A hierarchical analysis of land-cover and land-use change in tundra environments:
Remote sensing, ground-based observations of social and ecological factors, and models

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What are the causes of the greening observed in Arctic tundra regions during the period of satellite-based observations?

Abstract

Numerous satellite-based studies have noted that Arctic tundra regions have become greener in the past three decades. The International Polar Year Greening of the Arctic initiative (IPY-GOA, ID 569) focused on examining the changes using a hierarchical approach:

Panarctic scale: During 30-years of observations (1982-2011), using primarily data from AVHRR-sensors aboard NOAA satellites, the mean annual maximum normalized difference vegetation index (MaxNDVI, an index strongly correlated with maximum summer zonal tundra biomass) has increased 11.5% for the entire Arctic, 15.5% for the North America Arctic, and 8.2% for the Eurasia Arctic. Recent trends since about 2000 show diverging patterns of greening (large areas of decline in Eurasia) that appear to be related to different timing of ocean freeze up and increased snowfall in the Eurasian Arctic compared to North America.

Regional scale: We used ground-based studies along two long transects in North America and Eurasia to examine the possible contributing causes of the divergence in NDVI patterns. Differences in the climate, soils and vegetation are associated with more continental areas such as northern Alaska and the Canadian Archipelago versus more maritime parts of the Arctic such as the Barents and Kara Sea region. The timing of sea ice formation in the winter is a main determinant of continentality. More continental areas are changing more rapidly, possibly because of less vegetative cover and thinner moss carpets, which allows the soils to warm more readily and become more productive.

Local scale: At a local scale we examined several disturbance-related phenomena related to the changes in shrub abundance and increased tundra greenness. We examined the causes of the expansion of alder shrubs near the Arctic treeline and found that disturbances related to fire and strong frost heave in patterned-ground landscapes are major contributing causes, and that in some areas landslides and disturbances related to expanding natural resource development and reindeer grazing can be important. Petroleum-related infrastructure and changes in the economics of reindeer herding are the largest land-use-change factors affecting the local people of the Arctic.

Dynamics of greening associated with gas field development and reindeer on the Yamal Peninsula: We examined the trends of infrastructure expansion in the Russian gas field at Bovanenkovo, where the expanding networks of roads and pipelines are interacting with the growing populations of Nenets reindeer herders and their animals. Analysis of the changes due to resource development used Landsat and high-resolution (60-70-cm pixel) Quickbird satellite imagery. Interviews with the nomadic Nenets people provided a detailed picture of how the reindeer migration patterns and use of traditional rangelands are modified by the expanding infrastructure and natural changes to vegetation. The ArcVeg Model was used to examine the effects of climate warming and reindeer grazing on the productivity of tundra plant functional types in all 5 Arctic bioclimate subzones and on different textured soils.

NDVI: Integrator of Arctic change

Our LCLUC project is exploring spatial and temporal patterns of NDVI and vegetation production at circumpolar, regional and plot levels and how they are influenced by key disturbance factors including climate change, landslides, reindeer grazing and the rapidly expanding gas fields. We focus on the Yamal because this is a hot-spot of change in the Arctic. Remote sensing is a key tool for inventorying the change and as a means to assess the local people's perception of change.

The diagram below shows the webs of arctic social and ecological factors that can cause physical disturbance to land surfaces and influence vegetation productivity. The normalized difference vegetation index (NDVI) is a relatively easy-to-measure index of vegetation photosynthetic capacity that can be measured at plot to global scales.

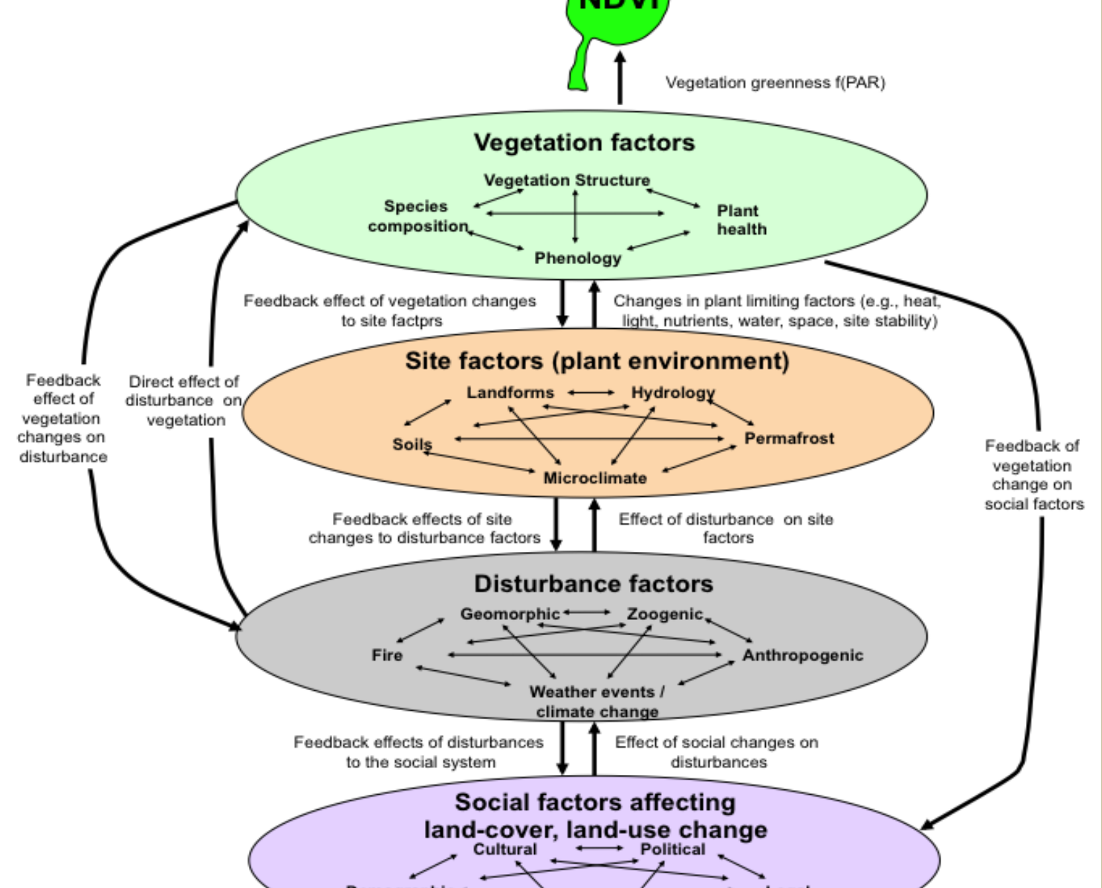

Diagram modified from Walker et al. 2009.

