GREENING OF THE ARCTIC: PARTITIONING WARMING VERSUS REINDEER HERBIVORY FOR WILLOW POPULATIONS ON YAMAL PENINSULA, NW SIBERIA

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Arctic warming has been linked to observed increases in tundra shrub cover and growth in recent decades based on significant relationships between deciduous shrub growth/biomass and temperature (Myers-Smith et al. 2011). These vegetation trends have been linked to Arctic sea ice decline and thus to the sea ice/albedo feedback known as Arctic amplification. However, the interactions between climate, sea ice, tundra vegetation and herbivores remain poorly understood. Here we reveal a 50-year growth response over a >100,000 km^2 area to a rise in summer temperature for alder (*Alnus*) and willow (*Salix*), the most abundant shrub genera respectively at and north of the continental treeline. We demonstrate that whereas plant productivity is related to sea ice in late spring (Fig. 1), the growing season peak responds to persistent synoptic-scale air masses over West Siberia associated with Fennoscandian weather systems via the Rossby wave train. Substrate is important for biomass accumulation, yet a strong correlation between growth and temperature encompasses all observed soil types. Vegetation is especially responsive to temperature in early summer (Macias-Fauria et al. 2012). However, the role of herbivores was not addressed. Here we explore the relationship between long-term herbivory and growth trends of shrubs experiencing warming in recent decades.

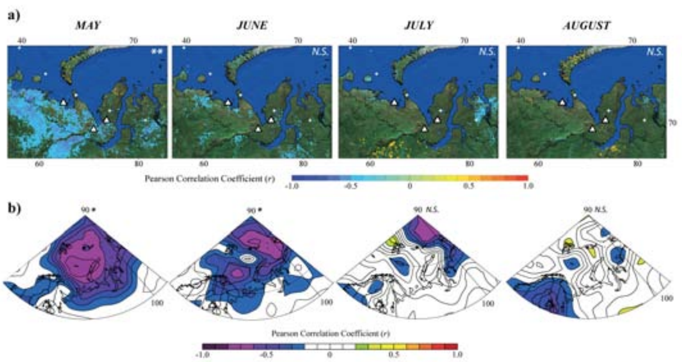

Fig. 1a Monthly Pearson correlation coefficients (*r*) between NDVI[16] and sea ice area in the Barents and Kara Seas (http://nsidc.org/data/nsidc-0079.html). Only significant (p<0.05) correlations are shown. Study sites are shown as filled white triangles. **b)** Monthly Pearson correlation coefficients between surface gridded temperatures from the Reanalysis project[17] and sea ice area in the Barents and Kara Seas. Period is 1982-2005, for which there is NDVI and sea ice data. Field significance, accounting for multiplicity[18], is shown in the upper part of each panel as: **: p < 0.01; *: p < 0.05; N.S.: non-significant. Note the disappearance of the relationship in NWET as the growing season advances and sea ice position recedes further away from the coast.

