Linkages between Patterned Ground, Alder Shrubland Development, and Active Layer Temperature in the Northwest Siberian Low Arctic

Gerald V. Frost, Howard E. Epstein
University of Virginia, Department of Environmental Sciences, Charlottesville, VA, USA

Donald A. Walker
Institute of Arctic Biology, University of Alaska Fairbanks, USA

Georgiy Matyshak
Lomonosov Moscow State University, Department of Soil Science, Moscow, Russia

Ksenia Ermokhina
Earth Cryosphere Institute, Siberian Branch of Russian Academy of Sciences, Moscow, Russia

Abstract

Satellite photo-comparisons indicate extensive expansion of alder (*Alnus*) shrubs since 1968 within tundra ecotones near Kharp in northwest Siberia. Field observations reveal that nearly all expansion occurred on exposed circles in patterned ground. We mapped the location of alders and circles and measured surface organic thickness, mineral soil thickness, near-surface soil temperature, shrub height, and Leaf Area Index along transects according to categories of alder stand-age. Young alders occur almost exclusively on circles that lack organic matter and competing vegetation, and are relatively warm in summer. Contrasts in the summer thermal regime of circles and inter-circles diminish during alder colonization and become reversed in older shrublands. We conclude that exposed circles comprise abundant microsites that are susceptible to shrubification in warmer areas of the Low Arctic; summer active layer temperatures decline and circles are inactivated after shrubification, as organic matter buildup and canopy shading reduce the potential for differential frost heave.

Keywords: alder; Arctic; patterned ground; permafrost; shrub expansion; Siberia.

Introduction

Multiple lines of evidence indicate that the abundance of erect shrubs is increasing in the Low Arctic. Experimental studies and simulation modeling have repeatedly shown that expansion of deciduous shrubs is one of the most likely land-cover changes to accompany climate warming in Low Arctic tundra (e.g., Chapin et al. 1995). Recent shrub proliferation has been well documented by observational studies in the North American Arctic, particularly in northern Alaska (e.g., Tape et al. 2006). Shrub expansion in the Eurasian Arctic, however, has received less attention. Here we explore linkages between cryogenic patterned ground and rapid expansion of alder (*Alnus fruticosa* ssp. *sibirica*) within a tundra ecotone near Kharp, Yamalo-Nenets Autonomous Okrug, northwest Siberia (Fig. 1).

Shrub expansion in tundra-dominated regions alters ecosystem structure and can initiate a suite of changes to biophysical attributes of arctic landscapes, including plant community composition (Walker et al. 2006), surface energy balance (Chapin et al. 2005), hydrology (Sturm et al. 2001), and ground thermal regime (Blok et al. 2010). Blok et al. (2010) found that active layer temperatures declined with increasing cover of low shrubs in northeast Siberian tundra. Such findings suggest that even as warming-induced shrub expansion exerts a positive feedback on atmospheric temperature by reducing surface albedo, shading by expanding shrub canopies could buffer permafrost from the effects of warming.

Expansion of alder in tundra-dominated areas represents a fundamental change to the ecosystem state because alder commonly reaches heights ≥2 m and can greatly overtop tundra vegetation and winter snowpack. Thus the development of tall shrublands in tundra is likely to have particularly strong effects on albedo, surface energy balance, hydrology, and, therefore, the thermal regime of permafrost.

Previous studies in the Low Arctic show that alder expansion tends to occur in parts of the landscape that are regularly disturbed, such as floodplains and colluvial slopes (Tape et al. 2006). It also occurs locally after episodic disturbances such as wildfire and retrogressive thaw-slumping (Lantz et al. 2009). Disturbed sites usually lack competing vegetation and the thick accumulations of organic material that are otherwise common in arctic environments. A mechanism for shrubification that has not been previously documented is colonization of mineral-dominated microsites in areas of patterned ground.