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I. A hierarchical analysis of Arctic land-cover changes

Ia. Panarctic changes in sea-ice, summer land temperatures, and vegetation greenness (NDVI)

Ice-free seas are linked to warmer summer land temperatures and increased tundra NDVI in most areas, but greater winter precipitation and colder temperatures in some areas decrease NDVI.

The extent of the tundra biome is to a large extent controlled by cold summer air masses associated with the Arctic ice pack. Models indicate that if sea-ice in the Arctic continues to decline, the adjacent tundra areas should warm and thaw permafrost (Lawrence et al 2008), although other models suggest that increased snow could also cool the tundra in summer and decrease the growing season length (Higgins and Cassano 2011). Numerous observations and experiments indicate a warming should increase tundra primary productivity. We studied the trends in sea ice, summer land temperatures, and tundra productivity using GIMSS3g+ AVHRR data **(Fig. 1)** (Bhatt et al. 2010; Walker et al. 2011a). During 30-years of observations (1982-2011), the MaxNDVI in the Arctic has increased 11.5% for the northern hemisphere Arctic, 15.5% for the North America Arctic, and 8.2% for the Eurasia Arctic (Bhatt et al. 2010 updated to 2011). Since 2005, MaxNDVI in North America has shown an increased upward trend, while MaxNDVI in Eurasia has been rather flat since 2001 **(Fig. 2)**. The summer land-temperatures in the tundra are also showing diverging patterns, with an overall +11% increase in North America and and a -2.6% decrease in Eurasia **(Fig. 1a)**. A strong relationship between NDVI and tundra aboveground biomass along two Arctic transects is used to map biomass changes between 1982 and 2010 **(Fig. 3)**. Seasonal differences in the development of sea ice in maritime vs. more continental portions of the Arctic (not shown) help to explain the diverging trends. Very late open water in the Barents, Kara and Laptev seas and more maritime portions of the Arctic appear to be providing a winter-long source of moisture to these areas, increasing atmospheric moisture, winter snowpack, decreasing winter temperatures (Muskett 2012, Liu et al. 2012, Cohen et al. 2012), and delaying the spring melt and initiation of tundra greening.

Circumpolar patterns of change to sea-ice, summer land temperatures and MaxNDVI

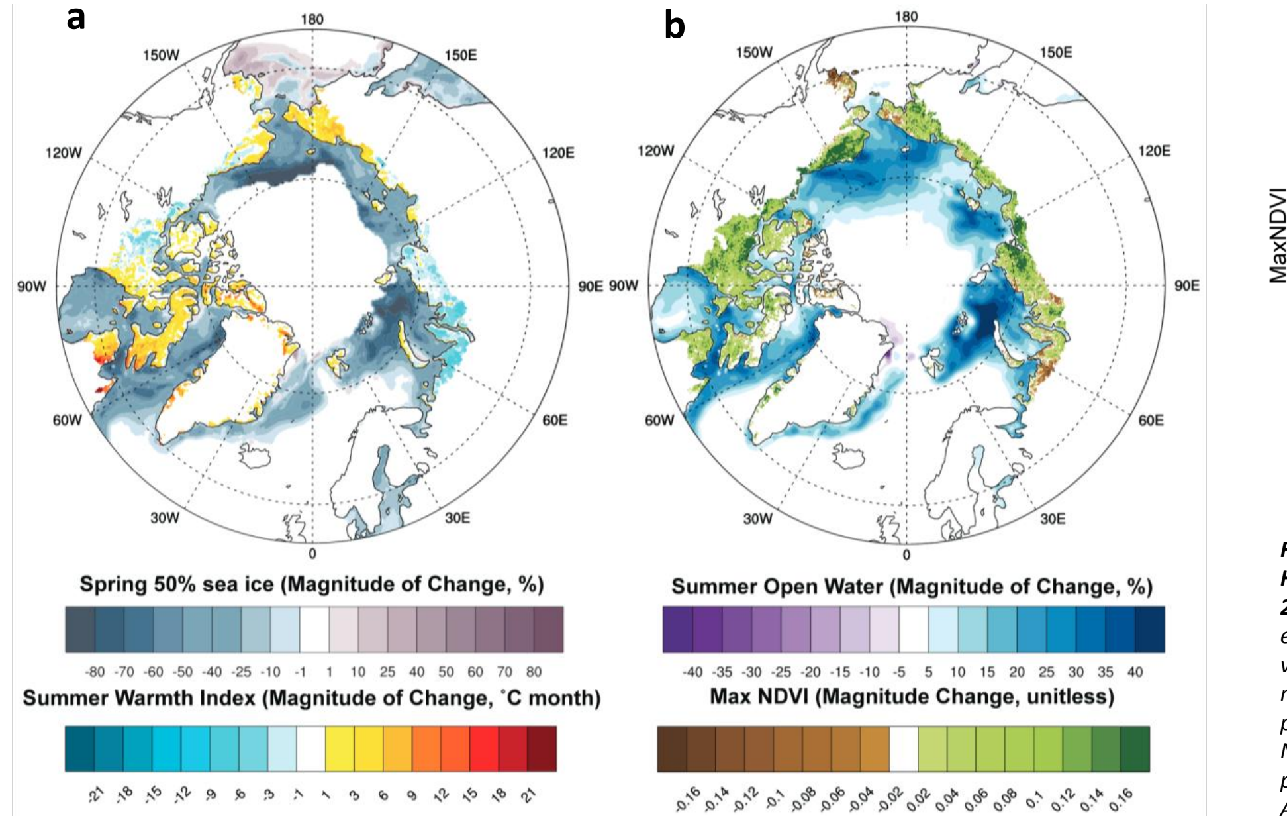


Figure 1. a) Magnitude of changes in spring sea ice and Arctic tundra summer land temperatures. b) Magnitude of changes in open summer open water and Arctic Tundra MaxNDVI. *Updated from Bhatt et al. 2010.*

