Effects of tall shrubland development on active layer temperatures in Siberian arctic tundra

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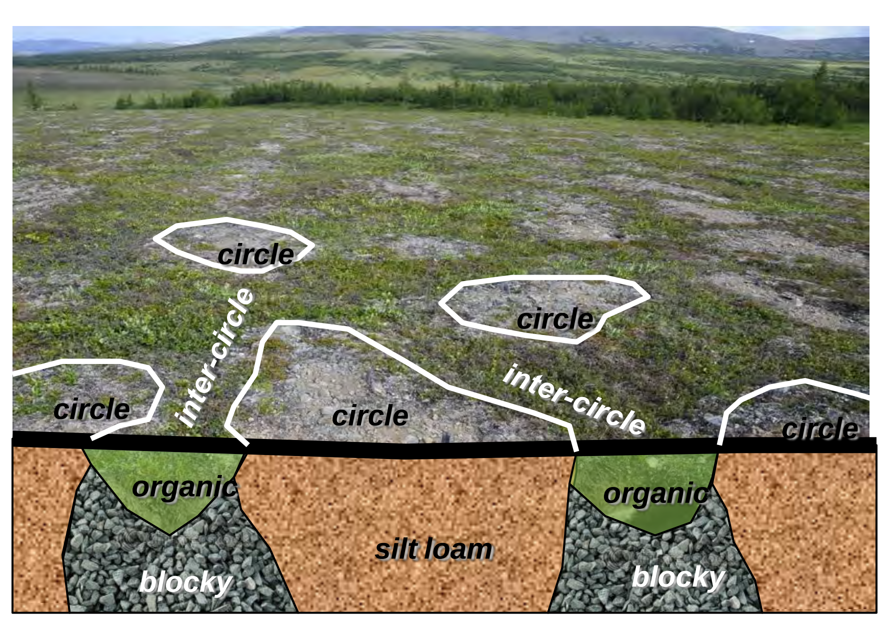
Abstract

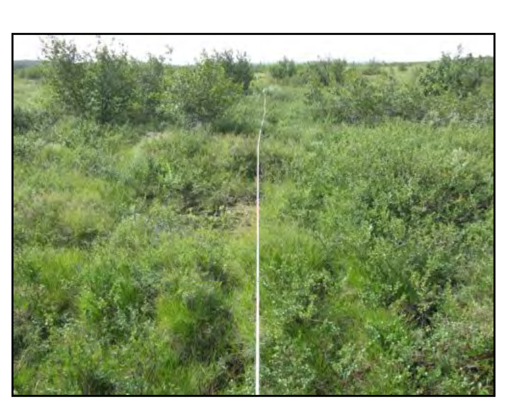
Permafrost soils are a globally significant carbon store, but changes in permafrost thermal regime observed in recent decades across much of the Arctic suggest that permafrost carbon balance is likely to change with continued climate warming. Critical to changes in permafrost carbon balance in a warmer world, however, are feedbacks between changes in the composition and density of surface vegetation, and the thermal state of permafrost. Shrub expansion has been widely observed in the northwest Siberian Low Arctic, but the magnitude and direction of shrub-induced impacts to permafrost temperature and stability remain poorly understood. Here we evaluate changes to active layer properties and thermal regime that occur during tall shrubland development (shrubs > 1.5 m height) within a northwest Siberian landscape dominated by well-developed, small-scale patterned ground features (e.g., non-sorted circles). We measured the annual time-series of soil temperature at 5 cm and 20 cm depth, and the structural attributes of vegetation at patterned-ground microsites across four stages of tall shrubland development: low-growing tundra lacking erect shrubs, newly-developed shrublands, mature shrublands, and paludified shrublands. Mean summer soil temperatures declined with increasing shrub cover and moss thickness, but winter soil temperatures increased with shrub development. Shrubland development strongly attenuated cryoturbation, promoting the establishment of complete vegetation cover and the development of a continuous organic mat. Increased vegetation cover, in turn, led to further reduced cryoturbation and a potentially aggrading permafrost table. These observations indicate that tall shrub expansion that is now occurring in patterned-ground landscapes of the northwest Siberian Arctic may buffer permafrost from atmospheric warming, and increase carbon storage in these systems at least in the short term.

