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, northeast Siberia. Comparison of high-resolution Corona and Quickbird satellite imagery shows that alder (Alnus viridis) 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 coincident 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 circles and alders 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 even-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, nontomrophic 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 change 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 tundra landscapes, including vegetation structure, surface energy balance, permafrost, and hydrology.

We visited a field site in a tundra ecotone near the town of Kharp in northwest Siberia (Fig. 1). Comparisons of high-resolution satellite imagery indicate that circle coverage 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 particularly interested in identifying important soil- and morphological site characteristics related to recent alder proliferation and increased vegetation productivity at Kharp.

**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 microthermal regime: circle centres lack insulating organic mat, so the subsurface freezes much more quickly than at vegetated inter-circles. A circle often has a “differential frost circle center, relative to the surrounding area (Peterson and Kraatz 2003). Over time, cores are heaved to the surface and accumulation of circle margins. Annual disturbance due to differential freeze-thaw 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 insolated by organic matter, differentiation becomes no longer occurs, and disturbances cease.

### Soil temperature effects on shrub growth

Soil temperatures show a strong relationship with the presence of alder shrubs, with warmer temperatures increasing the likelihood of alder establishment. Averaged 1960-2010 temperatures (Fig. 6) indicate that alder abundance increased dramatically in some areas, but was virtually unchanged in others. In expansion areas, temperatures (above left) are relatively high and shrubs grow very quickly. In other areas, alders mature, organic matter accumulates and soil temperatures decline dramatically. Alders are very long-lived, in paludified shrublands, they grow extremely slowly.

### 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 southwestern 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 freeze causes annualized, 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 buffer the active layer from climate change.

### Field methods

- 22 transects (20-100 m length, 4-8 m width) in alder shrublands and adjacent tundra:
  - alder-free tundras
  - alder colonization zones
  - mature shrubland (most shrubs ≥2m height)
  - paludified shrublands (very low shrubs)
- Measured soil organic depth and mineral horizon thickness systematically along transects, and at alders.
- Assessed the locations of alders and circles (where visible).
- Recorded daily soil temperature profiles at 5 cm depth using dataloggers.
- Obtained nutrient soil samples at the transects.

### Spatial distribution of microsites

**Alder density (shrubs m⁻²)**

- 20 alders
- 0 alders

### Literature Cited


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