Tall shrub expansion facilitated by patterned ground in the northwest Siberian Low Arctic

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Abstract

We integrated field data and remote-sensing to identify key environmental drivers of tall shrub expansion and increased vegetation productivity in a tundra ecotone near Kharp, northwest Siberia. Comparison of high-resolution Corona and QuickBird satellite imagery shows that alder (*Alnus viridis* ssp. *fruticosa*) cover increased by ~10% since 1968. Additionally, areas of sharply increasing productivity evident in a NDVI time-series derived from 1985-2009 Landsat data are co-incident with expanding shrublands. In the field, we found that most shrub expansion occurred in patterned-ground and virtually all recently-established shrubs occur on small, mineral-dominated microsites ("circles") that are annually disturbed by cryogenic processes.

In order to test if shrubland development is facilitated by circles, we established a series of transects in shrublands in varying stages of development. We mapped the location of alders and circles and measured surface organic depth and mineral horizon thickness systematically along the transects, and at alders. In recent colonization zones, young alders occur almost exclusively on circles that lack vegetation and surface organic matter. Spatial statistics indicate that most alders occur in evenly-spaced clumps that mirror the spacing of circles. This distribution pattern persists in mature shrublands where circles are large and widely-spaced. However, dense shrub thickets develop where circles are close-packed.

We conclude that circles strongly facilitate alder recruitment at Kharp. Physical processes in patterned-ground promote continuous, rather than episodic, disturbance that maintains a mosaic of seedbeds that may be exploited by fast-growing, minerotrophic shrubs during periods of favorable climate. We suggest that alder proliferation in patterned- ground has probably occurred in many other parts of the Low Arctic, such as in open alder shrublands in which shrubs and circles are distributed at similar spatial scales.

Study background

Numerous experimental and simulation modeling studies indicate that expansion of deciduous shrubs is the most likely land-cover changes to accompany climate-warming in Low Arctic tundra. Observational studies have corroborated these findings, particularly in the North American Arctic, but the Eurasian Arctic has received less attention. Shrubification of tundra-dominated regions has the potential to strongly influence a range of system properties in Arctic landscapes, including vegetation structure, surface energy balance, permafrost, and hydrology.

We visited a field site in a tundra ecotone in near the town of Kharp in northwest Siberia (Fig. 1). Comparisons of high-resolution satellite imagery indicate that cover of alder shrubs increased by ~10% in the Kharp study area between 1968 and 2003 (Fig. 2). Additionally, an NDVI time-series derived from 13 Landsat scenes from 1985-2010 indicate that strong "greening" occurred across much of the site, especially in and near alder shrublands. We were primarily interested in identifying important soil- and geomorphic site characteristics related to recent alder proliferation and increases in vegetation productivity at Kharp.

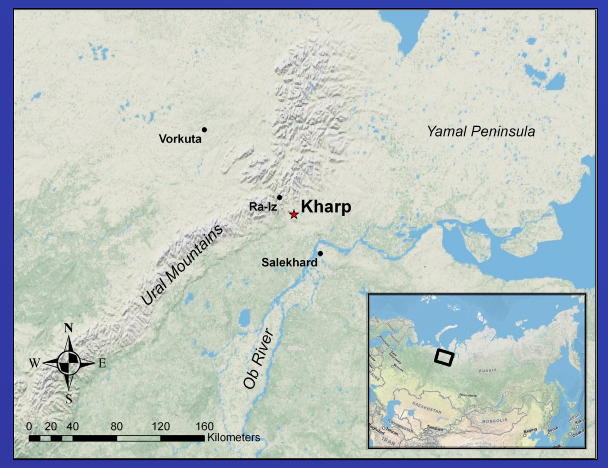


Fig. 1. Southern Yamal Peninsula region, showing location of Kharp study site in northwest Siberia.