Methods

This study was conducted in the eastern foothills of the Polar Ural Mountains, near the town of Kharp. Recent changes in shrub cover were known on basis of comparisons of high-resolution satellite imagery from 1968 and 2005. Patterned ground features, primarily sorted- and non-sorted circles ("frost circles") are widespread at the site. The cryoturbated, mineral-rich microsites at the circle centers facilitate shrub recruitment. iButton temperature loggers were placed at 5 cm and 20 cm depth in both frost circles (colonization and growth sites for alders) and in the inter-circle areas (already vegetated with short-statured tundra). Temperature loggers were placed in circle and inter-circle locations for four successional stages of shrubland development: Low-statured tundra (no shrubs), shrub colonization zone (shrubs absent in 1968), mature shrubland (large shrubs already present in 1968), and paludified shrubland (very old, largely moribund shrubs in wet, organic-rich soils). Approximately ten replicates of each stage x location x depth were sampled for a total of >150 loggers. Temperature loggers were programmed to record every four hours, and loggers were in place from 1 July 2012 through 8 June 2013.



Tundra (left) and Colonization Zone (right)



Mature Shrubland

Paludified Shrubland

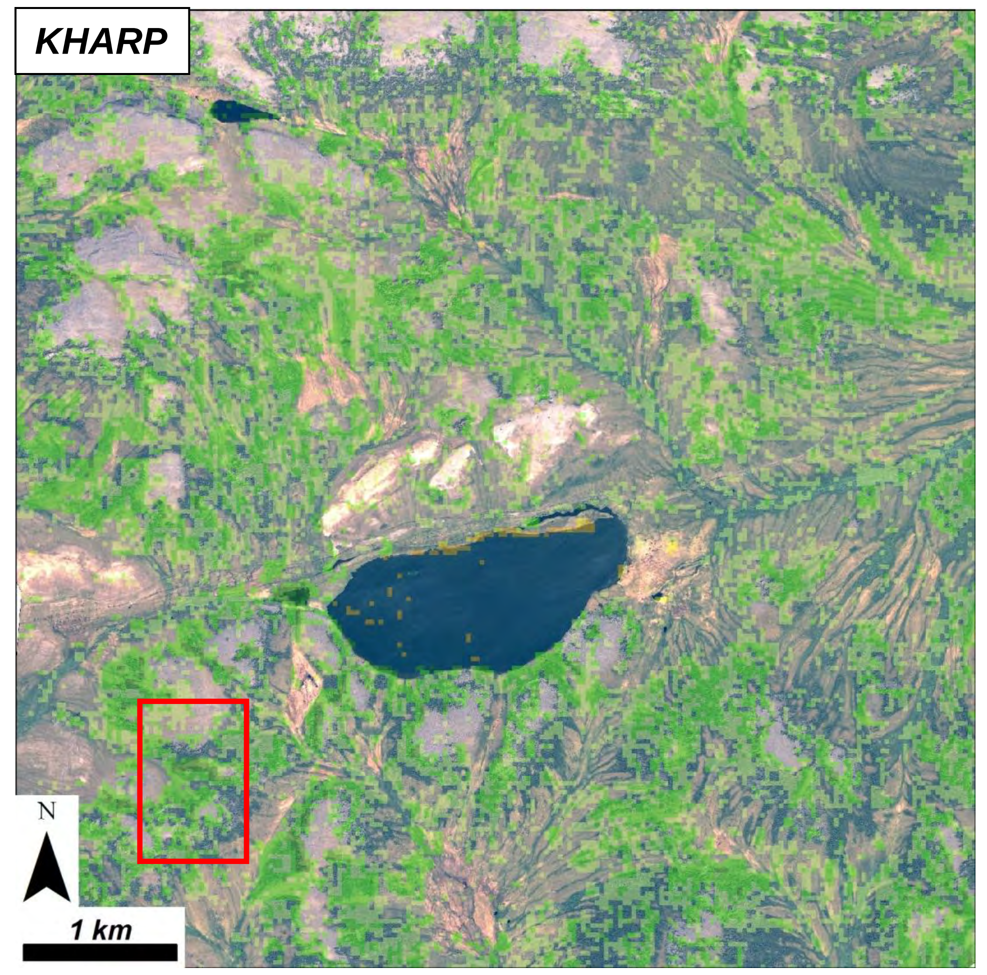


Fig. 1. NDVI trend map for Kharp study site. Landsat pixels with significant trends ($p<0.05$) are shown over a 2003 QuickBird image. Most greening occurred in shrubby areas, with the most intense greening in newly-established shrublands (e.g. red box above; Fig. 2 below). Note the lack of trends in moss-dominated bogs (reddish-brown photo-signature).

