Widespread expansion of boreal shrublands in the Siberian Low Arctic since the 1960s

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Abstract

Declassified imagery from the KH-4B “Corona” and KH-7 “Gambit” Cold War satellite surveillance systems (1963-1972) are a unique, high-resolution dataset that establishes a baseline for landcover-change studies in the Russian Arctic spanning 6 decades. We co-registered Corona/Gambit and modern high-resolution imagery for ten ~65 km^2 Low Arctic landscapes in northern Siberia and quantified changes in the extent of alder (*Alnus*) shrublands (7 sites) and larch (*Larix*) woodlands (5 sites). We made ground observations at several northwest Siberian sites to identify local mechanisms, related to soils, permafrost geomorphology, and disturbance, that result in landscape-scale heterogeneity in the response of vegetation to recent climate warming.

Alder shrubland cover increased at all sites; shrubland extent increased 5-27% at the northwest Siberian sites and ~9% at Chukotkan sites. In northwest Siberia, alder expansion was closely linked to disturbance processes in permafrost, while most of the alder expansion in Chukotka occurred on hillslope colluvium and floodplains. We observed modest increases in larch abundance at four sites, while dramatic die-back occurred at one site due to thaw of ice-rich permafrost. The close correspondence between areas of vegetation change and cryogenic disturbance indicates that the response of vegetation in tundra ecotones to climate change is largely mediated by geomorphic processes in permafrost.

Methods

The Siberian Arctic represents a large knowledge-gap in studies of tundra shrubification (Fig. 1). We compared very-high-resolution (VHR) satellite imagery from the 1960s and recent years to quantify changes in shrubland and tree extent in ten widely-distributed Siberian tundra ecotones over a ~45 year time period. Coverage of KH-4B Corona imagery (~2-m pixel) is extensive for northwest Siberia, Yakutia, and Chukotka. Additional KH-7 Gambit imagery (~70-cm pixel) exists for smaller areas across the Siberian Arctic. We identified ecotonal landscapes with overlapping historical and modern VHR imagery, co-registered the images, overlaid a grid of sampling-points at 30 m spacing, and quantified changes in alder and larch abundance using a point-intercept sampling approach.

We also compiled Landsat stacks (1985-2011) for northwest Siberian sites and applied pixel-based linear regression to examine landscape-scale heterogeneity in trends of the Normalized Difference Vegetation Index (NDVI). We derived surface reflectance values for the Landsat data using the LEDAPS algorithm (Masek et al. 2008), computed the NDVI, and conducted linear regression for each pixel. Finally, we compiled weather data from ground stations near the study areas and determined trends in summer temperature for the satellite period-of-record (1965-2011).

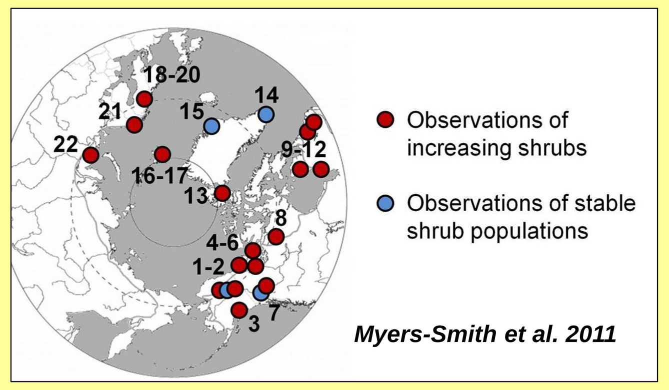


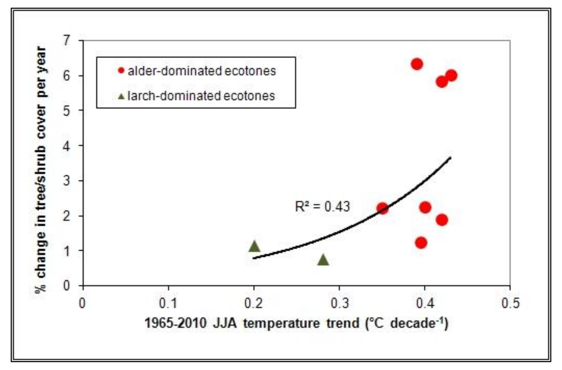
Fig. 1. Locations of observational studies of changes in tundra shrub abundance. Very little information exists for the Siberian Arctic, and inferences of circumpolar shrubification have largely been based on observations in the North American Arctic.