Trends of MaxNDVI

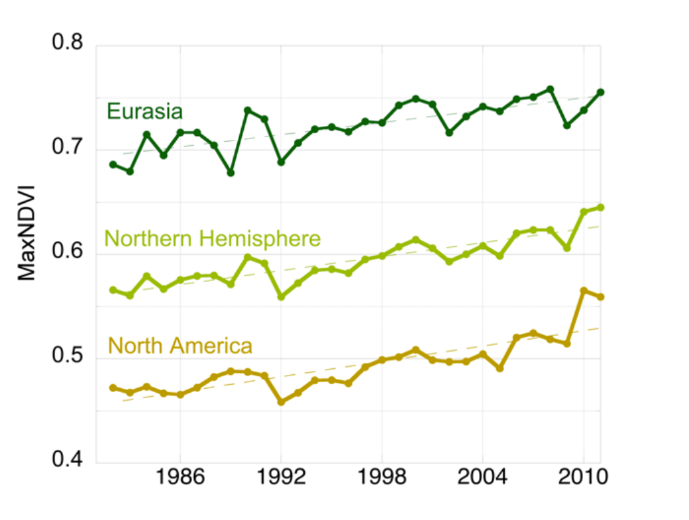


Figure 2. Trends in mean MaxNDVI for Eurasia, Northern Hemisphere, and North America Arctic for the period 1982-2011. *MaxNDVI is the mean maximum NDVI attained during each growing season and reflects the maximum of the vegetation at the peak period of the growing season. The lower mean NDVI values in North America are caused by the large proportion of relatively poorly vegetated High Arctic tundra in North America. Note the divergence of the trends in the last part of the records. The upward trend of MaxNDVI in North America MaxNDVI has trended sharply upward since 2005, whereas the trend in Eurasia has been relatively flat. Updated from Bhatt et al. (2010).*

Change in aboveground tundra biomass

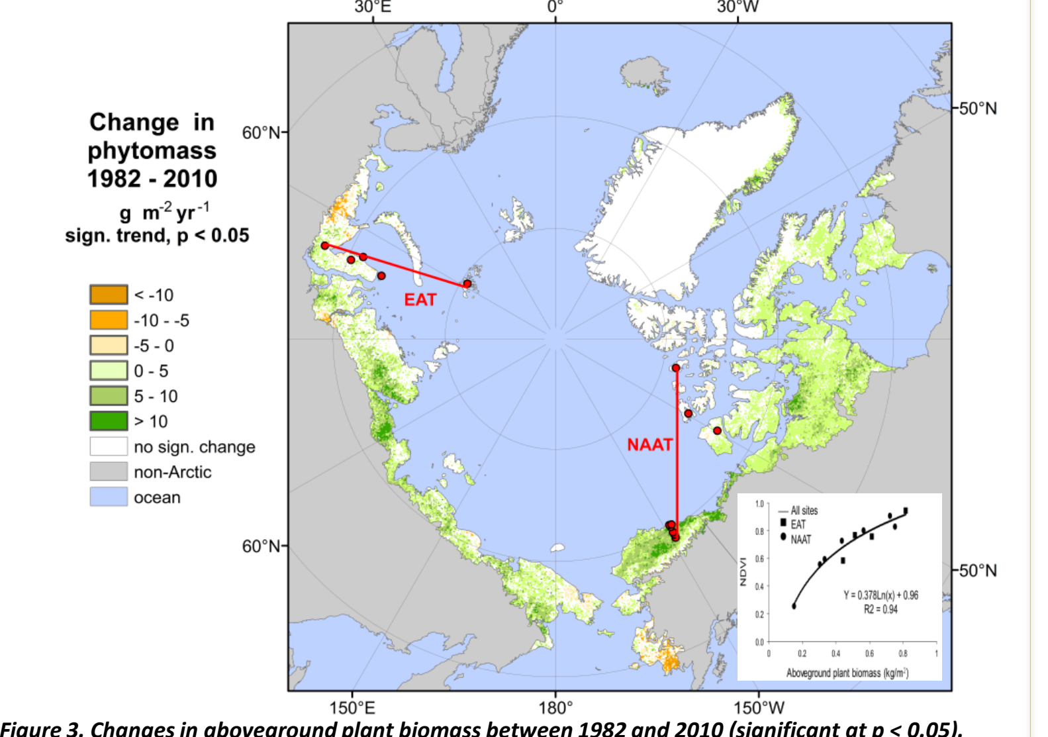


Figure 3. Changes in aboveground plant biomass between 1982 and 2010 (significant at p < 0.05). *North American and Eurasia Arctic Transects are shown (NAAT and EAT respectively).The biomass NDVI relationship in the inset is derived from clip-harvests from 13 zonal sites representing all 5 Arctic bioclimate subzones. Inset: Relationship between aboveground tundra biomass (g m−2) and Maximum 1982-2010 NDVI (GIMMS3g+ data) for 13 field sites across the NAAT and EAT. Bars are ± one standard error for the biomass samples within each site. Data are from Raynolds et al (2012). Note the generally strong positive change along the NAAT and the generally neutral change along the EAT. Modified from Epstein et al. (2012).*

Ib. Comparison of climates, soils, vegetation and NDVI along two Arctic transects

A continental and a maritime Arctic transect:

Detailed land-based observations of tundra environments, vegetation, and spectral properties were made along the North America Arctic Transect (NAAT) (1750 km long) and the Eurasia Arctic Transect (EAT) (1500 km long) (Walker et al. 2012) **(Fig. 4 & 5, Table 1)**. Primary study locations along each transect are shown. The NAAT transect has a more continental climate due to a much earlier freezing ocean in the Beaufort Sea than in the Barents and Kara Sea region of the EAT.

