Spatio-temporal trends in tree and tall shrub cover in the circumpolar Arctic: evidence from repeat ground photographs and 1960s satellite imagery

Abstract

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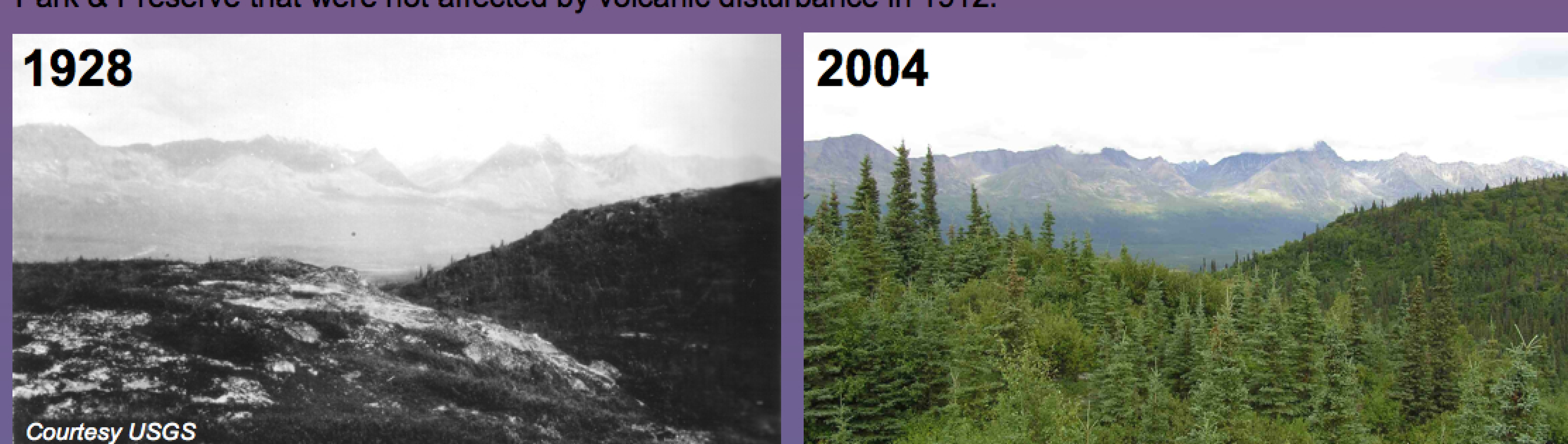
Patterns of tree and tall shrub occurrence form conspicuous and dynamic ecological boundaries across arctic regions. The northward and upslope encroachment of trees and shrubs into tundra-dominated areas is one of the principle changes to arctic land cover expected with climatic warming, and there is evidence that ecological state-shifts are already occurring in ecotones of the North American low Arctic. The ubiquity of these state-shifts across the circumpolar low Arctic is unclear, however, because few data exist for the vast Eurasian continent. This study is quantifying state-level vegetation change in geographic and altitudinal tundra ecotones at ~25 study sites in northern Eurasia and Alaska using comparisons of circa 1965 "Corona" and contemporary high-resolution satellite photography.

Corona was the world's first operational satellite surveillance system and today offers a readily available data source for land surface change studies over a ~40 year temporal interval. Ground-based repeat photography of Alaskan tundra ecotones has documented widespread tree and shrub expansion in southwestern[1] and northern[2] Alaska, and indicates that the spatio-temporal resolution of Corona photography (~40 yr, 2 m) is sufficient for meaningful change-detection in low Arctic ecosystems. The degree to which patterns of vegetation change are shared among ~25 widely distributed study sites will indicate the ubiquity of ecological state-shifts in the low Arctic, as well as the relative influence of large-scale forcing mechanisms (e.g., climatic change) and local environmental controls (e.g., distribution of favorable geomorphic features in the landscape) on tree and tall shrub expansion. Remote sensing and ground-based data indicate that mean annual temperatures have increased over the last ~50 years at all of the study sites, although there is considerable variability in the magnitude of warming (~1.5 - 4 °C).