Fig. 2. Study landscapes in the Siberian Low Arctic. Landscapes are ~65 km^2 in size and encompass tundra ecotones with alder shrublands (northwest Siberian and Chukotkan sites) and/or larch woodlands (mainly north-central Siberia). The area highlighted in red represents the warmest, southernmost subzone of Arctic tundra (Circumpolar Arctic Vegetation Map; Walker et al. 2005).

Results

Summary of changes in cover of boreal shrubs and trees (below left), and correlation between rates of boreal vegetation expansion and summer temperature increase (below, right). Shrub and tree cover increased at all but one site; alder expansion rates were generally much higher than for larch. Expansion was fastest in northwest Siberia. Expansion rates correlate well with the magnitude of warming when tree- and shrub-dominated sites are considered together; however, shrub-dominated sites experienced similar warming but had highly variable expansion rates. These differences are largely explained by landscape-scale factors.

			Alder cover (km^2)			Larch cover (km^2)			Relative change (% decade^{-1})	
Site	Area (km^2)	Interval (yrs)	1960s	2000s	Δ	1960s	2000s	Δ	Alder	Larch
Kharp	64	42	7.2	7.8	0.6	0.6	0.6	trace	1.9	0.1
Obskaya	59	36	4.8	5.8	1.0	3.8	4.3	0.5	5.0	3.1
Tanlova	65	43	5.5	7.0	1.5	-	-	-	6.7	-
Tazovskiy	55	42	9.3	9.8	0.5	-	-	-	1.3	-
Dudinka	58	43	12.8	16.2	3.3	0.1	0.1	trace	6.2	0.9
Hatanga	34	43	-	-	-	1.4	1.4	0.1	-	1.2
Uyandi	53	50	-	-	-	1.0	1.1	0.1	-	0.9
Cherskiy	44	38	-	-	-	3.7	3.1	-0.6	-	-4.0
Belaya	73	41	8.4	9.2	0.8	-	-	-	2.2	-
Velikaya	78	40	9.2	10.0	0.8	-	-	-	2.1	-



*thermokarst site omitted from plot

Continental-scale vegetation changes (1965-2010)