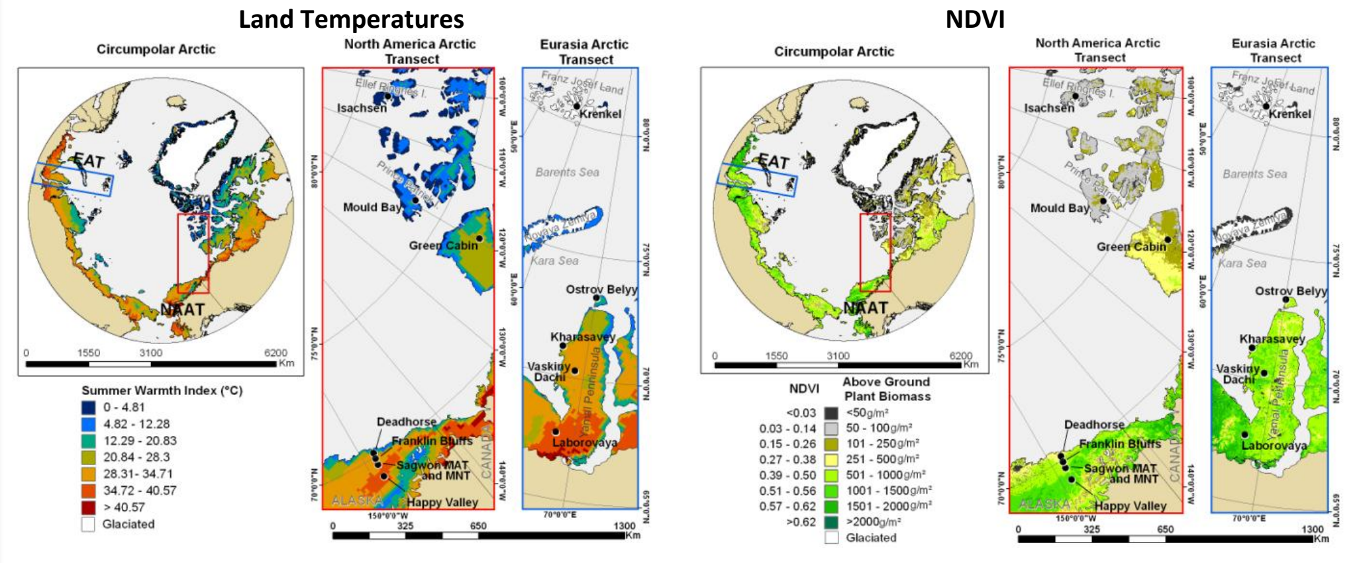


Figure 4. Maps of summer warmth index and Max NDVI for the circumpolar Arctic, the North America Arctic Transect (NAAT) and the Eurasia Arctic Transect (EAT). *Bioclimate subzones in Table 1 refer to zonal subdivisions portrayed on the Circumpolar Arctic Vegetation Map (CAVM, Walker et al. 2005).*

Table 1. Comparison of climate and soil along two Arctic transects

Arctic Bioclimate subzone (Walker 2005)	Transect: location	Latitude Longitude	SWI (˚C mo)		Precipitation (mm)			Soil texture pH
			Air (SWIa)	Surface (SWIs)	Total	Summer JJA	Winter S-May	
A	NAAT: Isachsen	78.7˚ N 103.6˚ W	3	6.8	114	53	61	Clay 5.8
	EAT: Krenkel	80.6˚ N 57.9˚ E	1	1.9	282	56	211	Sandy loam 6.2
B	NAAT: Mould Bay	76.2˚ N 119.3˚ W	4.6	6.5	104	47	66	Sandy loam 7.8
	EAT: Ostrov Belyy	73.3˚ N 70.1˚ E	11.5	11.5	234	74	154	Loam 4.6
C	NAAT: Green Cabin	73.2˚ N 119.6˚ W	16.6	22.7	156	63	91	Sandy loam 7.7
	EAT: Kharasavey	71.2˚ N 67.0˚ E	15.5	28.7	298	89	192	Silt loam 4.5
D	NAAT: Franklin Bluffs	69.7˚ N 148.7˚ W	24.2	32.7	179	61	86	Loam 7.4
	EAT: Vaskiny Dachi	70.3˚ N 68.90˚ E	na	29.6	277	100	186	Silt loam 4.5
E	NAAT: Happy Valley	69.147˚ N 148.8˚ W	29.5	36.2	198	72	99	Silty clay loam 5.1
	EAT: Laborovaya	67.7˚ N 68.0˚ E	na	36.4	664	224	443	Clay loam 4.6

Comparison of aboveground biomass along the transects

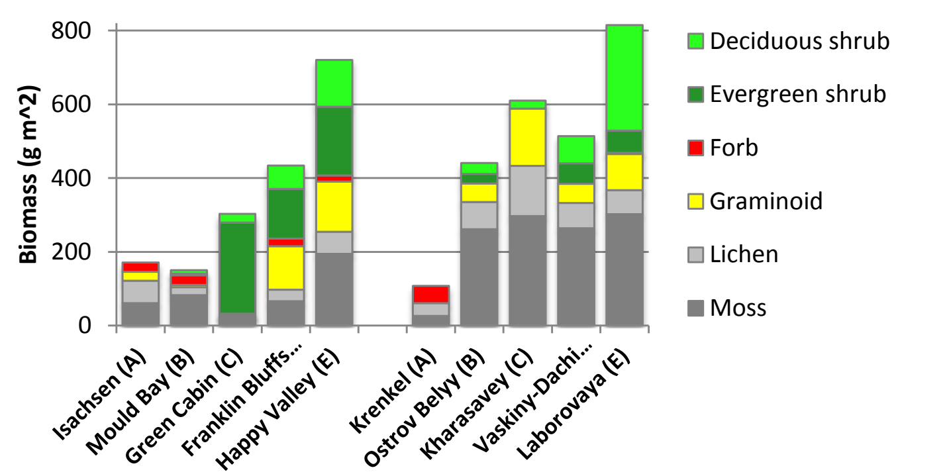


Figure 5. Total aboveground biomass broken down by plant functional types along the NAAT and EAT.