Patterned ground features (PGFs) are more or less ubiquitous in arctic landscapes (Washburn 1980). The attributes and mode of formation of PGFs vary according to many factors including climate, soil texture, vegetation cover, and landscape age. Non-sorted circles are common PGFs that are maintained by annual disturbance, which occurs due to sharp gradients in soil thermal properties between circles and inter-circles (Peterson & Krantz 2003). Vegetation and organic matter insulate the subsurface and tend to develop in inter-circle areas; during winter freeze-up, unvegetated circles freeze much more rapidly than inter-circles, resulting in differential frost-heave. Thus the disturbance regime of circles differs from that of permafrost thaw features because disturbance is not episodic but instead is renewed annually.

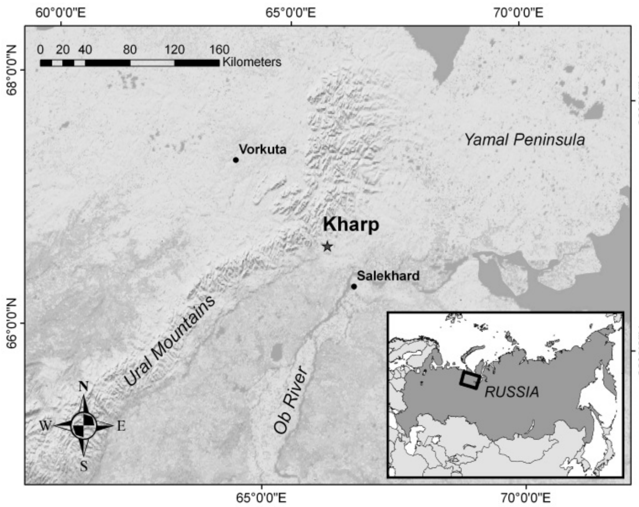

Figure 1. Map of the southern Yamal region showing location of the Kharp study area.

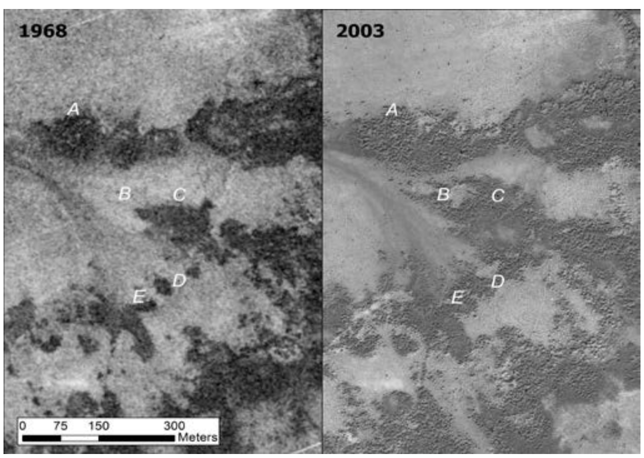

Figure 2. Comparison of 1968 (Corona) and 2003 (QuickBird) imagery showing part of the Kharp study area. Letters indicate areas with recently established alder cover.

During a brief reconnaissance in 2009, we observed that circles are widespread and extensive at Kharp, and it appeared that young alders were concentrated on the exposed centers of circles. These observations prompted us to organize a field expedition to determine important geomorphic site characteristics associated with alder expansion and to evaluate consequences to the ground temperature regime that result from shrubland development.

The objectives of field studies were to (1) test the hypothesis that alder expansion is facilitated by circles; (2) determine if an initial pattern of recruitment on circles explains the distribution of alders in older shrublands; and (3) evaluate changes in the summer active layer thermal regime that occur during shrubland development.

Methods

Study area

We conducted field studies in a 64-km^2 forest-tundra ecotone in the foothills of the polar Ural Mountains near the town of Kharp (66.83°N, 65.98°E). Terrain in the study area varies from ~200 to 300 m elevation and consists of gently sloping low hills separated by small alluvial valleys. Common vegetation communities include dwarf shrub tundra dominated by dwarf birch (*Betula nana*) and ericaceous shrubs <30 cm in height; low scrub dominated by dwarf birch and willows (*Salix* spp.); tall alder scrub strongly dominated by alder; and sparse woodlands of Siberian larch (*Larix sibirica*). The Kharp region experiences a continental subarctic climate. Long-term meteorological records at Salekhard, ~35 km southeast of Kharp, indicate a mean annual temperature of -6.5°C and mean annual precipitation of 464 mm.

