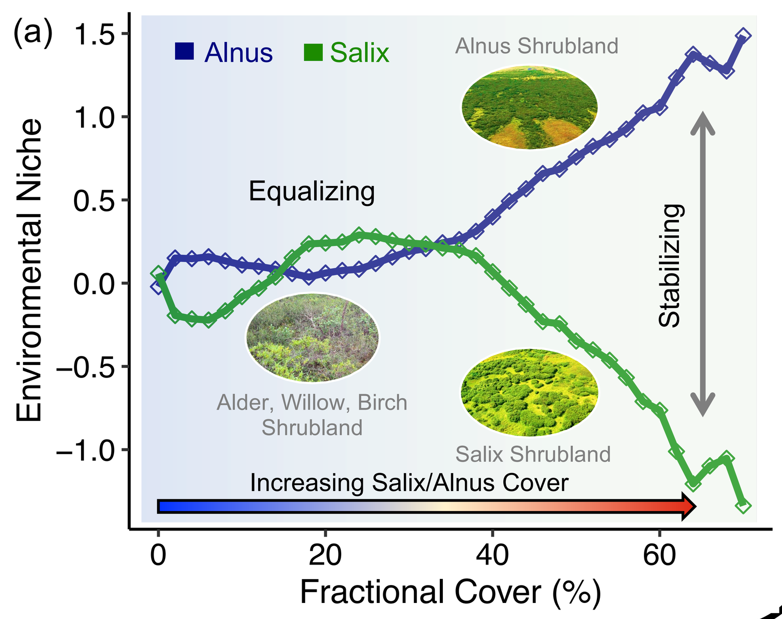


Fig. 5: Euclidean distance between the centers of *Alnus* and *Salix* in hypervolume environmental space. The distance shown is relative to the center of the combination of *Alnus* and *Salix* environmental space.

5. Controls of *Alnus* and *Salix* Distribution

Topography-controlled processes (e.g., cryogenics and hydrology and) importantly control the distribution of deciduous tall shrubs, with ***Alnus* survives better at slopy uplands and *Salix* thrives at low elevations with rich soil moisture.**