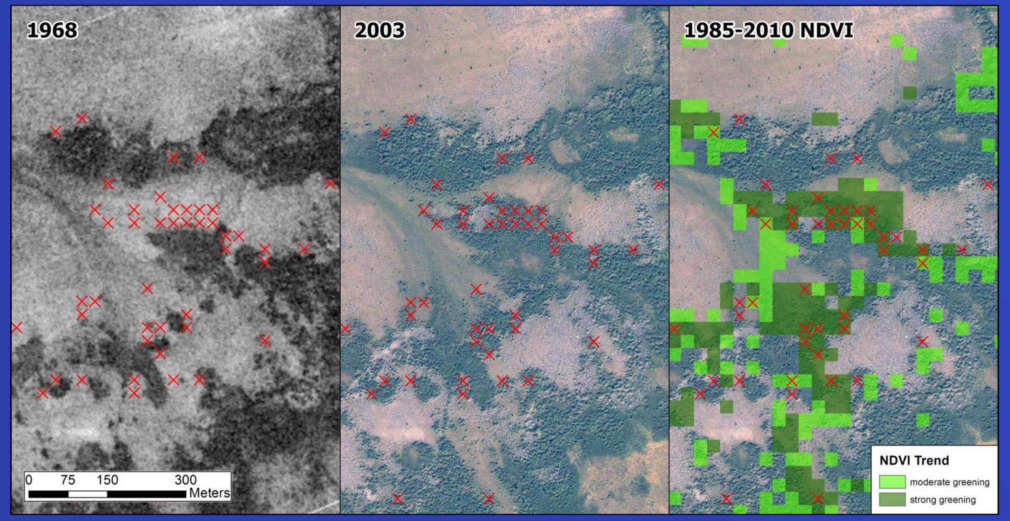


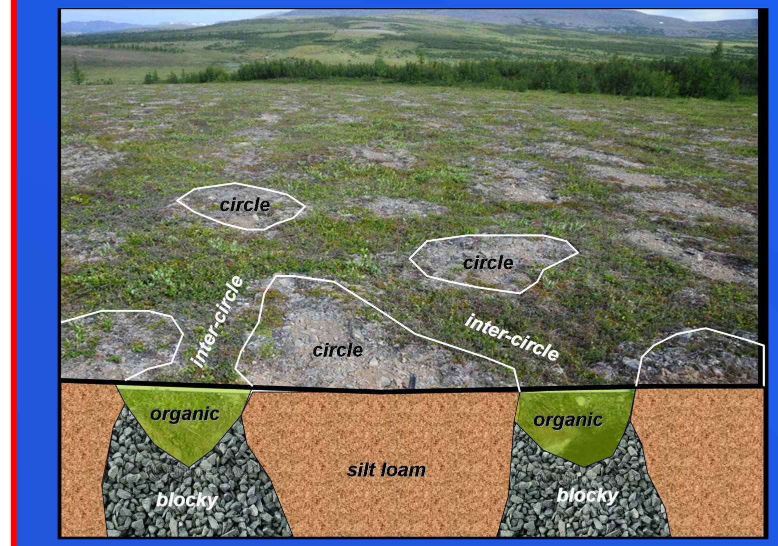
Fig. 2. Satellite images from 1968 (Corona; left) and 2003 (QuickBird; center) showing an area of recent alder expansion. Red markers denote points with new alder cover. Landsat pixels with highly significant linear trends (p<0.01) in NDVI for 1985-2010 (right) are highly co-incident with shrub expansion areas.

Fig. 3. We used a steel thaw probe to measure organic depth, mineral horizon thickness, and thaw depth.

Field methods

- 22 transects (20-100 m length, 4-8 m width) in alder shrublands and adjacent tundra:
  - alder-free tundra
  - alder colonization zones
  - mature shrublands (most shrubs >2m height)
  - paludified shrublands (very old shrubs)
- measured soil organic depth and mineral horizon thickness systematically along transect centerline and at alders (Fig. 3)
- mapped the locations of alders and circles (where visible)
- recorded daily soil temperature profiles at 5-cm depth using iButton dataloggers
- obtained mineral soil samples at the transects

Microsite facilitation of alder expansion



"Circles" (left) are widespread patterned-ground landforms that are characterized by regularly-spaced, approximately circular patches of mineral soil within a matrix of vegetated inter-circles. Circles develop due to complex physical processes during winter freeze-up. The development of an organic mat in "inter-circles" results in sharp gradients in microsite thermal regime: circle centers lack insulating organic matter, so the subsurface freezes much much more quickly than at vegetated inter-circles. This results in severe frost-heave ("differential heave") at circle centers, relative to the surrounding area (Peterson and Krantz 2003). Over time, rocks are heaved to the surface and accumulate at circle margins. Annual disturbance due to differential heave prevents tundra plants from establishing at circles, but fast-growing boreal species can become established if the climate is warm enough. Once that happens, circles become insulated by organic matter, differential heave no longer occurs, and disturbance ceases.