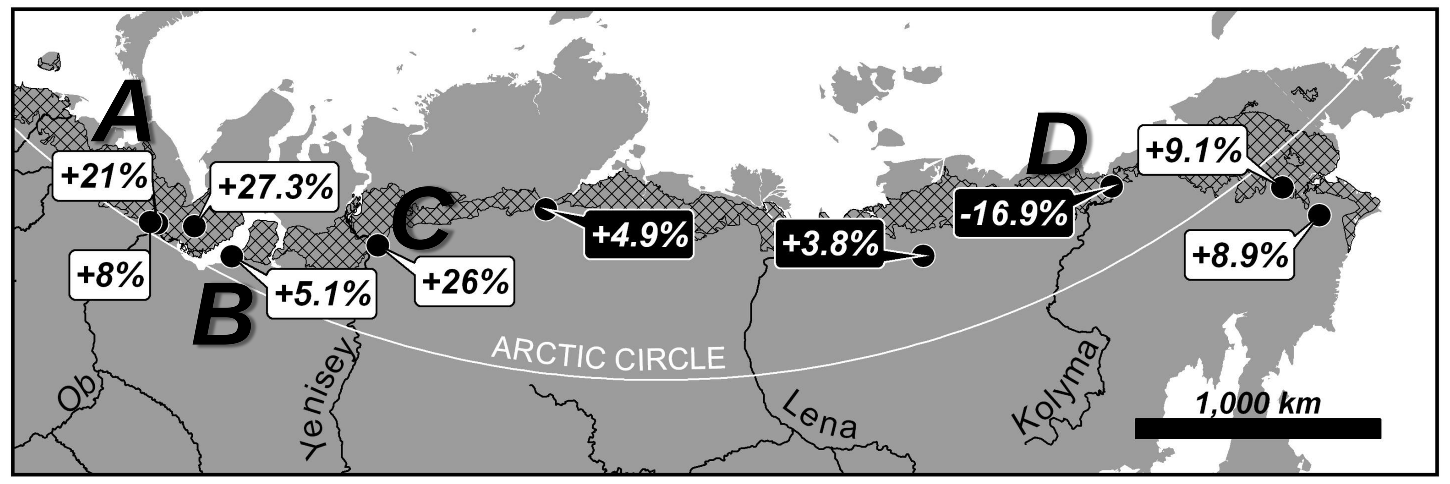
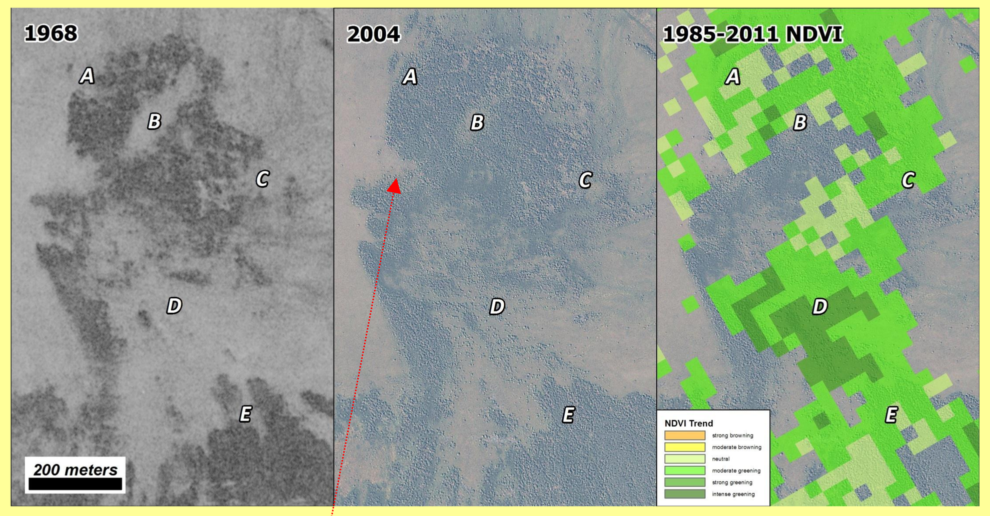
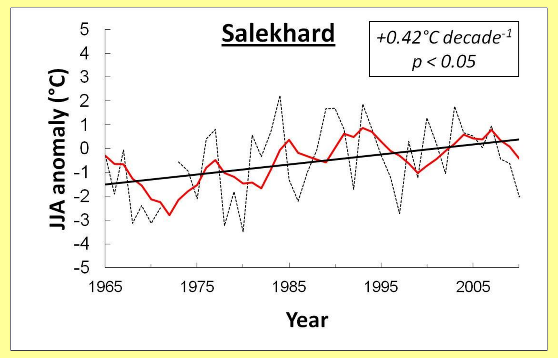


Fig. 4. Summary of changes in cover of boreal shrubs (white boxes) and trees (black boxes) in the Siberian Low Arctic, 1965-2010. Values refer to the % change in modern shrub/tree cover relative to 1960s cover. Shrub and tree cover increased at all sites except one, where thaw of ice-rich permafrost caused extensive die-back of woodlands. The largest increases in shrub cover occurred in the northwest Siberian region. At the landscape-scale, areas of vegetation change were closely linked to specific geomorphic features and disturbance processes that promote seedling recruitment. Letters indicate landscapes examined in panels A-D, below and right.