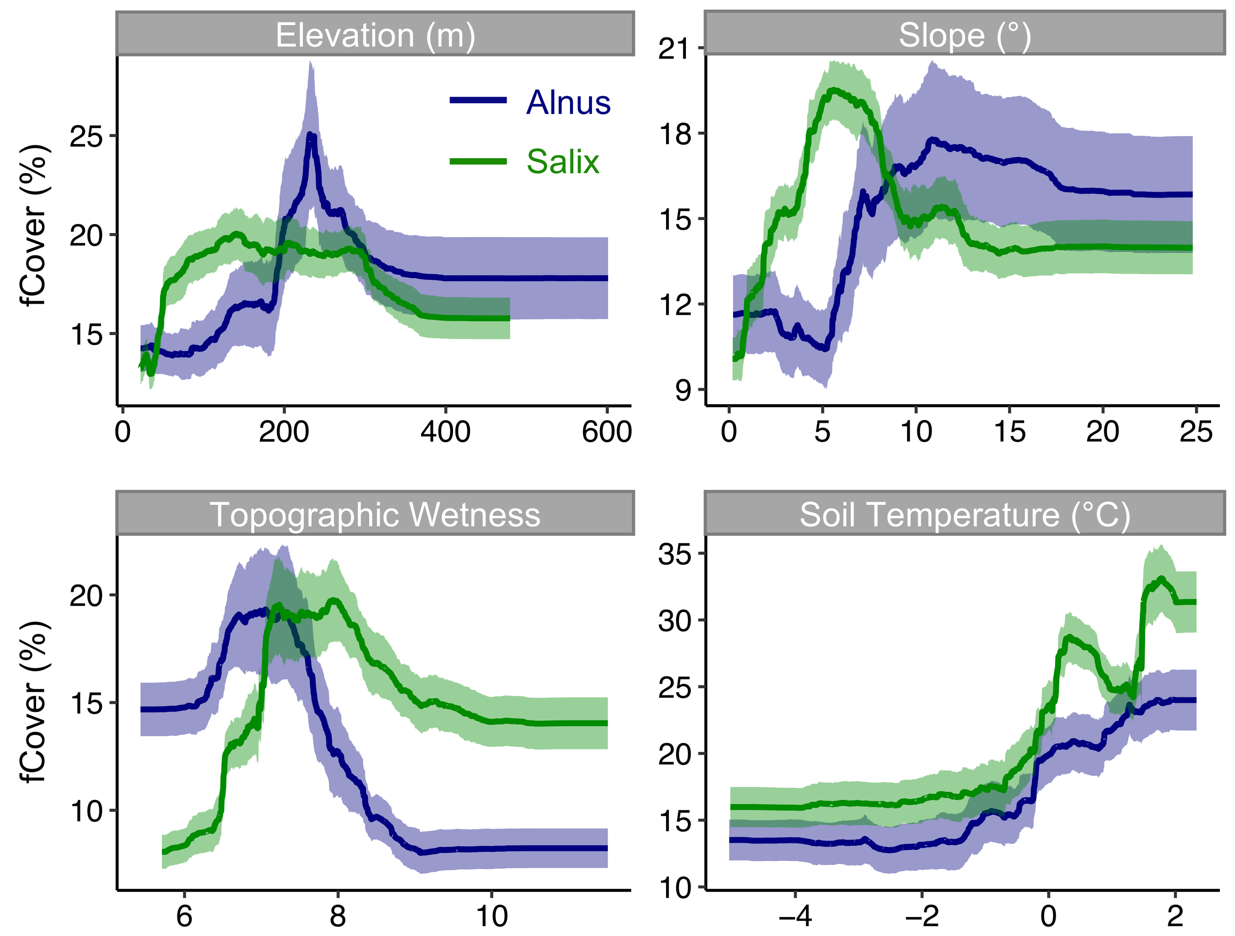
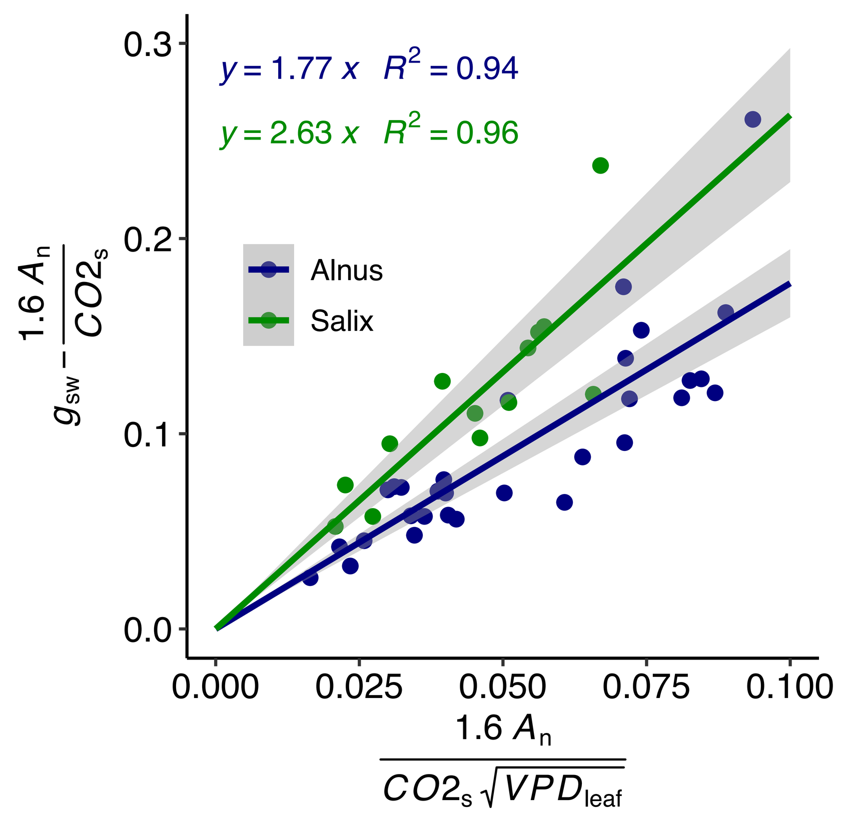


Fig.6: Partial dependence plot (PDP) of the first four most important environmental drivers for modeling the spatial variation in *Alnus* and *Salix* fCover using Random Forest.

$$g_s = g_0 + 1.6\left(1 + \frac{g_1}{\sqrt{VPD_s}}\right)\frac{A_n}{CO2_s}$$



The better survival of *Salix* in regions with higher soil moisture is potentially caused by its low water use efficiency (WUE).

Fig. 7: Stomatal slope of *Alnus* and *Salix* derived from gas exchange measurements using the Medlyn model. A larger stomatal slope indicates lower leaf water use efficiency (WUE), and vice versa.

6. Take home messages

- **Patterns:** The distribution of deciduous tall shrubs is highly variable in low-Arctic tundra and differs between species (*Alnus* and *Salix*).
- **Niche:** The formation of large shrub communities has more specialized resources requirements that of individual plants.
- **Controls:** Topography-control processes importantly determine the deciduous tall shrub distribution & expansion.

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