Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows

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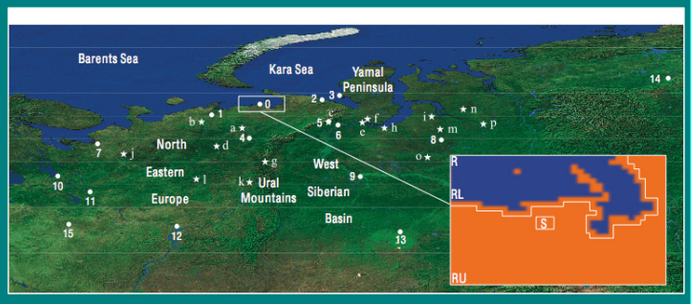
Growth in arctic vegetation is generally expected to increase under a warming climate, particularly among deciduous shrubs. We analyzed annual ring growth for an abundant and nearly circumpolar erect willow (*Salix lanata* L.) from the coastal zone of the northwest Russian Arctic (Nenets Autonomous Okrug) (Fig. 1). The resulting chronology is strongly related to summer temperature for the period 1942-2005. Remarkably high correlations occur at long distances (>1600 km) across the tundra and taiga zones of West Siberia and Eastern Europe (Fig. 2). We also found a clear relationship with photosynthetic activity for upland vegetation at a regional scale for the period 1981-2005, confirming a parallel 'greening' trend reported for similarly warming North American portions of the tundra biome (Fig. 3). The standardized growth curve suggests a significant increase in shrub willow growth over the last six decades (Fig. 4). These findings are in line with field and remote sensing studies that have assigned a strong shrub component to the reported greening signal since the early 1980s. Furthermore, the growth trend agrees with qualitative observations by nomadic Nenets reindeer herders of recent increases in willow size in the region (Fig. 5). The quality of the chronology as a climate proxy is exceptional. Given its wide geographic distribution and the ready preservation of wood in permafrost, *S. lanata* L. has great potential for extended temperature reconstructions in remote areas across the Arctic. See http://www.arcticcentre.org/willowrings (and Forbes et al. 2009).

Fig. 1: Map of northern Eurasia meteorological stations used. Lowercase letters and white stars indicate boreal tree-ring width chronologies compared with our *S. lanata* chronology.



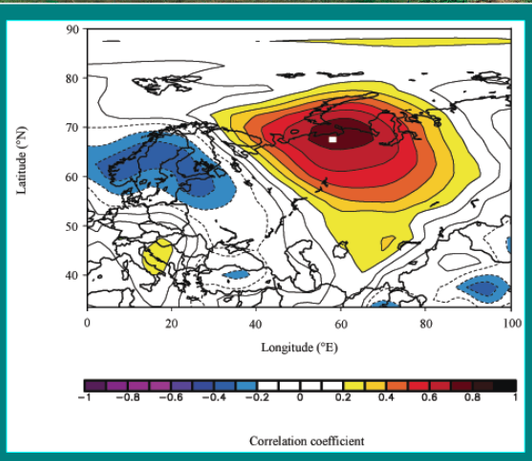


Fig. 2: Correlation map between *Salix lanata* ring width residual chronology and summer temperature over North-Western Eurasia. Time period is 1948–2005. Location of the *Salix lanata* chronology is shown as a white filled square. Note high correlations occurring at long distance towards the south-east well into the boreal zone.

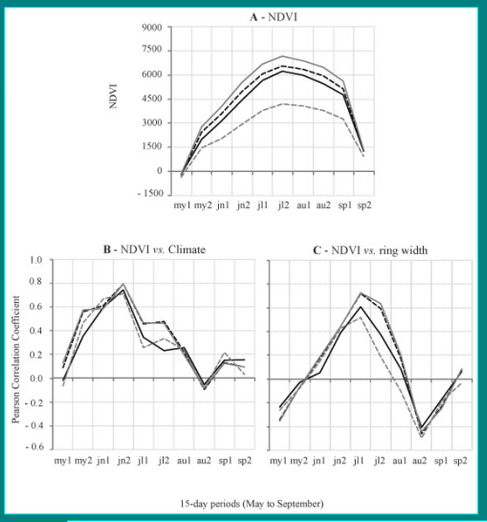


Fig. 3: A) Average 15-day NDVI values indicating peak total biomass in the second half of July; B) relationships between Regional 15-day NDVI and monthly temperature indicating peak productivity in the second half of June; C) Correlation between *Salix lanata* residual ring width chronology and 15-day NDVI values, indicating a peak in the first half of July. NDVI regions: black continuous line, Site; black dashed line, Regional; grey continuous line, Regional-Upland; grey dashed line, Regional-Lowland (see Fig. 1 and Materials and Data in paper for definition and display of the areas).

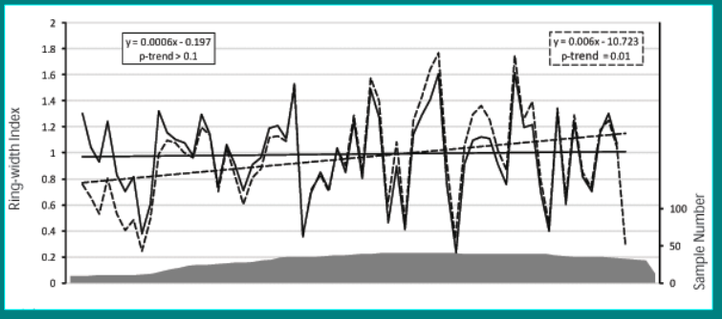


Fig. 4: *Salix lanata* ring width STD32 = continuous line, standardized with a 32 years smoothing spline; and RCS = dashed line, standardized with the regional curve standardization procedure. Chronologies cover 1942-2005. Sample depth (number of individuals) is shown as a filled grey area. Note the clear low frequency component in the chronology obtained by RCS, specifically designed to preserve it, suggesting a significant increase in *Salix lanata* growth for the period 1942-2005.

Fig. 5: Reindeer grazing among *Salix* thickets in Nenets Okrug. Herders note that when the tallest shrubs exceed the antler height of standing reindeer (ca. 1.8 m), animals can disappear from sight when browsing within thickets and subsequently be lost during summer migration. Nomads now in their fifties report that when they were young men following these same routes that the shrubs were significantly shorter. Olofsson et al. (2009) have argued that herbivory must be considered in order to understand how a changing climate may or may not affect shrub abundance. We found no evidence of browsing on erect individuals with heights ranging 2–2.5 m.

Literature cited:

Forbes, B.C., M. Macias Fauria and P. Zetterberg (2009) Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. *Global Change Biology* doi: 10.1111/j.1365-2486.2009.02047.x.

Olofsson J, Oksanen L, Callaghan T, Hulme PE, Oksanen T, Suominen O (2009) Herbivores inhibit climate-driven shrub expansion on the tundra. *Global Change Biology* doi: 10.1111/j.1365-2486.2009.01935.x.

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