Expansion and patch dynamics of alder shrublands in the Siberian Low Arctic: evidence from remote-sensing spanning the Space Age

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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 nine ~65 km^2 Low Arctic sites—four in northwest Siberia, three in Yakutia, and two in Chukotka—and quantified changes in the distribution and extent of tall alder (*Alnus fruticosa* spp. *sibirica*) and larch (*Larix* spp.) using a point-intercept sampling approach. Photo-interpretation was facilitated by field data from the Kharp site in southern Yamal. We also produced Landsat TM/ETM+ time-series of Normalized Difference Vegetation Index (NDVI) for the northwest Siberian sites for ~1985-2011, and applied pixel-based linear regression to identify areas with significant trends in vegetation productivity.

Alder cover increased at six shrub-dominated sites; in northwest Siberia, shrubland extent increased by 5% (Taz), 8% (Kharp), 14% (Obskaya) and 31% (Dudinka), and by 9% at both Chukotkan sites. In northwest Siberia, alder expansion was closely linked to disturbances in permafrost related to patterned-ground (Kharp, Obskaya, and Dudinka) and cryogenic landslides (Taz). At the Chukotkan sites, most alder expansion occurred on mountain slopes (Anadyr), and on floodplains (Velikaya); we also observed modest increases in Siberian dwarf pine (*Pinus pumila*). Close correspondence between expanding shrub patches and disturbance processes indicates that sparsely-vegetated, mineral-rich seedbeds strongly facilitate alder recruitment, and that the spatio-temporal attributes of disturbance mechanisms are a key determinant of landscape susceptibility to shrub expansion.

Most Landsat-derived spectral changes indicate "greening" at the sites, but intensity and spatial patterns differed markedly at the three sites with widespread, strong greening at Kharp and Dudinka, and slight browing at Taz. At all sites, areas of strong greening tended to coincide with known shrub expansion areas, and "background" greening tended to coincide with shrubby areas in general. By linking significant spectral changes to known shrub expansion areas, we are developing spectral signatures for shrub expansion that will support regional-scale, Landsat-based analyses of alder shrubland dynamics throughout the northwest Siberian Low Arctic.

Methods

We compared high-resolution satellite imagery of tundra ecotones from the 1960s and recent years to quantify changes in shrubland and tree extent over a ~45 year time period. Coverage of KH-4B Corona imagery (2-m spatial resolution) is extensive for the Polar Urals and Yamal regions, Yakutia, and Chukotka (Figure 1). Additional KH-7 Gambit imagery (70-cm resolution) exists for smaller areas across the Siberian Low Arctic. We co-regisetered the images and used a point-intercept approach at 30-m spacing to quantify changes in shrubland abundance at four sites in northwest Siberia and two in Chukotka; we also quantified changes in larch (*Larix* spp.) abundance at three treeline sites in Yakutia (Figures 2 and 3).

We also compiled Landsat stacks (1985-2011) for the Kharp, Taz, and Dudinka sites and applied pixel-based linear regression (e.g., Fraser et al. 2011) to examine spatial patterns of greening at the landscape scale, and to isolate the spectral signature of shrub expansion areas and other land-cover types (Figures 4-X, right). 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.

Satellite photo comparisons (1966-2010)

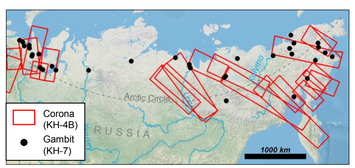


Fig. 1. Spatial coverage of Corona and Gambit imagery in northern Siberia. The footprints shown were acquired during the growing season (June-August) and are mostly free of clouds.

Fig. 2. Study sites in Low Arctic Siberia and Chukotka. Sites are ~65 km^2 in size and encompass tundra ecotones with alder shrublands (northwest Siberian and Chukotkan sites) or larch woodlands (Khatanga, Deputatskiy, and Cherskiy).

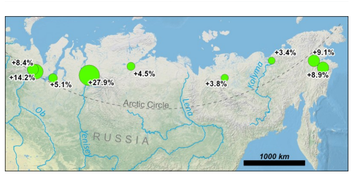


Fig. 3. (left) Summary of changes in shrub and tree abundance at the study sites. Relative to 1960s baselines, the cover of tall shrubs and trees increased at all nine sites. The greatest increases occurred at the northwest Siberian and Chukotkan sites, where alder shrublands are abundant. Modest increases in tree cover occurred at the Yakutian sites.