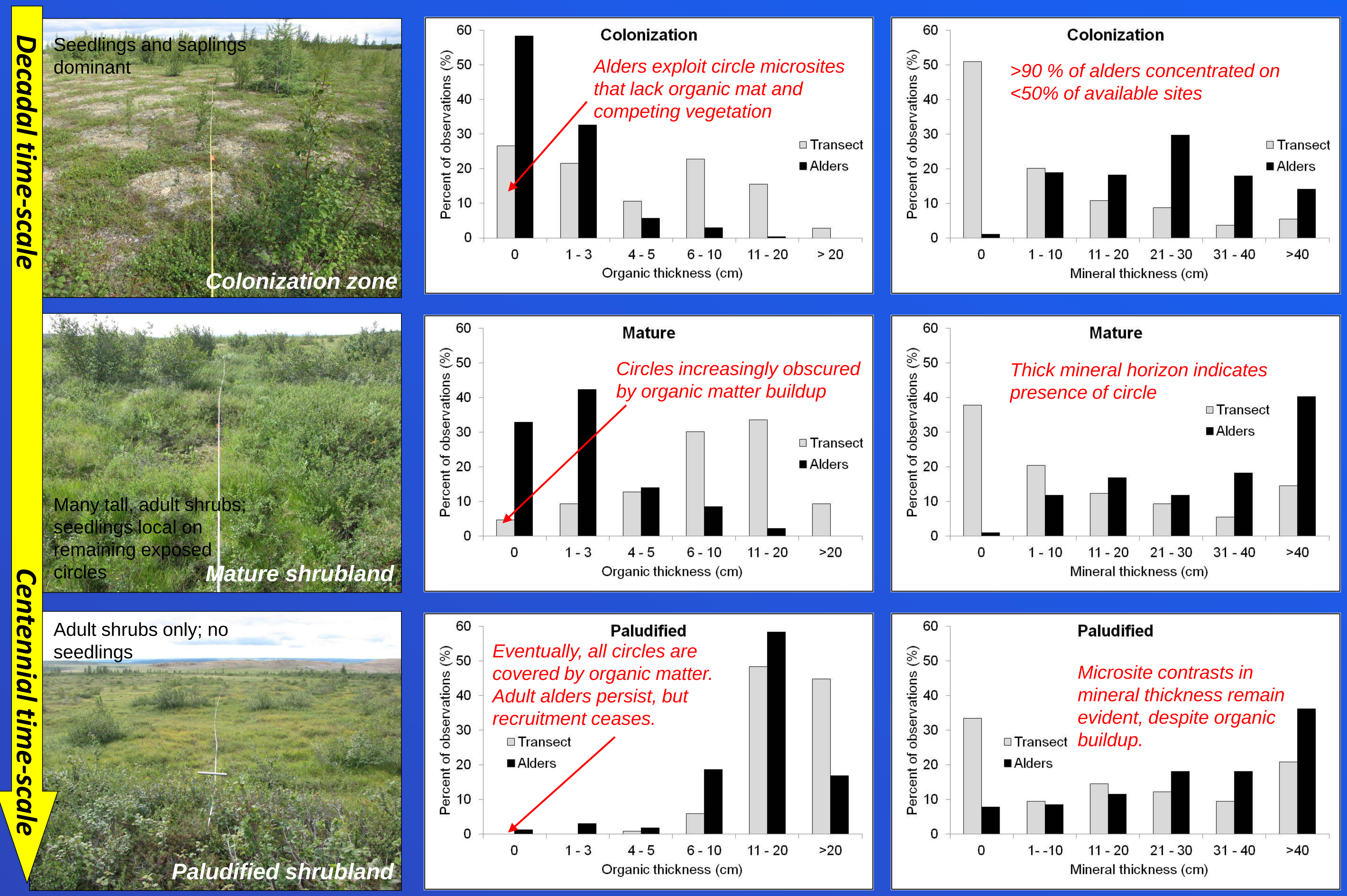


Fig. 5. Photos and soil properties at transects in (top to bottom) alder colonization zones, mature shrublands, and paludified shrublands. Surface organic depth is significantly less, and mineral horizon soil thickness greater, at alders relative to the systematic transect measurements regardless of stage (p<0.01 for all; Kruskal-Wallis one-way ANOVA). Mean surface organic depth increases monotonically with increasing shrubland age. As organic matter accumulates, annual disturbance ceases and circles become obscured from view but their presence is still evident in soil profile measurements. However, shrub demographics shift, with little or no recruitment in paludified stage.