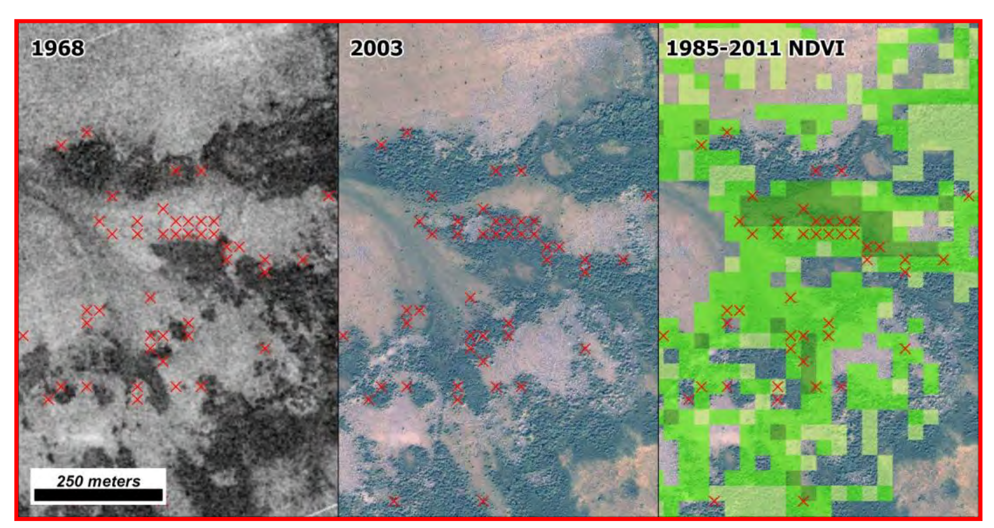


Fig. 2. Comparison of 1968 and 2003 photos, and NDVI trends for shrub expansion area at Kharp. Red markers denote points with newly-developed alder cover. Strongly-greening Landsat pixels tend to coincide with shrub expansion areas, where shrubs are colonizing mineral soils in patterned ground (Fig. 3, below). Many of the denser, long-established shrublands show no significant NDVI trend.

Fig. 3. Alders colonizing non-sorted circles, Kharp. Active patterned-ground features are closely linked to shrub expansion areas at Kharp and many other northwest Siberian tundra locations.