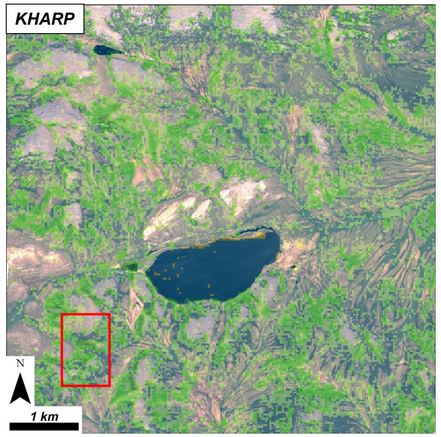


Fig. 4. NDVI trend map for Kharp. Landsat pixels with significant trends (p<0.05) are shown over a 2003 QuickBird image. Most greening occurred in shrubby areas, with the most intense greening in newly-established shrublands (Figure 5, below). Note the lack of trends in moss-dominated bogs (reddish-brown photosignature). The only browning occurred due to erosion on the north shore of the lake.

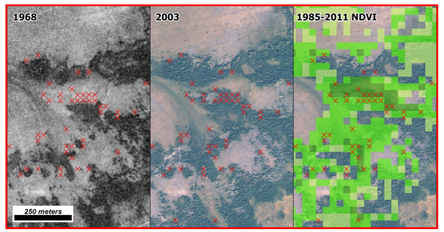


Fig. 5. Comparison of 1968 and 2003 photos, and NDVI trends for shrub expansion area at Kharp. Red markers denote points with newly-developed alder cover. Strongly-greening Landsat pixels tend to co-incide with shrub expansion areas, where shrubs are colonizing mineral soils in patterned ground (Fig. 6, below). Many of the denser, long-established shrublands show no significant NDVI trend.

Fig. 6. Alders colonizing non-sorted circles, Kharp (right). Active patterned-ground features are closely linked to shrub expansion areas at Kharp, Obskaya, and Dudinka (Frost et al., in review, *Nature-Geosciences*).

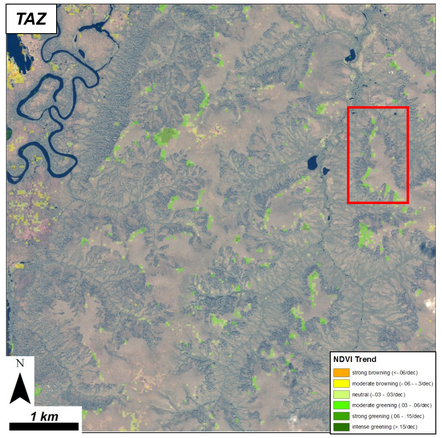


Fig. 7. NDVI trend map for Taz. Landsat pixels with significant trends (p<0.05) are shown over a 2002 IKONOS image. Greening is very limited and is mostly seen on the upper margins of cryogenic landslides (Fig. 8, below), possibly because nutrient-rich marine clays are becoming more accessible to vegetation as overlying sandy deposits erode away. Lake extent has increased on the floodplain (upper left).

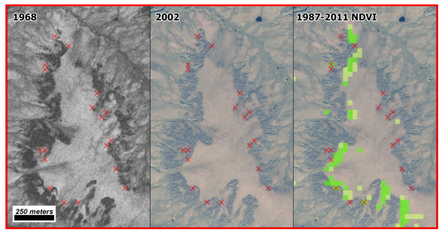


Fig. 8. Comparison of 1968 and 2002 photos, and NDVI trends for cryogenic landslide area at Taz. Red markers denote points with newly-developed alder cover. Greening and shrub expansion are both concentrated on the upper margins of cryogenic landslides (Fig. 9, below). However, the shrub expansion areas generally do not coincide with greening pixels, perhaps because the expansion occurred before the Landsat record began (1987).

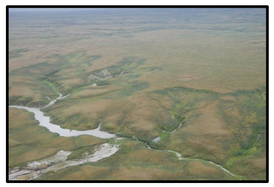


Fig. 9. Aerial view of active-layer detachments on central Yamal Peninsula (right). Shrub thickets are conspicuous in the upper margins of the landslide features, similar to the satellite imagery for Taz. *Photo Skip Walker*

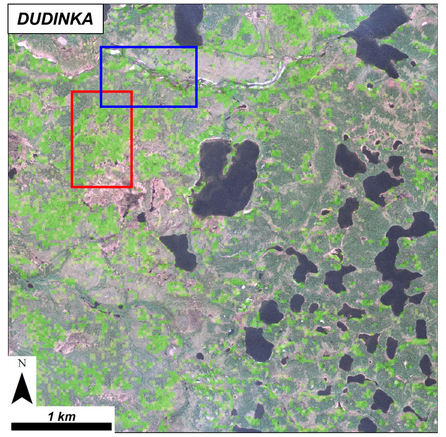


Fig. 10. NDVI trend map for Dudinka. Landsat pixels with significant trends (p<0.05) are shown on a 2009 GeoEye image. Most greening occurred in shrublands (Fig. 11, below), but there is a lack of greening in dense stands (right), possibly because of the high (saturated) NDVI values in these areas. Note the lack of trends in wet lowland tundra. Interestingly, the strongest greening occurred in snowbeds (Fig. 12, bottom).