Spatial distribution of shrubs and microsites

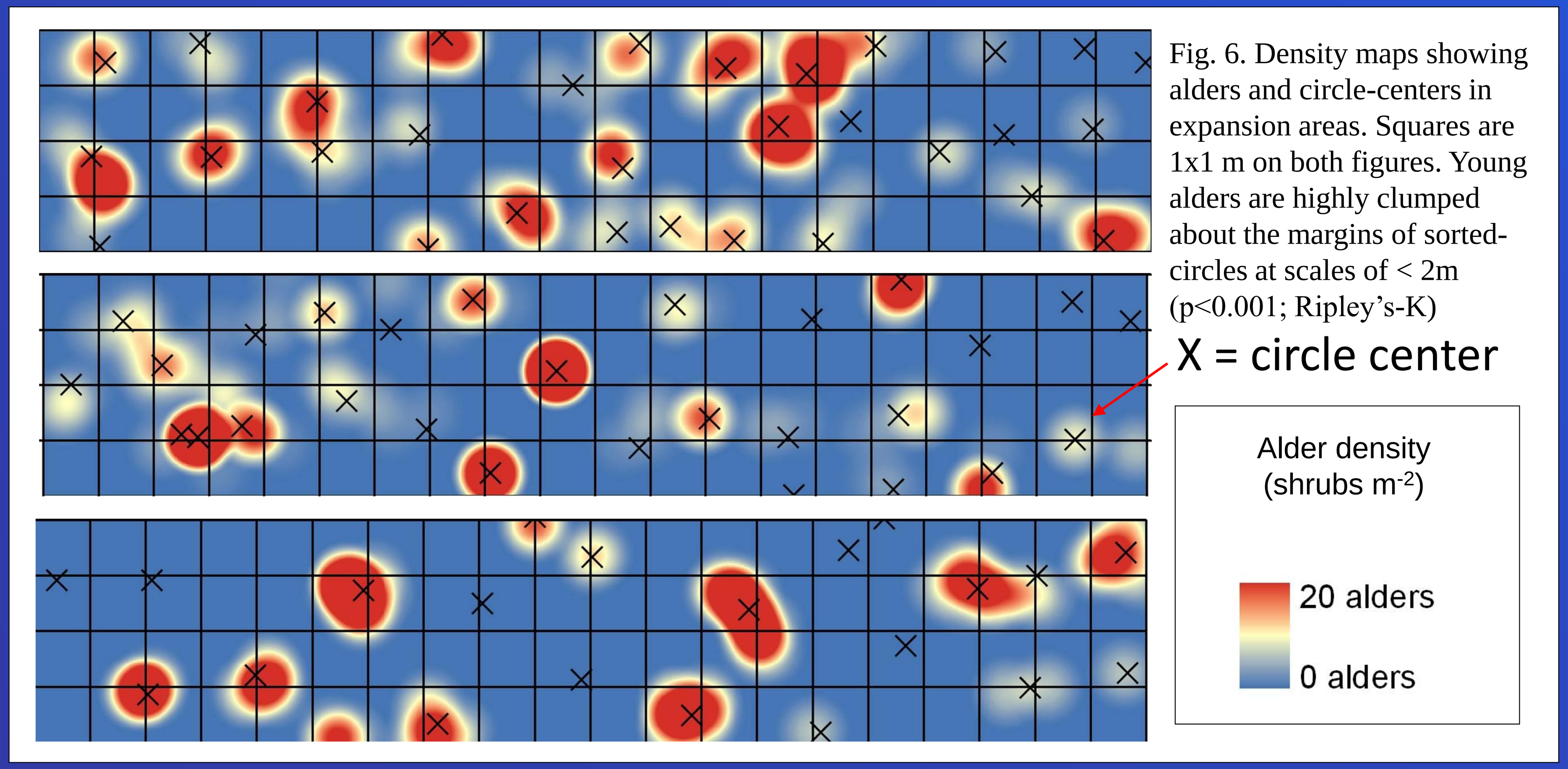


Fig. 6. Density maps showing alders and circle-centers in expansion areas. Squares are 1x1 m on both figures. Young alders are highly clumped about the margins of sorted-circles at scales of < 2m (p<0.001; Ripley's-K)