Sorted and non-sorted circles are common and widespread at the Kharp site. The surficial geology of the area is dominated by ultramafic rocks, which weather directly to silt- and clay-sized particles; the prevalence of fine-grained mineral soils is conducive to differential frost-heave. The size and spacing of circles vary across the study area but typically occur at one of two scales: small non-sorted circles ~70 cm in diameter and spaced ~2 m apart, and larger sorted-circles circles ~2 m in diameter and spaced ~4 m apart. Non-sorted circles are separated by narrow, stony inter-circles that are covered by vegetation. Among sorted-circles, inter-circles typically contain large blocks that often remain barren in exposed locations.

Visual comparison of high-resolution satellite images from 1968 (KH-4B "Corona") and 2003 (QuickBird) indicates that alder shrubland extent increased ~10% over the 35-year interval (Fig. 2). Using this imagery, we identified expanding and unchanged shrublands for field sampling.

Field data collection

We established a series of transects according to four categories of alder stand-age: tundra, alder colonization zone, mature shrubland, and paludified shrubland (Fig. 3). Tundra transects were placed in alder-free areas of patterned ground adjacent to colonization zones. Colonization zones were along the margins of alder thickets that had not developed until after 1968. Vegetation and geomorphic features in colonization zones were comparable to the tundra transects, except that circle centers were dominated by young alders (<30 cm tall). Mature shrublands were dominated by large alders (typically >2 m in height) that were already evident in 1968 imagery. Paludified shrublands were characterized by open stands of very old alders, often with low vigor (e.g., many moribund or dead ramets), occurring on sites with heavy moss cover, a thick surface organic layer, and wet soils. Observations of soil profiles, alder characteristics, and the spatial distribution of shrublands indicated that the three alder stand-ages described above correspond to a chronosequence of successional stages, and therefore are representative of changes in the summer active layer thermal regime that occur during alder shrubland development over multi-decadal to centennial timescales.

Transect size varied depending on the density of alders and PGFs (20–100 m length, 4–10 m width); we established larger transects where PGFs and alders were widely spaced in order to obtain adequate sample size. We established three transects in each stand-age. At each transect, we made systematic measurements of surface organic depth, thaw depth/depth to rock, and Leaf Area Index (LAI) at 50-cm intervals (20 m transects) or 1-m intervals (longer transects) along the transect centerline. Transects were placed in areas with homogeneous vegetation and geomorphology, so we assumed that the centerline measurements represented mean conditions. We also recorded surface organic depth and thaw depth/depth to rock at the base of each alder, regardless of size, within each transect. From the soil profile measurements, we calculated the total mineral soil thickness (thaw depth/depth to rock minus surface organic depth). Most thaw probe measurements were of depth to rock (usually frost-shattered blocks), rather than thaw depth. Soil profile measurements were made with a steel thaw probe, and LAI was measured using a LAI-2000 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln NE, USA).

We mapped the locations of alders and the centers of exposed sorted-circles within the transects using X/Y coordinates. When possible, we visually recorded the microsite in which alders were rooted (e.g., center of active circle, margin of active circle, inter-circle). We also measured the height of the dominant ramet of each individual alder. Finally, we embedded 5–10 Thermochron iButton dataloggers (Embedded Data Systems LLC, Lawrenceburg, KY, USA) to measure microsite variation in soil temperature along 1–2 transects in each stand-age. iButtons were distributed at the base of alders and in alder-free inter-circles. All iButtons were placed at a depth of 5 cm; an additional iButton was placed in a shaded location at a height of 2 m to record air temperature at each transect. All iButtons recorded temperatures simultaneously at 4-hour intervals during the 5-day period July 27–August 1.