Differences in continental and maritime parts of the Arctic: Although the EAT and NAAT have broadly similar summer-temperature regimes and overall vegetation physiognomy, there are major differences in the soil pH, disturbance regimes, and precipitation (especially winter precipitation) (see Table 1, left) that cause important differences in the relative abundance of the major plant functional types and total aboveground plant biomass **(Fig. 5)**. These differences have important implications for ecosystem response to a warmer climate in continental versus more maritime parts of the Arctic **(Fig. 6)**.

More oceanic conditions along the EAT

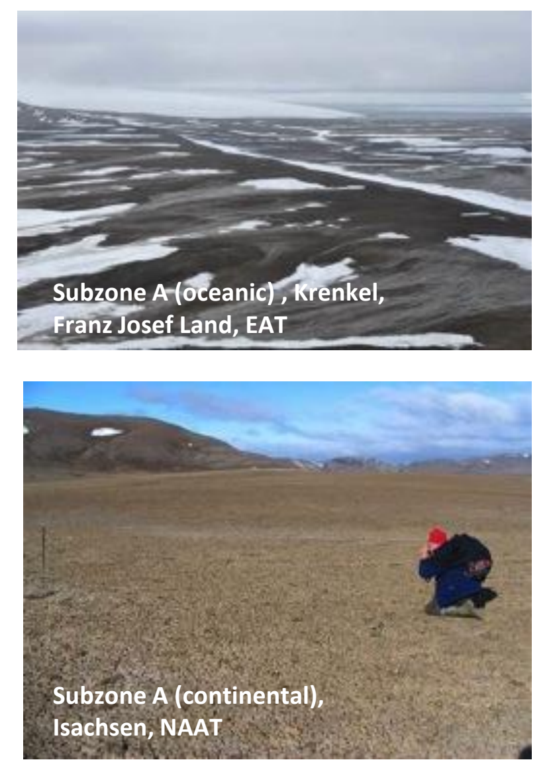


Figure 6. Oceanic (top) vs. continental environments of bioclimate subzone A along the EAT and NAAT.

Ic. Detailed observations of greening due to shrub expansion

Shrub expansion is facilitated by disturbance.

Expansion of tall shrublands into tundra ecosystems is an important land-cover change issue occurring in southern parts of the Arctic tundra biome. The shrubs cause fundamental changes to ecosystem structure and alter system properties including surface albedo, hydrology, and permafrost thermal regimes, as well as wildlife and human use of these lands. The spread of shrubs is not, however, a uniform process. Our earlier LCLUC reports have noted the strong expansion of willows on landslides in the central Yamal (Walker et al. 2009, Leibman and Kizyakov 2007**,** Ukraintseva 2008). Another study focused on increases in biomass/height of *Salix lanata* in relatively stable habitats within the tundra zone and found a strong correspondence between willow-shrub growth-ring widths, NDVI and regional summer temperatures (Forbes et al. 2010). *S. lanata* is one of the key forage species for Nenets reindeer from spring through autumn. More recently, an area of particularly rapid alder (*Alnus viridis*) expansion was identified near the northern treeline at Kharp in the Polar Urals, **(Fig. 7)**. Comparison of high-resolution satellite imagery indicates that alder shrubland extent increased ~11% within the study area over the period 1968-2003 **(Fig. 8)**. Ground-observations indicated that virtually all of the expansion occurred on disturbed microsites in patterned-ground landscapes **(Fig. 9)**. Disturbed sites favor rapid development of alder seedlings because they lack competing vegetation and soils are relatively warm. An intense, ~200-year old fire was likely a trigger-disturbance that initiated a long period of more active frost boil activity by removing overlying peat deposits. Once a vegetation mat becomes established, canopy shading and paludification (the formation of a deep organic mat) strongly reduces the flux of heat to the soils and buffers the active layer from climate change, reducing the establishment of new shrubs and the growth of existing shrubs **(Fig. 10)**.

Alder expansion near Kharp observed with time series of Corona, Landsat, and Quickbird images

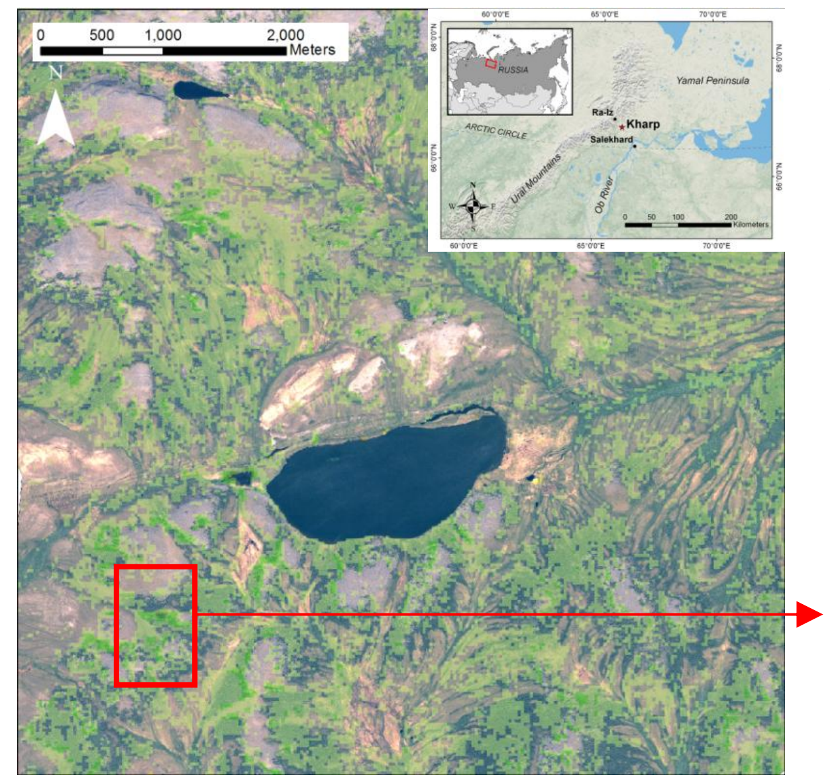
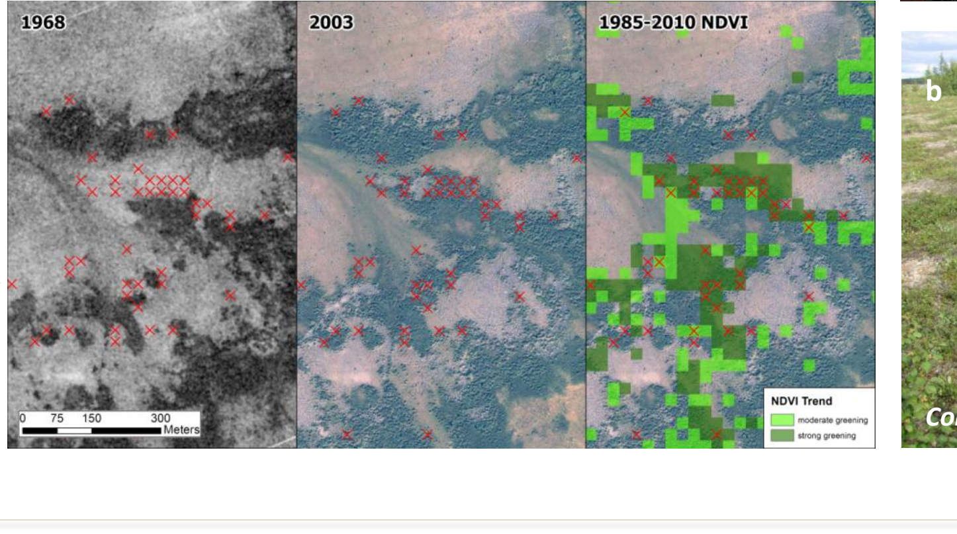