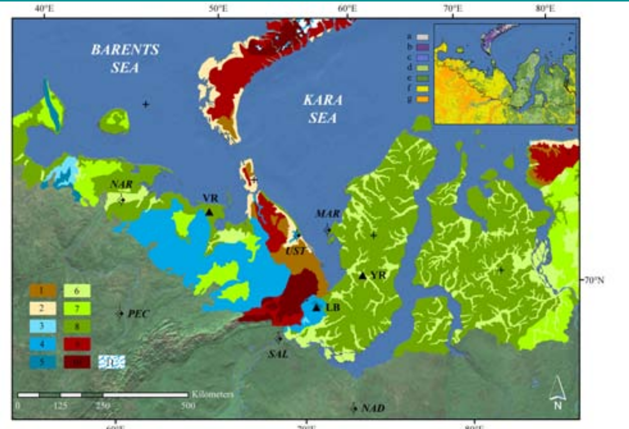

Fig. 2 Map of north-western Eurasian tundra (**NWET**). Sites where dendrochronologies were extracted are shown with a filled black triangle and two letters: **VR**: Varandei; **LB**: Laborovaya; **YR**: Yuribei River. Meteorological stations < 400 km away from the sites used in the computation of response functions are shown with a black rhomboid symbol and three letters: **NAR**: Naryan Mar; **PEC**: Pechora; **SAL**: Salekhard; **UST**: Ust Kara; **MAR**: Marre Sale; **NAD**: Nadym. Major landscape units and depositional origins are depicted for the tundra[19]: **1-2**: foothills, **1**: glacial and glaciofluvial, **2**: marine; **3-5**: high plains and plateaus, **3**: erosional-denudational, **4**: glacial and glaciofluvial, **5**: tablelands; **6-8**: low plains, **6**: fluvial, lacustrine, **7**: glacial and glaciofluvial, **8**: marine and ice-rich marine; **9-10**: mountains, **9**: erosional-denudational, **10**: table mountains, mountain ranges; **11**: ice caps and glaciers. **Upper-right inset**: circumpolar maximum NDVI of arctic tundra. This image is a mosaic of AVHRR data portraying the maximum NDVI for each 1 km pixel during the summers of 1993 and 1995, 2 years of relatively low summer cloud cover in the High Arctic[1]. **a**: <0.03; **b**: 0.03-0.14; **c**: 0.15-0.26; **d**: 0.27-0.38; **e**: 0.39-0.50; **f**: 0.51-0.56; **g**: >0.57. Note the sharp contrast in productivity as seen by NDVI values and its spatial agreement with major changes in substrate.

Figure 3. Reindeer grazing among erect shrub willows (*Salix* spp.). Nenets herders report that shrubs have increased in height in recent decades. The tallest shrubs exceed the height of antlers of standing reindeer.

Within the Arctic, north-western Eurasian tundra (NWET) is unique in being one of the warmest regions, as measured by the summer warmth index (i.e. growing season temperature), and in having highly variable sea ice, lower overall than other arctic seas, due to the direct influence of atmosphere and ocean heat transport via the North Atlantic storm track. NDVI, a decadal satellite-based proxy for vegetation productivity, highlights most of NWET as extremely productive, with a sharp productivity drop in the geologically distinct Yamal, Gydan and Taz Peninsulas (Fig. 2). Tree sized, tall (> 2 m) deciduous shrubs have developed in recent decades within the region, demonstrating an *in situ* change of the low arctic tundra structure that is quantifiable but has also been observed in detail by indigenous Nenets reindeer herders both west and east of the Polar Ural Mountains (Fig. 3; Forbes and Stammler 2009).

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Figure 4. Heavily grazed/trampled ridge-top tundra w/prostrate shrubs

Yamal Peninsula is characterized by mostly low, rolling topography with elevations above 80 m being rare. The northern half of the peninsula has greater clay content in the soils with landslides being a common and cyclic phenomenon at the landscape scale. Old landslides are typically dominated by closed canopies of tall willows. Large herds of semi-domestic reindeer managed by indigenous Nenets nomads occur at high densities in summer on exposed ridge tops (Fig. 4), heavily grazing and trampling on prostrate and low erect willows (Fig. 5). A few meters away in moderately sloped landslides (Fig. 6) tall willows remain virtually ungrazed as their canopies have grown above the browse line of ca. 180 cm.

Figure 5. Heavily browsed low willows

Figure 6. Old landslide habitat with tall, virtually unbrowsed willows

Live stems sampled from tall shrubs of *Salix lanata* were in the range of 80 – 118 years old and very reliable for reconstructing a summer temperature signal for the past 50-60 years (Macias-Fauria et al. 2012). Prostrate shrub stems proved so strongly scarred by browsing and trampling (Fig. 7) that it was impossible to recover chronologies from the growth rings. This supports the assertion by Olofsson et al. (2009) that heavy herbivory may be able to check climate-related growth increases in height/abundance of key forage shrubs. We are in the process of corroborating these preliminary findings with long-term exclosure data from other sites. At a minimum, it appears that reindeer and, by extension their human handlers, have the potential to influence tundra greening at local and possibly regional scales. At the same time, the net contribution of landslide activity to greening remains unclear. Future research will need to address the respective roles of herbivory, warming and landslide processes.

Figure 7. Scarred ridge-top stem

Key literature:
Forbes, B.C. and F. Stammler (2009) Arctic climate change discourse: the contrasting politics of research agendas in the West and Russia. *Polar Research* **28**: 28–42.
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Olofsson, J. et al. (2009) Herbivores inhibit climate-driven shrub expansion on the tundra. *Global Change Biology* doi: 10.1111/j.1365-2486.2009.01935.x.