Soil temperature effects on shrub growth

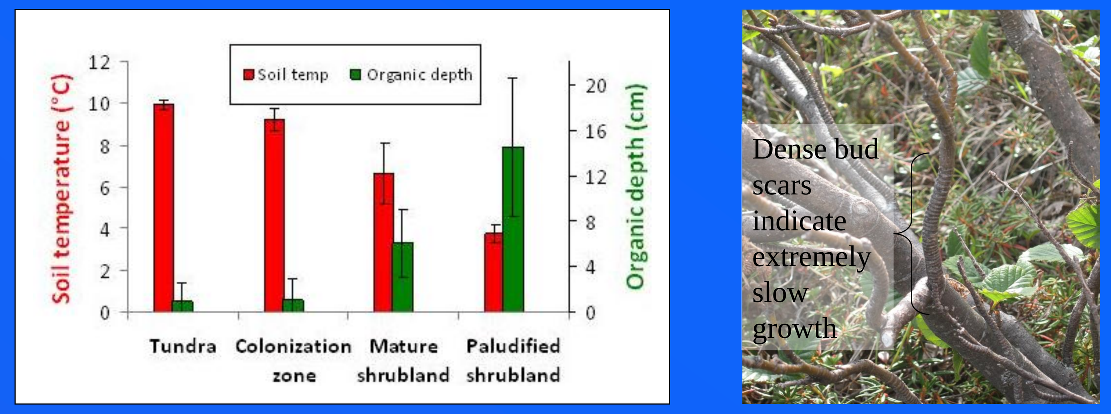


Fig. 7. Since 1968, alder abundance increased dramatically in some areas, but was virtually unchanged in others. In expansion areas, soil temperatures (above left) are relatively high and shrubs grow very quickly. As shrublands mature, organic matter accumulates and soil temperatures decline dramatically. Alders are very long-lived; in paludified shrublands, they grow extremely slowly

Regional climate warming

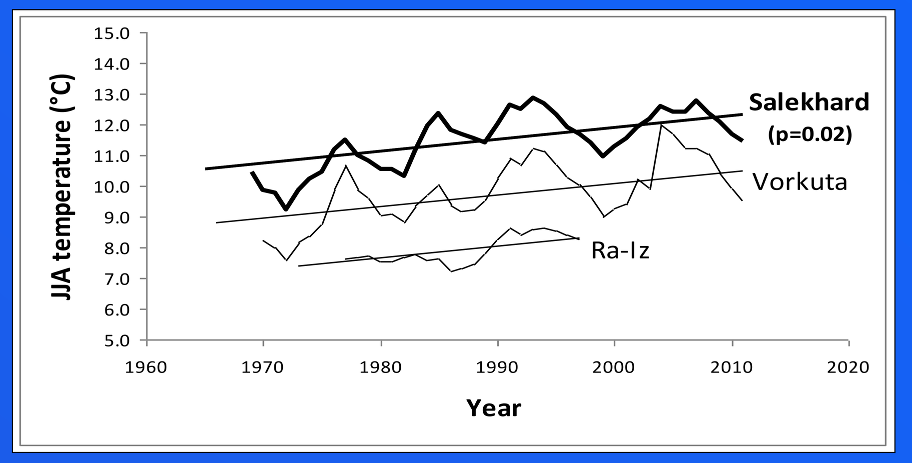


Fig. 8. Five-year moving averages and linear trendlines of mean June-July-August (JJA) temperature for Salekhard (35 km SE of Kharp) and nearby Vorkuta and Ra-Iz (high elevation) weather stations, 1965-2011. Warmer growing season temperatures have probably contributed to recent shrub expansion at Kharp.

Summary and conclusions

1) Integration of satellite- and ground-based observations show that exposed circles are "hot-spots" of alder recruitment.
2) Active circles in the southernmost Arctic are susceptible to persistent changes in land-cover because they are good seedbeds for fast-growing, boreal shrubs.
3) Circles favor rapid development of alder seedlings because they lack competing vegetation and soils are warm.
4) A trend of increasing summer warmth in recent decades has probably contributed to alder shrubland expansion at Kharp.
5) Differential heave causes annual, rather than episodic disturbance. Thus, it maintains a mosaic of favorable microsites that shrubs can exploit during periods of favorable climate.
6) Spatial patterns of alder colonization persist throughout shrubland development and may explain the uniform spacing of shrubs in some Low Arctic "alder savannas."
7) Shrubland development has important implications for permafrost because canopy shading and the formation of an organic mat strongly buffers the active layer from climate change.

Literature Cited

Peterson, R.A. and Krantz, W.B. 2003. A mechanism for differential frost heave and its implications for patterned ground formation. Journal of Glaciology 49:69-80.

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