Figure 7 (left). Overview of Kharp showing areas of significant increases in NDVI (green pixels). *Landsat TM/ETM+ pixels with significant NDVI trends (p<0.05) derived from a pixel-based linear regression of Landsat scenes from 1985-2010 are overlaid on a 2003 QuickBird image. Most greening occurred in shrubby areas; little change is evident on exposed, rocky hilltops (gray photo-signature) and paludified, moss-dominated lowlands (golden-brown photo signature).*

Figure 8 (below) Satellite images from 1968 (Corona; left) and 2003 (QuickBird; center) and with Landsat NDVI trends overlaid (right) from an area of recent alder expansion. *Xs denote grid points with new alder cover. Landsat pixels with highly significant NDVI trends (p<0.01) and high rates of greening are clustered near shrub expansion areas. From Frost et al. (Ph. D. thesis in prep.)*



Alder expansion in cryoturbated sorted polygons

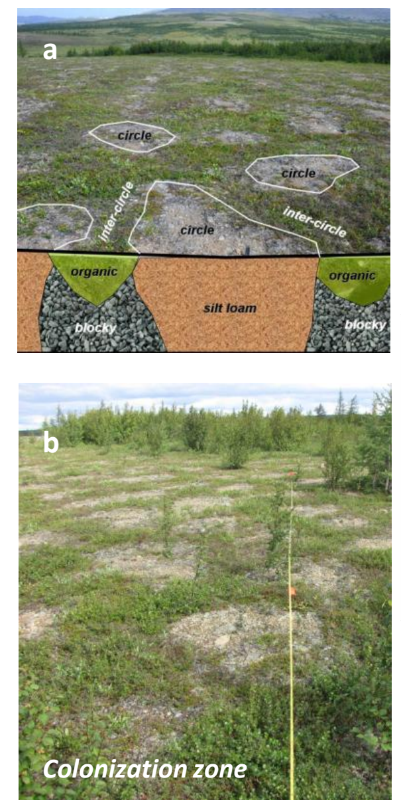


Figure 9 (left) (a) Patterned ground features at Kharp. *Sorted circles are well-expressed near hill crests, and are characterized by regularly-spaced, approximately circular patches of mineral soil within a matrix of vegetated inter-circles. The circles are caused by "differential frost heave" whereby soils heave much more in the poorly vegetated centers of the circles relative to inter-circle areas (Walker et al. 2008). Over time, soils become strongly sorted as rocks are heaved to the elevated (in winter due to frost heave) surface of the centers and accumulate by gravity at circle margins.* ***(b) Alder colonization on circles.*** *Annual frost-heave prevents slow-growing tundra plants from establishing at circles, but fast-growing boreal shrubs such as alder readily exploit these microsites.*

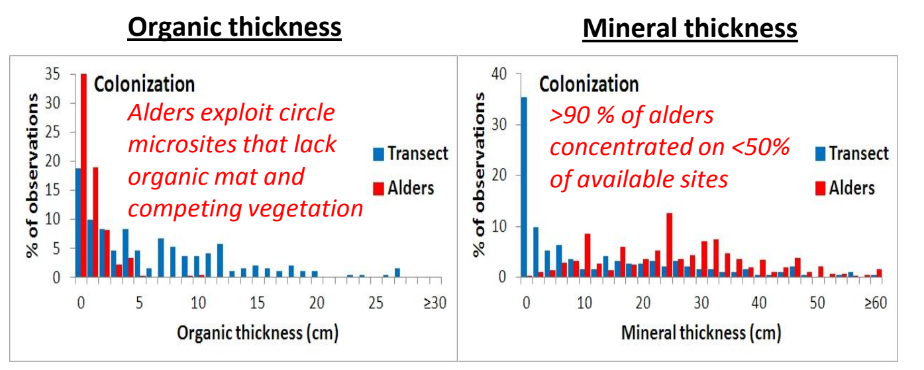
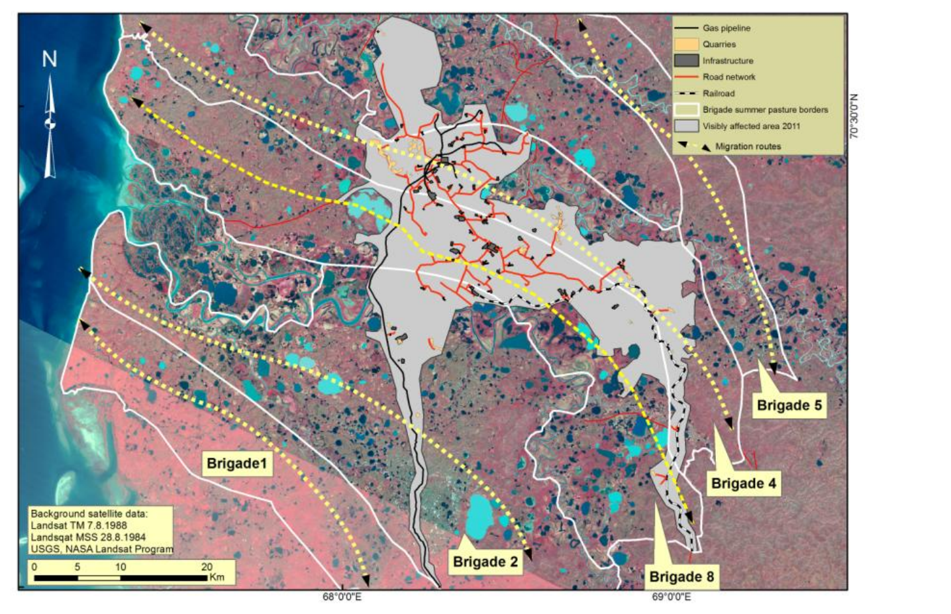