Data analysis

In order to test if alder establishment is facilitated by circle microsites, we compared surface organic depth and mineral soil thickness between transect centerlines and alders within each stand-age. We also computed the mean soil temperature for each iButton datalogger and compared these means between circles and inter-circles for each stand-age. In order to characterize changes in active layer summer thermal regime that occur during shrubland development, we compared surface organic depth and mean soil temperature for transect centerlines and alders across stand-ages. We also compared LAI and shrub height across stand-age.

We applied two-tailed T-tests for comparison of normally distributed variables, and non-parametric Kruskal-Wallis tests for non-normally distributed variables. We used SAS 9.2 (SAS Institute, Inc., Cary NC, USA) for all statistical procedures. Finally, we generated time series for circle and inter-circle soil temperature for each stand-age; this was done by computing the mean temperature for each time-step and interpolating the time-steps across the 5-day observation period.

Results

Soil properties

Surface organic depth and mineral soil thickness for transect centerlines and alders show strong and consistent patterns of variation across all stand-ages. Surface organic depth was significantly less, and mineral soil thickness was significantly greater, for alders relative to the centerline measurements (Kruskal-Wallis; $p<0.001$ for all stand-ages) (Table 1). Mean surface organic depth increases monotonically with increasing alder stand-age.

Transect mapping

In colonization zones, where circle centers were seldom covered by vegetation, observed locations of alders and circles indicated that alder recruitment occurred almost exclusively on exposed circles. Of 272 alders recorded in colonization zones, only 2 were found emerging from inter-circles. Most alders occurred along circle margins rather than in the central part of the circle. This distribution pattern was often visible as a ring of small alders growing around circle margins. In mature and paludified shrublands, circles were usually not visible, but alders typically displayed a distribution pattern of more or less uniformly spaced clumps, similar to what we observed in colonization zones. Where exposed circles did occur in mature and paludified shrublands, we frequently observed seedlings and/or saplings growing on them except on very wet sites.

Active layer temperature and shrub canopy attributes

Mean soil temperatures are warmer at circles than at inter-circles in tundra and colonization zones (T-test; $p<0.05$) (Table 2). This pattern is reversed in paludified shrublands (T-test; $p<0.05$). Mean temperatures are not significantly different between microsites in mature shrublands.

Across stand-ages, mean soil temperature at circles declines monotonically from one shrubland stage to the next (T-test; $p<0.05$). The same pattern is evident at inter-circles, except that there is no significant difference in mean soil temperature between the tundra and colonization stages. LAI and shrub height increase monotonically from tundra to mature stages but decline from the mature to paludified stages (T-test; $p<0.05$).

Temperature time series for tundra transects show strong microsite variation in mean temperature, maximum temperature, and diurnal variability for circles and inter-circles (Fig. 4). Circle soil temperatures closely track air temperature and are usually ~2°C warmer than adjacent inter-circles. Diurnal fluctuations in temperature are ~6°C for circles and only ~3°C for inter-circles. Microsite variation in temperature is qualitatively similar in alder colonization zones, but the differences are less pronounced. In mature shrublands, the pattern of microsite variation seen in earlier stand-ages is reversed as circle soil temperatures are less variable than at inter-circles. A qualitatively similar pattern exists for paludified shrublands, but there is a sharp decline in temperature for all microsites.

Discussion

Microsite facilitation of alder recruitment

Our field observations, in conjunction with remote-sensing data spanning five decades, demonstrate that rapid and widespread alder expansion has occurred in areas of PGFs at

Table 1. Means and sample sizes of surface organic depth and mineral soil thickness measurements by stage. Ranges are given in parentheses.