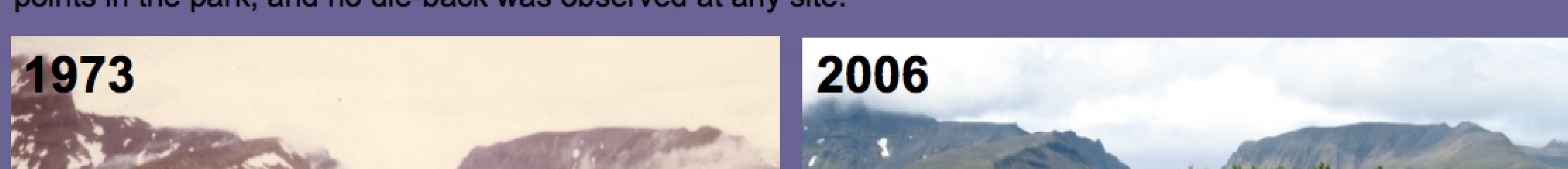
Preliminary findings indicate that tall shrublands have expanded at several sites in northwestern and far eastern Siberia and northwestern Alaska. Expansion is most apparent on floodplains, uplands, and drained lake basins. Across most of north-central Eurasia, tundra ecotones are primarily defined by larch (*Larix*) woodlands. Infilling of pre-existing woodlands and larch establishment ~0.25 km beyond the 1965 treeline position have been detected on the lower Khatanga and Kolyma river floodplains. All changes observed so far are unidirectional, with no die-back of forest or shrubland at any site, but the extent of expansion is highly variable both within and among sites. Large-scale, synchronous expansions have occurred in the past (e.g., mid-Holocene) and associated changes to land surface-atmosphere interactions could have far-reaching effects on atmospheric circulation and global climate.

Repeat Ground Photographs

Uplands near King Salmon, southwest Alaska in 1918 (Hagelbarger) and 2005 (Frost)[1]. Birches (*Betula*) and white spruce (*Picea glauca*) have expanded dramatically in the area over the last century. Tree and/or shrub expansion was evident at all eleven historical photopoints re-occupied in tundra ecotones of Katmai National Park & Preserve that were not affected by volcanic disturbance in 1912.



Uplands near Two Lakes, Lake Clark National Park & Preserve, south-central Alaska, in 1928 (Capps) and 2004 (Jorgenson)[1]. The presence of trees on the background slope in 1928 indicates tree expansion, rather than recovery after fire, at this ~850 m site. Tree and/or shrub expansion was apparent at 19 of 34 ecotonal photo-points in the park, and no die-back was observed at any site.