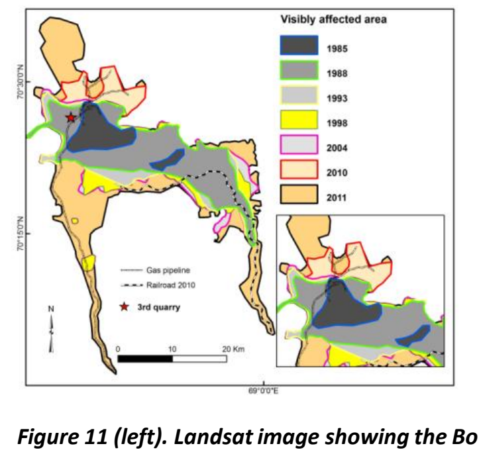
Figure 10 (above). *Comparison of measurements of organic depth* ***(left)*** *and mineral thickness* ***(right)*** *taken uniformly along transects, and at the base of alders, indicate that circles are "hotspots" of shrub recruitment. Differential heave causes annual, rather than episodic disturbance. Thus, it maintains a mosaic of favorable microsites with warm soils that are immediately available to shrubs during periods of favorable climate. From Frost et al. 2012 submitted to* Nature *and in press).*

II. Dynamics of greening associated with climate, gas-field development, and reindeer on the Yamal

IIa. Mapping infrastructure and vegetation change and recording the local perceptions of change



Gas was discovered at Bovanenkovo in 1971. Gas-field development has occurred at Bovanenkovo, Kharasavey, and few other localities on the peninsula since the late 1980s. However, the pace of development was rather slow between the mid-1990s and 2009 due to environmental and social concerns of the Nenets people and the lack of transportation corridors to the south. The maps shown here show the growth of the main gas field at Bovanenkovo on the Yamal Peninsula, Russia, and the impacts to the migration corridors used by the Nenets reindeer herders **(Fig. 11, 12, 13, 14)**. Since 2009, the pace of development has increased, and in 2010 a railroad link to the south was completed. It is anticipated that future development of pipelines will now proceed quickly. The direct and indirect impacts of gas-fields have affected summer pastures used by reindeer herds of the Nenets people **(Fig. 11, 15, 16)**. Details of the analysis are in several publications (e.g., Forbes et al. 2009, Kumpula et al. 2010, 2011, 2012 in press).



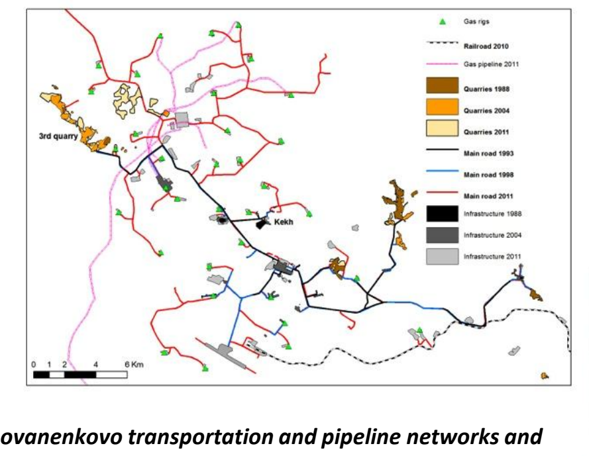


Figure 11 (left). Landsat image showing the Bovanenkovo transportation and pipeline networks and the main area impacted by gas-field activities as of 2011. *Also shown are the migration routes of five Nenets reindeer-herder brigades. In 2011, the gas field was connected by railroad to southern transportation networks by railway (dashed line). Prior to 2011, Brigade 2 had been relatively unaffected, but since then pipeline and railroad construction has increased impacts significantly on lands used by herders south of the Mordy-yakha River, which empties into the Kara Sea on the upper left of the image.*

Figure 12 (left above). The stages of visibly affected area expansion encompassing off-road tracks, roads, quarries and residential or other buildings. *The last three years has been a period of rapid infrastructure expansion, including railroad and pipeline building.*

Figure 13 (middle above). Growth of permanent infrastructure development including roads, pipelines, quarries and residential or other buildings. *Since the mid-1990's new infrastructure advanced slowly. Most of the expansion since 1998 has occurred between 2009-2011.*