Stage	Surface organic depth (cm)		Mineral soil thickness (cm)		n	
	Transect	Alders	Transect	Alders	Transect	Alders
tundra	5.7 (0-16)	-	7.3 (0-33)	-	22	
colonization	7.2 (0-27)	1.1 (0-11)	9.8 (0-45)	28.5 (0-69)	82	272
mature	9.4 (0-38)	4.3 (0-16)	12.2 (0-87)	34.4 (4-96)	158	71
paludified	25.2 (10-44)	14.3 (7-25)	21.0 (0-61)	44.3 (0-79)	101	59

Table 2. Mean and sample size of soil temperature, LAI, and alder height measurements by stage. Standard deviation is given in parentheses.

	Soil temperature (°C)							
	Mean		n		LAI		Shrub height (cm)	
Stage	Inter-circle	Circle	Inter-circle	Circle	Mean	n	Mean	n
tundra	8.9 (0.4)	9.9 (0.3)	7	7	0.3 (0.3)	22	-	-
colonization	8.6 (0.4)	9.2 (0.5)	8	7	0.6 (0.5)	144	23.5 (40.0)	272
mature	7.2 (0.5)	6.6 (1.5)	6	6	2.0 (1.0)	111	173.1 (119.9)	72
paludified	5.6 (1.2)	3.7 (0.4)	6	5	1.3 (0.7)	101	90.5 (50.3)	59

Kharp. Mean surface organic depth was much less, and mineral horizon thickness much greater, at alders relative to transect centerlines in colonization zones. These measurements, along with the observed distribution pattern of young alders on exposed circles, show that exposed circles facilitate alder recruitment at Kharp.

Unvegetated circles are common across the arctic tundra biome because they are annually disturbed, and most arctic plants grow too slowly to become established during the short growing season. We suggest that alder is able to exploit these circle microsites in warmer parts of the Low Arctic for several reasons. First, alder is a boreal species with much higher potential growth rates than tundra plants. Second, alder seeds are minerotrophic, and seedling survivorship is higher on mineral versus organic soils (Chapin et al. 1994). Third, alder is an N_2-fixing species, which may enable it to maintain rapid growth on mineral-dominated soils that lack organic N. Finally, although active circles are annually disturbed by differential frost heave, and there is probably high mortality of alder seedlings, circles are favorable seedbeds for alder because soils are warm and there is little competing vegetation.

Legacy of recruitment pattern in alder shrublands

Surface organic depth was much less, and mineral horizon thickness much greater, at alders relative to transect centerlines in mature and paludified shrublands. Although most PGFs were obscured from view in mature and paludified shrublands, subsurface profiles at alders indicate that adult shrubs occupy circle microsites that had become covered by vegetation and organic matter. In mature shrublands, we seldom observed alder seedlings except on a few remaining exposed circles; we almost never recorded seedlings in paludified stands. Therefore, we conclude that (1) the spatial distribution of adult alders is consistent with initial recruitment on circles; and (2) alder recruitment slows dramatically as soil temperatures decline and circles become covered by vegetation and organic material. Chapin et al. (1989) identified intense nutrient competition as the primary factor driving uniform spacing of alders at an Alaskan site. However, we conclude that patterns of initial recruitment alone are adequate to explain the distribution of shrubs in open alder shrublands ("savannas") at Kharp.

Alder is a long-lived species; in Interior Alaska, the same species persists from early to late succession in boreal forest despite dramatic changes in soil conditions and competition (Mitchell & Ruess 2009). Observations of alders in paludified shrublands indicate that most shrubs are very old and have slow current rates of growth (e.g., abundant bud scars on small twigs, short internodes and ramet height). Mean circle soil temperature beneath shrubs was 5.5°C lower in paludified shrublands relative to colonization zones. Additionally, the organic-rich soils in paludified shrublands retained water and were frequently saturated at shallow depth. Although adult alders are capable of tolerating cold, wet soils, these conditions are unfavorable for alder recruitment. This would explain in part how "hotspots" of expansion at Kharp are inter-mixed with areas in which shrub cover is identical to that in 1968.