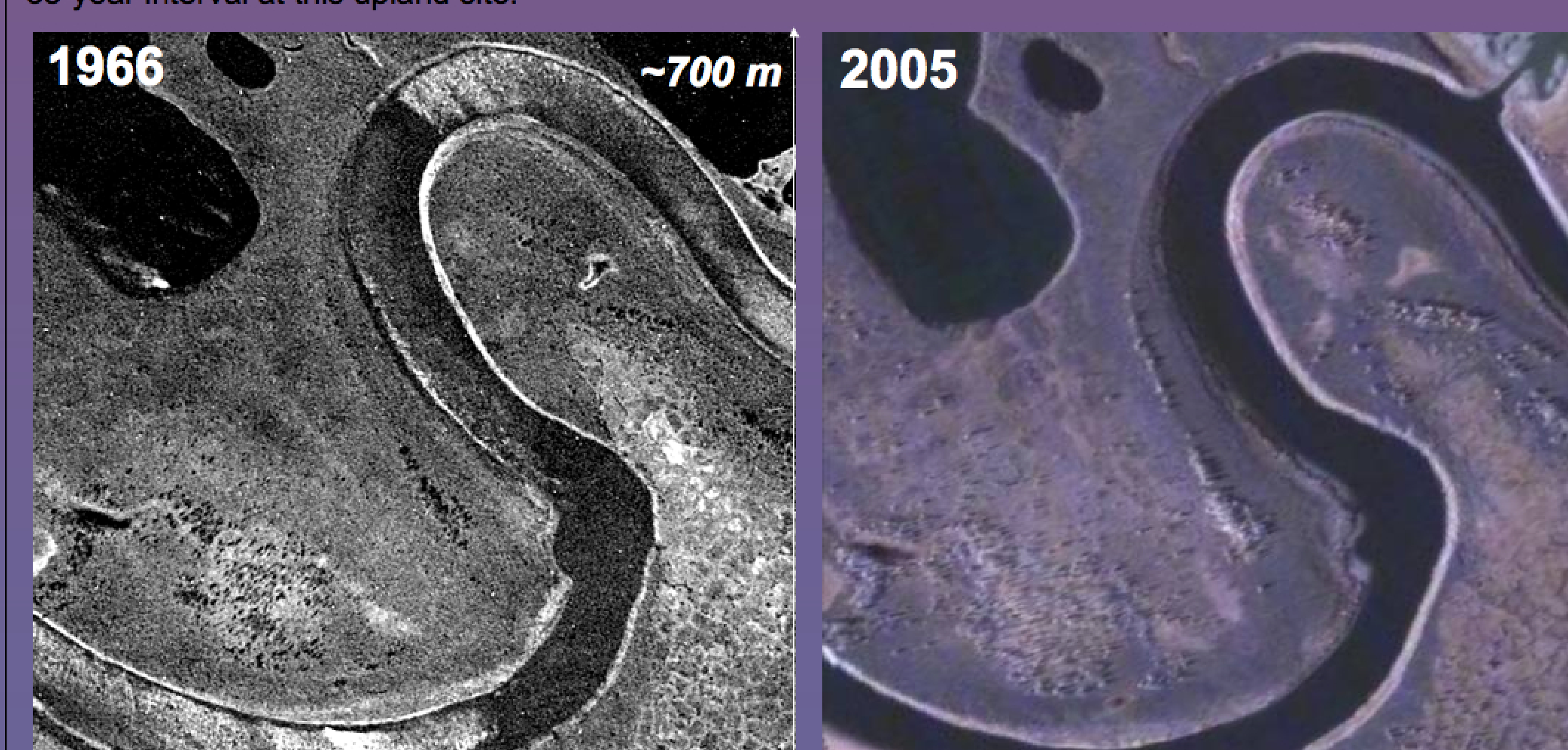
Study Components and Questions

1. Is tree and shrub expansion a ubiquitous phenomenon in eco-tonal regions of the circumpolar low Arctic?
2. What environmental factors are important determinants of the observed changes?
3. What do observed changes indicate regarding the relative influence of large-scale forcing mechanisms and local environmental controls on tree and shrub expansion?
4. How do recent expansion rates compare to those that would have produced prior Quaternary interglacial treeline positions estimated in the literature?
5. To what extent do changes in tree and shrub cover explain anomalies detected in the Normalized Difference Vegetation Index (NDVI) over the last ~25 years?

Corona and Gambit Satellite Photography

The escalation of the Cold War in the 1950s led to rapid advances in aerospace technology, culminating in the dawn of the Space Age. In 1959, the U.S. Department of Defense initiated the development of "Corona", the world's first satellite reconnaissance system. Corona's primary objectives were to monitor Soviet military assets and acquire cartographic data[3]. Today, Corona imagery provides historical land surface data for remote areas for which aerial photography is unavailable. Corona achieved spatial resolution of 2 m for 1968-1972. A related mission, "Gambit", operated from 1963-1967 and achieved spatial resolution of ~0.75 m. The resolution of Corona and Gambit is comparable to that of modern commercial satellites such as Quickbird and IKONOS, facilitating delineation of shrub patches and even individual trees.

Corona (19 August 1968; left) and Quickbird (24 July 2003; right) photos of a shrubland-tundra ecotone near the polar Ural Mountains, Russia (67°N). On both images, the photo-signature of tall shrubs (darkest patches) is readily distinguished from tundra. A substantial increase in shrubland cover is apparent over the 35-year interval at this upland site.