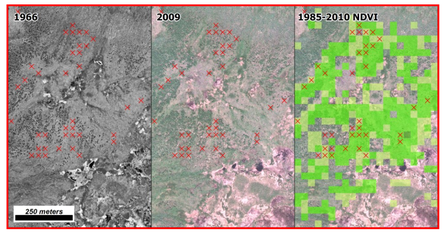


Fig. 11. Comparison of 1966 and 2009 photos, and NDVI trends for shrub expansion area at Dudinka. Red markers denote points with newly-developed alder cover. Dudinka had the highest observed increases in shrubland cover (28%).

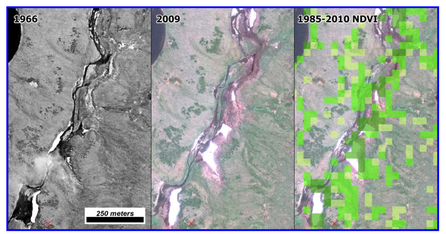


Fig. 12. Comparison of 1966 and 2009 imagery, and NDVI trends for snowbed area at Dudinka. Widespread, spatially coherent patterns of greening are apparent in snowbeds throughout the study area.

Landsat NDVI trends

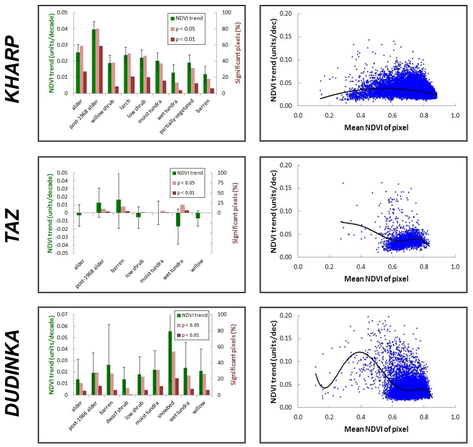
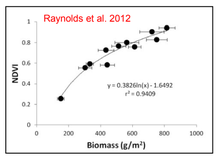
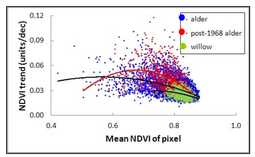


Fig. X. (left column) NDVI trends by land-cover type. At Kharp, greening occurred in all land-cover types, with the highest increase in expanding shrublands. At Taz, NDVI trends were flat and some land-cover types are "browning." At Dudinka, greening occurred in all land-cover types, but increases are modest considering the extent of shrub expansion; surprisingly, the largest NDVI increases were in snowbed areas. **(right column) NDVI sensitivity to changes in biomass.** At all sites, the highest rates of greening are seen in pixels with intermediate NDVI values, with diminished trends seen in highly productive land-cover types . This is consistent with empirical relationships of AVHRR NDVI and above-ground biomass **(below, left)** and is also evident in comparisons of willow and alder shrublands **(below, right)**.





Summary and conclusions

1) Shrub and tree cover increased at all nine sites, but the magnitude of increase varied (+3 - 28%).
2) Shrub expansion was closely linked to landscape patches where active disturbance processes promote the development of mineral-rich seedbeds with little competing vegetation.
3) The three sites with the largest shrub increases encompass extensive areas of active, patterned-ground features.
4) Landsat NDVI time-series reveal spatially-coherent patterns of greening (and browning) that are consistent with field observations and readily interpreted in terms of known land-cover changes, geomorphic processes, and disturbance processes.
5) For the most part, there is close correspondence between shrub expansion areas and pixels with significant greening trends.
6) The apparent lack of greening in dense shrublands could be an artifact of the diminished sensitivity of NDVI to changes in highly productive land-cover types.
7) NDVI trends generally negative or flat for wet tundra and moss-dominated communities.
8) Landsat data will be used to examine regional trends in shrubland abundance in northwest Siberia.

Literature Cited

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Acknowledgements

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