Implications for permafrost

Soil temperature profiles recorded at the Kharp transects indicate that a sequence of changes in microsite and overall active layer thermal regime occur during alder shrubland development in pattered ground. In tundra, prior to alder establishment, temperature profiles of circle centers and inter-circles contrast sharply in mean and maximum temperature and diurnal variability. Circle soil temperatures closely track atmospheric temperature because surface organic material (which reduces thermal conductivity) and overtopping vegetation (which intercepts incident solar radiation) are lacking. These sharp gradients in soil thermal properties

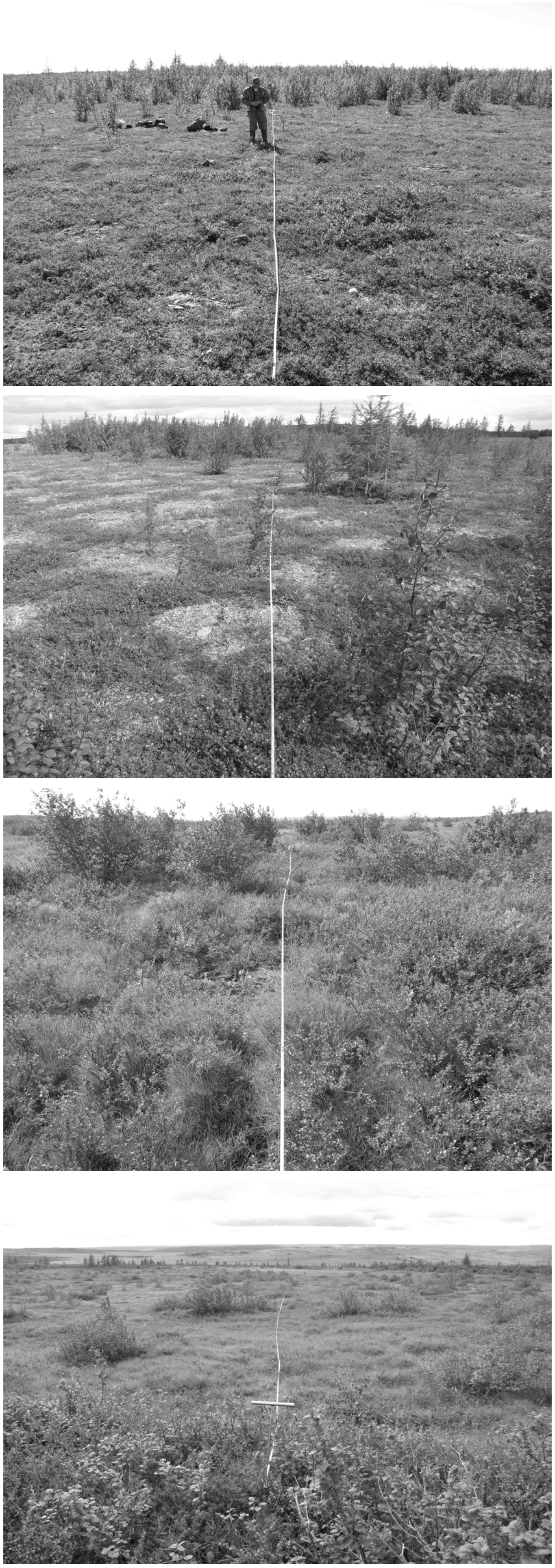

Figure 3. Sample photographs of transects in (top to bottom) tundra (foreground only), alder colonization zone, mature shrubland, and paludified shrubland. Note the low stature of alders in the paludified shrubland.