Acknowledgements

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Results

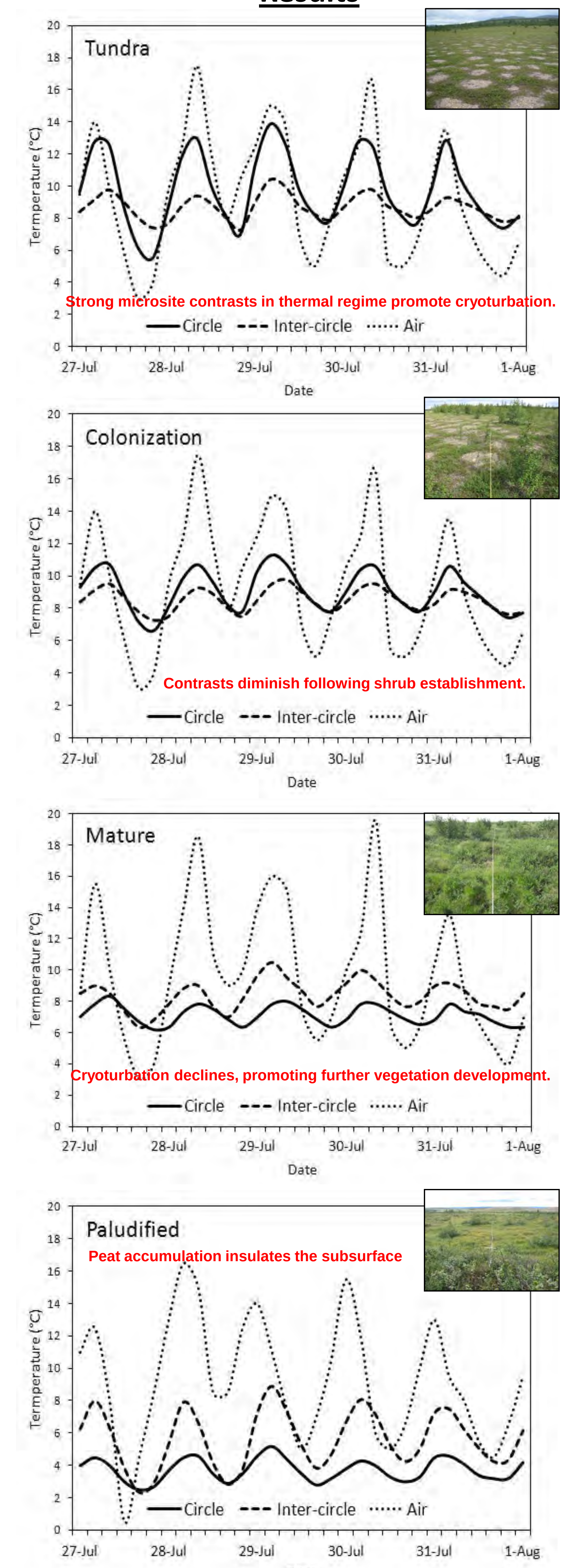

Fig. 4. Soil temperature at 5cm depth for a 6-day period in late July. Data indicate a switch during shrubland succession, whereby warm summer soils under barren circles, become substantially cooler (~8 °C) following shrub colonization, cessation of cryoturbation, and accumulation of peat.

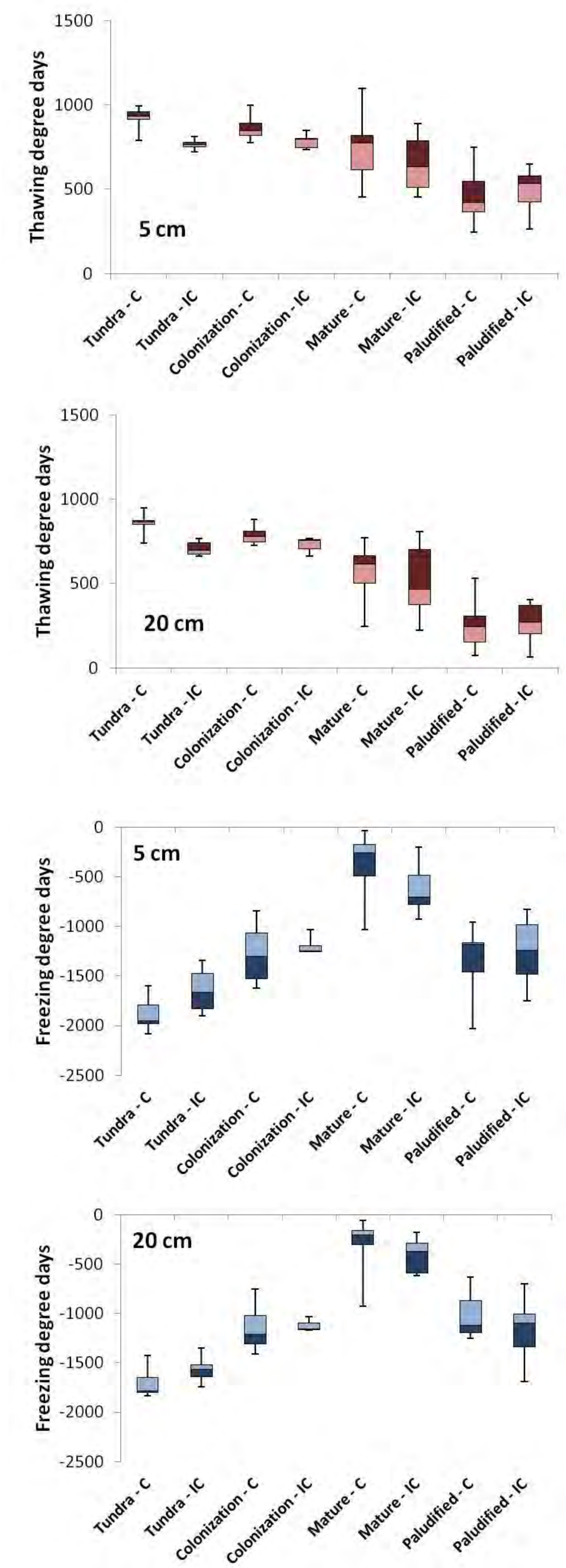

Fig. 5. Thawing and freezing degree days at 5 cm and 20 cm depth for circle and inter-circle locations across the four stages of shrubland succession. Box and whisker plots display medians, first and third quartiles, and range. Shrub expansion generally cools summer soils and warms winter soils, however the temporal dynamics are non-linear.