A — Shrub expansion in patterned-ground



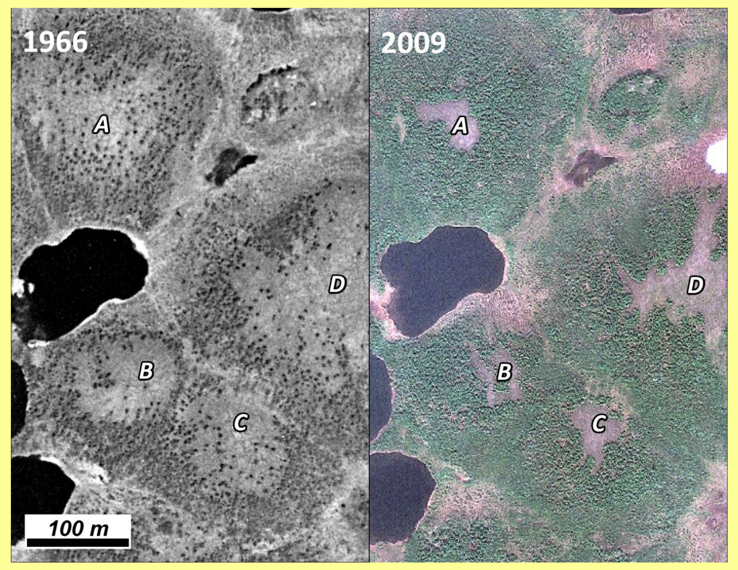
Comparison of 1968 (Corona) and 2004 (IKONOS) photos, and NDVI trends for shrub expansion area at Obskaya. Letters indicate areas with newly-developed alder cover. Shrub expansion and greening are concentrated in areas with active patterned-ground features (below left).



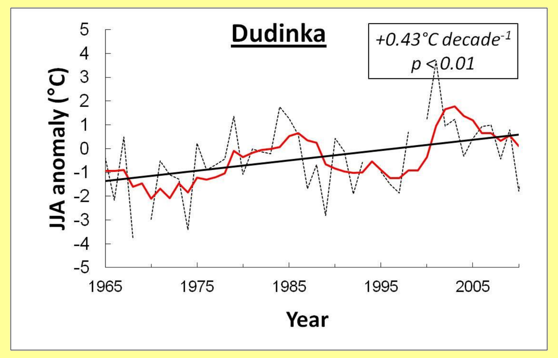
Summer temperature time-series at Salekhard, 40 km southeast of Obskaya. Raw values (dotted line), 5-year running average (red), and linear trendline (black) are shown.

Ground (left) and aerial (right) photos of alder shrublands in patterned-ground. Circles offer a multitude of favorable seedbeds, facilitating rapid shrub expansion (Frost *et al.*, in review)

C

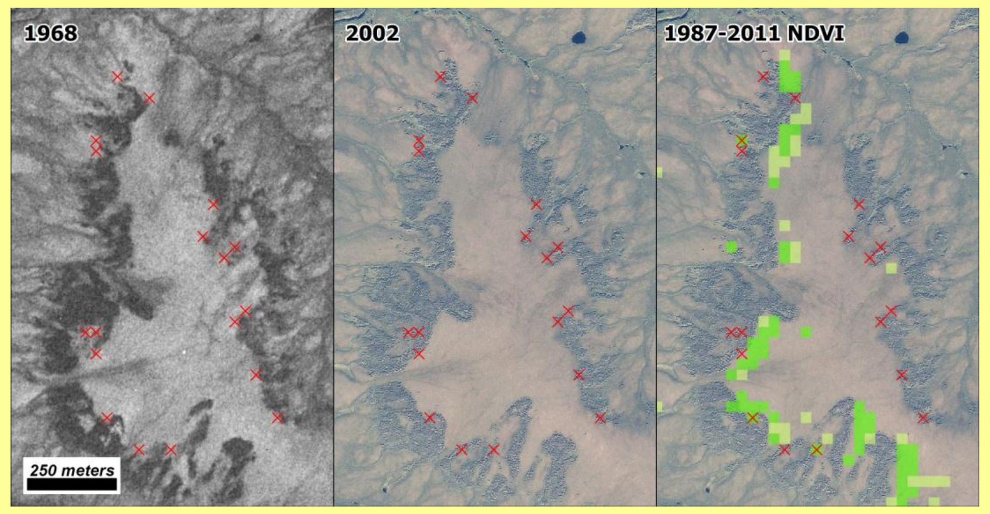


Comparison of 1966 (Gambit) and 2009 (GeoEye-1) imagery showing expansion of alder shrublands on hilltops near Dudinka, northwest Siberia. Shrub expansion at Dudinka is closely linked to patterned-ground, similar to that seen at Obskaya (panel A).