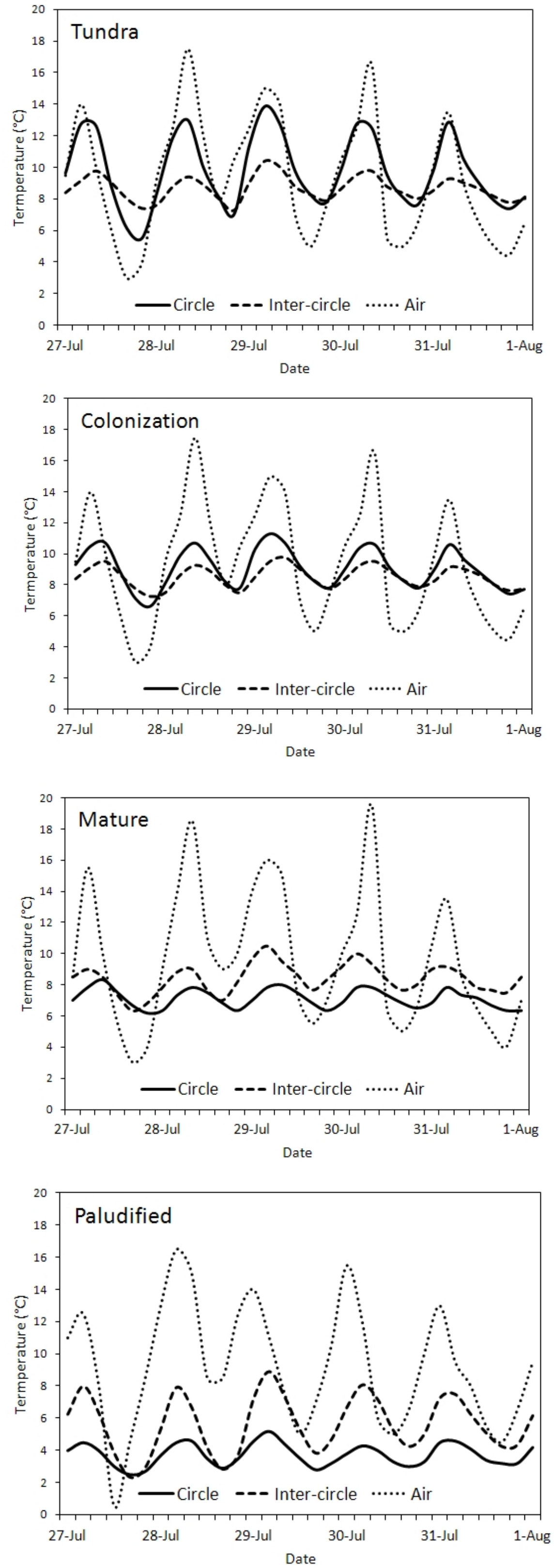

Figure 4. Soil- and air temperature time series recorded along four transects in (top to bottom) tundra, alder colonization zone, mature shrubland, and paludified shrubland. For soil time series, curves are interpolated to mean temperatures for 3 iButtons.

promote differential frost heave as soils freeze in early winter (Peterson & Krantz 2003), maintaining annual disturbance on circles.

Following alder colonization, microsite differences in soil temperature diminish. Our data suggest that this may occur quickly—within only a few years—as diurnal variability in circle soil temperature is significantly lower in colonization zone transects relative to alder-free tundra, with only modest increases in LAI and shrub height. As alders mature and understory vegetation develops, the initial microsite thermal gradient observed in tundra becomes reversed, with circle soils cooler than at inter-circles. This reversal intensifies in moisture-gathering parts of the landscape that are prone to paludification (e.g., toe slopes and lowlands), likely due to positive feedbacks between soil moisture, moss growth, and organic matter accumulation.

A recent dendrochronology study of shrubs at a site ~130 km northeast of Kharp indicates contemporaneous increases in summer temperatures and shrub productivity in recent decades (Forbes et al. 2010), suggesting that climate warming may have played a role in alder expansion at our site. If so, what are the likely implications of land-cover change and climate warming on permafrost at Kharp? Our soil temperature data indicate that alder shrubland development strongly buffers permafrost from changes in atmospheric temperature in the summer. Early in shrubland development, this buffering effect is primarily due to shading by alder canopies, as there is little surface organic matter beneath the colonizing shrubs. As alders grow larger and organic matter begins to accumulate, reduction in differential frost-heave and increased snow-trapping likely allows other vegetation to spread onto circle microsites. The proliferation of vegetation—especially mosses—plays a key role in reducing soil temperature by lowering thermal conductivity. As shrublands age and organic matter accumulates, ground- and atmospheric temperatures become increasingly uncoupled and there is a cessation of cryogenic disturbance.