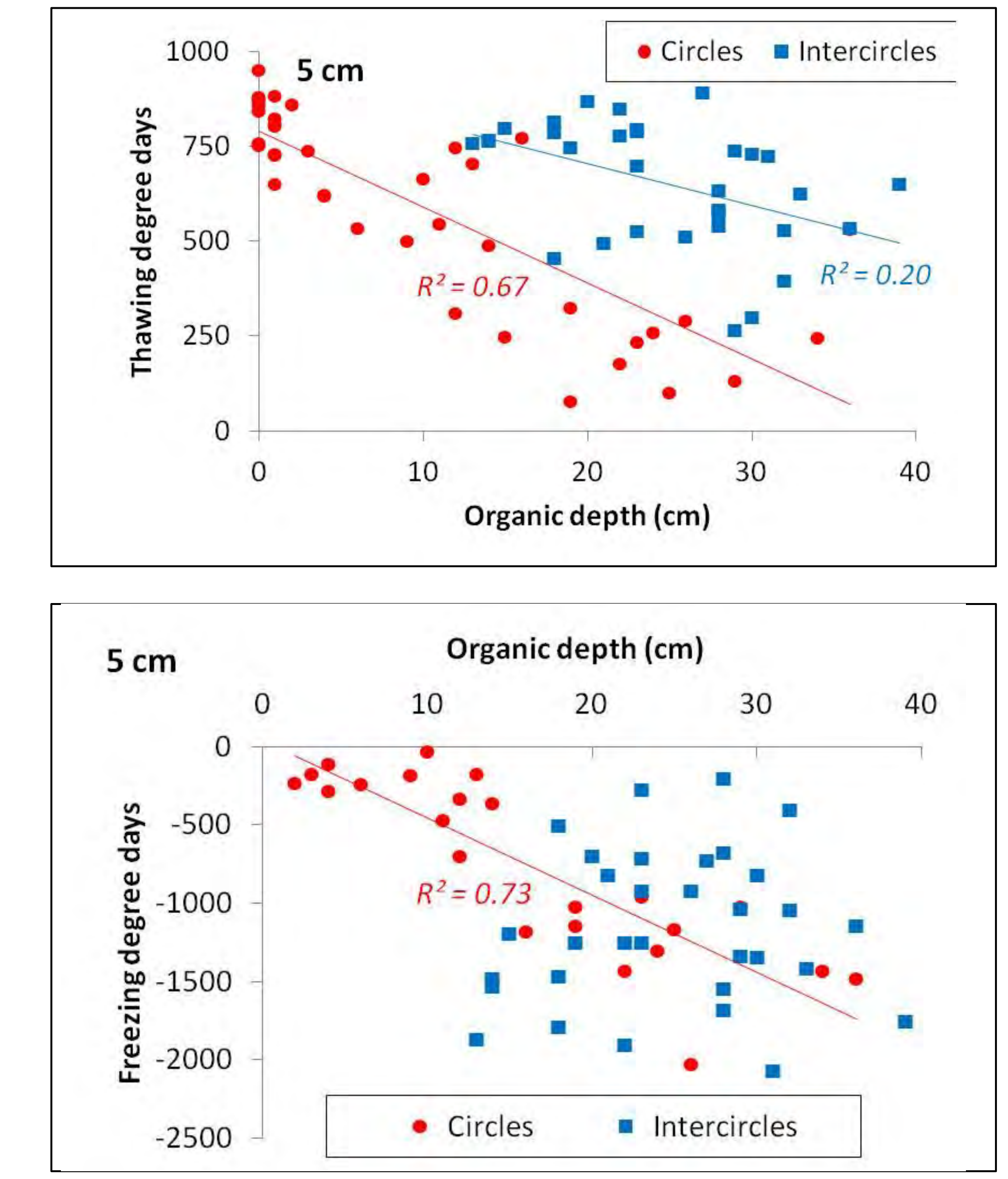

Fig. 6. Relationships between thawing/freezing degree days and depth of the organic layer at 5cm. Thicker organic layers reduce thawing degree days and increase (absolute value) freezing degree days.

Summary and Conclusions

- Expansion of tall shrubs is occurring on patterned-ground landscapes within the forest-tundra ecotone of northwest Siberia, and differential frost-heave (i.e. the presence of frost circles) appears to be strongly facilitating alder recruitment and growth.

- Summer shallow active-layer temperatures can decline dramatically throughout shrubland succession with approximately an 8 C difference at 5 cm depth between barren frost circles and former circles in now-paludified shrubland. This is also illustrated in the decline in thawing degree days throughout shrubland succession.

- In contrast, shrub development strongly reduces (absolute value) freezing degree days through the mature shrubland phase, but then winter soils get colder again with paludification. Tall, dense shrub canopies in mature shrublands likely trap more snow.

- The depth of the soil organic layer, leaf area, and shrub height, through insulation, shading, and snow-trapping exert key controls on the dynamics of freezing and thawing, cryoturbation, and accumulation of soil carbon.

BOTTOM LINE FOR PERMAFROST:
Shrubland expansion may buffer permafrost from increases in atmospheric temperatures through reductions in summer thawing and active layer development.