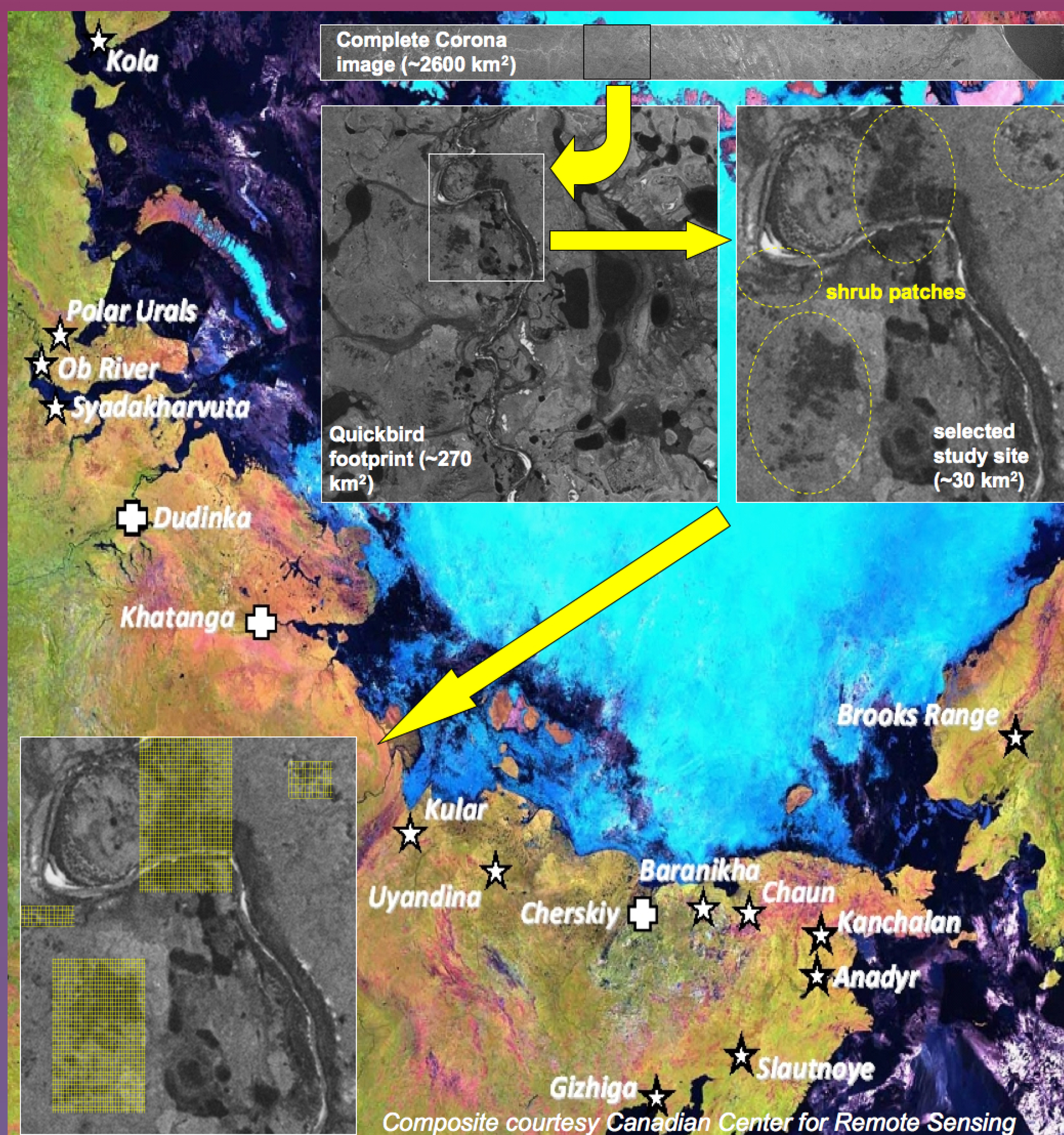


Gambit (13 July 1966; left) and Quickbird (11 September 2005; right) photos of a forest-tundra ecotone near

Methods

This research approach examines recent vegetation change in low Arctic ecosystems at sites with a much broader geographic distribution than achieved by previous studies. As of March 2009, ~25 study sites have been identified with co-incident 1960s and contemporary photography (stars are Corona, crosses are Gambit). Additional Gambit photography has not yet been reviewed for several potential sites in northwestern and north-central Canada.

Most study sites are ~30 km^2 in size. Following image co-registration, a sampling grid overlay is applied to eco-tonal areas within each photo pair, and the presence/absence of tree and shrub cover is determined at each grid node in a GIS. The distance between grid nodes is ~20 m. Additionally, the number of trees within each grid cell is counted for forested sites with higher-resolution Gambit imagery. From these data, the absolute (m^2) and relative (% cover) change in tree and shrub cover are determined for each photo pair. Change in tree abundance is also determined for photo pairs with Gambit imagery.



Ancillary environmental data are also incorporated into the vegetation change GIS. These data include (1) elevation and hillslope aspect derived from digital elevation models; (2) remotely sensed land surface temperature; (3) climatic data for sites with nearby weather stations; and (4) multi-temporal NDVI data from the Advanced Very High-Resolution Radiometer (AVHRR). Additionally, geomorphic units (e.g., floodplain, patterned ground) and physiographic units (e.g., riverine, palustrine, upland) are digitized for each scene using manual photo-interpretation techniques. These data are then used to rank the importance of local- and regional-scale environmental factors in driving the observed vegetation changes.

Descriptive statistics will be used to develop data summaries relating the vegetation change metrics and the environmental strata within and between study areas. Spatial data will also be used to develop mathematical functions describing patch dynamics, and inferential statistics (e.g., ANOVA) will be used to evaluate the relative influence of the environmental strata as determinants of the extent and distribution of vegetation change. Finally, multi-temporal NDVI data layers will be added to the vegetation change GIS in order to estimate the extent to which tree and shrub dynamics have contributed to NDVI anomalies observed at each site since 1981. Quantitative assessments of the pace and extent of changes in the structure of northern ecosystems will improve understanding of associated impacts to a range of climatic, hydrological, and biogeochemical processes within—and beyond—the Arctic.