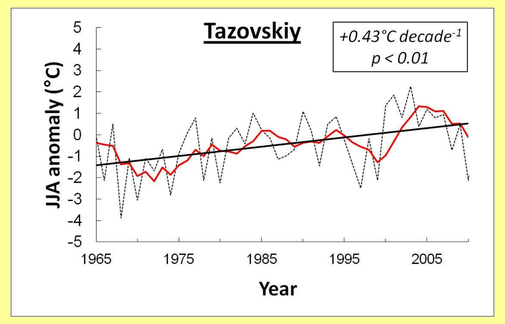
Summer temperature time-series at Dudinka (1965-2010). The late 1960s and early 1970s were relatively cool throughout most of Low Arctic Siberia.

B — Shrub expansion on cryogenic landslides

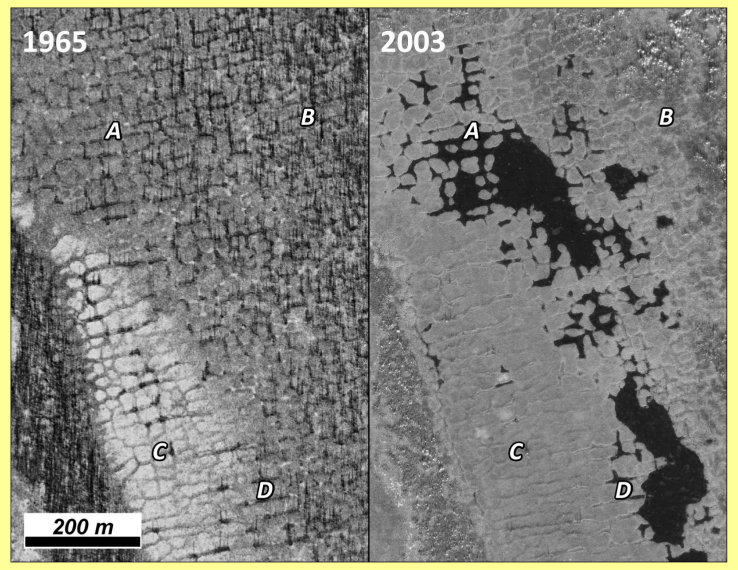


Comparison of 1968 and 2002 photos, and NDVI trends for cryogenic landslide area at Tazovskiy. Red markers indicate points with newly-developed alder cover. Shrub expansion and greening are concentrated on the upper margins of cryogenic landslides (Fig. 9, right). Increases in shrub cover at Taz were modest compared to other northwest Siberian sites, despite comparable trends in summer temperature (below right). This is probably due to the limited extent of favorable, mineral-rich substrates for alder recruitment.

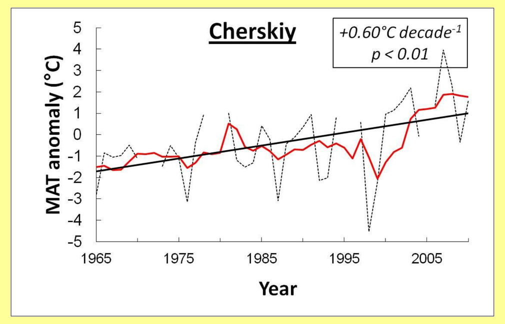
Aerial view of active-layer detachments on central Yamal Peninsula (right). Shrub thickets are conspicuous in the upper margins of the landslide features, similar to the satellite imagery for Taz. *Photo Skip Walker.*



D — Forest die-back after thermokarst



Thermokarst and degraded ice-wedges (left) and time-series of mean annual temperature (below), Cherskiy, Yakutia. Thaw of ice-rich floodplain deposits has led to extensive loss of larch woodland near the Kolyma River. Cherskiy experienced the strongest increases in mean annual temperature of any study site.



Summary and conclusions

1) Boreal shrub cover increased at all seven shrub-dominated sites, but the magnitude of increase varied (+5 – 28%). Modest increases in tree cover occurred at 4 of 5 sites; extensive die-back of larch occurred at one site due to thermokarst.
2) Shrub expansion was closely linked to landscape patches where active disturbance processes create mineral-rich seedbeds with little competing vegetation.
3) The susceptibility of tundra landscapes to boreal shrub advance is highly dependent on the frequency and scale of disturbance processes that create favorable seedbeds.
4) Widespread changes in Low Arctic land-cover due to shrub increase are possible within multi-decadal timescales, whereas the spread of trees is much slower.
5) **Northward expansion of boreal vegetation is a global phenomenon that behaves according to local rules.**

Acknowledgements

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