We conclude that (1) exposed circles in the southernmost Low Arctic are susceptible to rapid changes in land-cover and ecosystem state because they comprise favorable seedbeds for fast-growing, minerotrophic shrubs such as alder; (2) spatial patterns of alder colonization are persistent and may explain the uniform spacing of shrubs in Low Arctic alder "savannas;" (3) shrubland development initiates a cascade of effects on summer soil thermal properties and energy balance due to canopy shading and deposition of organic matter; (4) canopy shading buffers the active layer against atmospheric warming driven by local reductions in albedo and larger-scale forcings; and (5) the breakdown and reversal of microsite thermal gradients following shrub expansion result in inactivation of circles and greatly diminish cryogenic disturbance.

Acknowledgments

This work was funded by the NASA/NEESPI Land-Cover and Land-Use Change Initiative, grants NNG6GE00A and NNX09AK56G, and the Department of Environmental Sciences at the University of Virginia. We also thank Marina Leibman and Roman Ivanov, Earth Cryosphere Institute, for their indispensable help with field logistics.

References

Blok, D., Heijmans, M., Schaepman-Strub, G., Kononov, A., Maximov, T., & Berendse, F. 2010. Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology* 16:1296-1305.

Chapin, F.S., III, McGraw, J.B., & Shaver, G.R. 1989. Competition causes regular spacing of alder in Alaskan shrub tundra. *Oecologia* 79:412-416.

Chapin, F.S., III, Walker, L.R., Fastie, C.L., & Sharman, L.C. 1994. Mechanisms of primary succession following deglaciation at Glacier Bay, Alaska. *Ecological Monographs* 64:149-175.

Chapin, F.S., III, Shaver, G.S., Giblin, A.E., Nadelhoffer, K.J., & Laundre, J.A. 1995. Responses of Arctic tundra to experimental and observed changes in climate. *Ecology* 76:694-711.

Chapin, F. S., III, Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., Rupp, T.S., Lynch, A.H., Schimel, J.P., Beringer, J., Chapman, W.L., Epstein, H.E., Euskirchen, E.S., Hinzman, L.D., Jia, G., Ping, C.L., Tape, K.D., Thompson, C.D.C., Walker, D.A., & Welker, J.M. 2005. Role of land-surface changes in arctic summer warming. *Science* 310:657-660.

Forbes, B.C., Fauria, M.M., & Zetterberg, P. 2010. Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. *Global Change Biology* 16:1542-1554.

Lantz, T.C., Kokelj, S.V., Gergel, S.E., & Henryz, G.H.R. 2009. Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. *Global Change Biology* 15:1664-1675.

Mitchell, J.S. & Ruess, R.W. 2009. N_2-fixing alder (*Alnus viridis* spp. *fruticosa*) effects on soil properties across a secondary successional chronosequence in interior Alaska. *Biogeochemistry* 95:215-229. doi: 10.1007/s10533-009-9332-x.

Peterson, R.A. & Krantz, W.B. 2003. A mechanism for differential frost heave and its implications for patterned ground formation. *Journal of Glaciology* 49:69-80.

Sturm, M., Douglas, T., Racine, C., & Liston, G.E. 2005. Changing snow and shrub conditions affect albedo with global implications. *Journal of Geophysical Research–Biogeosciences* 110:1–13, doi 10.1029/2005JG000013.

Tape, K., Sturm, M., & Racine, C. 2006. The evidence for shrub expansion in northern Alaska and the Pan-Arctic. *Global Change Biology* 12:686-702.

Walker, M.A., et al. 2006. Plant community response to experimental warming across the tundra biome. *Proceedings of the National Academy of Sciences* 103:1342-1346.

Washburn, A.L. 1980. *Geocryology: a survey of periglacial processes and environments.* New York, John Wiley, 406 pp.