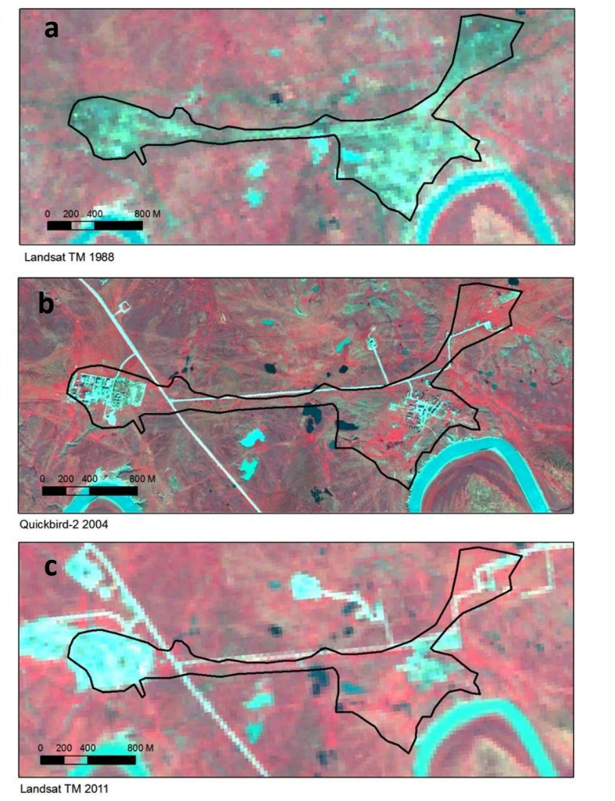


Figure 14 (3 panels, right above). Patterns of mechanical surface disturbance and revegetation in the vicinity of Kekh, *the first gas worker settlement to be established at Bovanenkovo in the late 1980s.* ***(a)*** *In 1988, when the development had just began, a large zone of exposed mineral soils (marine clay) was denuded of vegetation by heavy off-road vehicle traffic and construction activities. The black polygon circumscribes the extent of disturbance beginning in 1988 and remains consistent across all three images for spatial reference.* ***(b)*** *VHR Quickbird-2 shows the extent of revegetation after 14 years of natural regeneration.* ***(c)*** *Landsat TM scene indicates that much of the bare ground has been totally revegetated by 2011. In addition, a significant amount of new permanent infrastructure was built after 2004.*

Figure 15*. Nenets brigade crossing the Se-yakha river in the center of Bovanenkovo gas field on 5 July 2011. (Photo by Timo Kumpula).*

Figure 16. *Participant observation in winter pastures on the south side of Ob Bay: left Dr. Nina Meschtyb and right Nenets reindeer herding brigadier Nyadma Khudi from Yarsalinskii sovkhoz brigade 4. Photo from Nina Meschtyb archive.*

IIb. Modeling the effects of climate change and reindeer grazing on tundra biomass

The ArcVeg model: Predicting the impact of climate warming and changes in grazing on Arctic plant communities is complex. Simulation modeling can be used to examine multiple factors collectively and provide insights to the functionality of arctic systems across a broad range of scenarios (Yu et al. 2009). Arctic plant communities comprise a range of plant functional types (PFTs), including mosses, lichens, graminoids, forbs, evergreen shrubs and deciduous shrubs. We applied the ArcVeg model (Epstein et al. 2000) to explore the impacts of climate and grazing change at the PFT level within 11 different combinations of bioclimate subzone and soil texture along the Yamal Peninsula. Grazing impact was expressed as a function of both foliar nitrogen concentration and reindeer diet preferences (Yu et al. 2011). ArcVeg is driven mainly by soil organic nitrogen levels and temperature, and derives biomass of tundra plant functional types.

Methods: We used data from field-collected soils to calculate mean soil organic nitrogen for each site. Grazing is simulated with two components: frequency and percentage. For example, (0.1, 25%) means the grazers will graze the same area every ten year and each time there can be a maximum of 25% biomass to be removed. We simulated four levels of grazing intensity: (0.1, 25%), (0.1, 50%), (0.5, 25%) and (0.5, 50%). Plant functional type biomass values were compared and evaluated across all sites on the Yamal Peninsula under the different grazing scenarios with a 2 ˚C warming. In total we simulated 1500 years of change. At year 1000, the 2 °C warming was initiated and ramped linearly for 50 years; after that, the climate stayed at the warmer state for another 450 years. We calculated the mean biomass for each plant functional type for 100 years before warming (year 901 to year 1000), for 100 years during the transient warming period (year 1001 to year 1100), and for 100 years after warming (year 1401 to year 1500).

Effects of climate change, soil texture, and grazing on plant-functional-type and total-aboveground tundra biomass

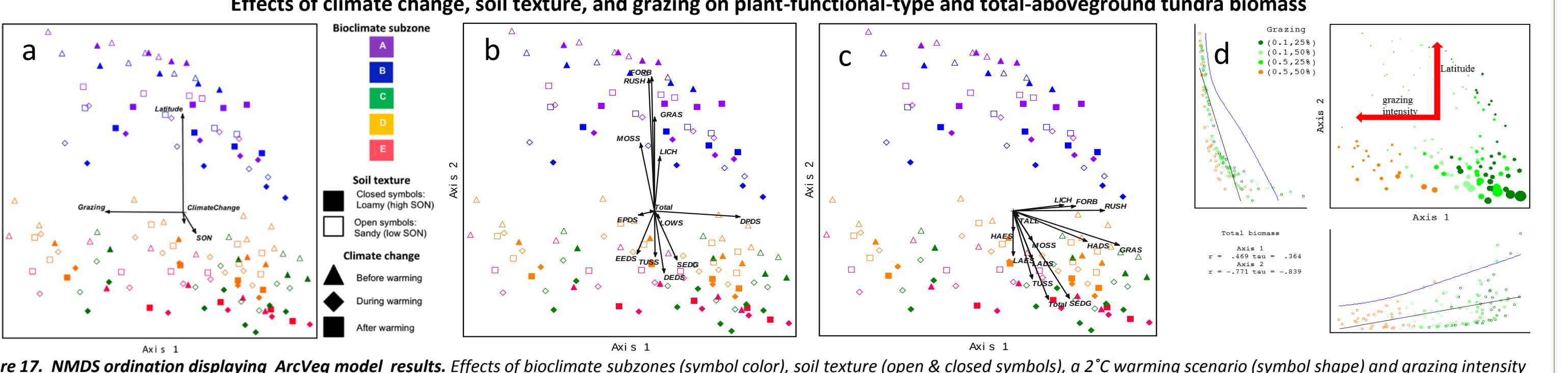


Figure 17. NMDS ordination displaying ArcVeg model results. *Effects of bioclimate subzones (symbol color), soil texture (open & closed symbols), a 2˚C warming scenario (symbol shape) and grazing intensity (panel d) are shown. Biplots (cluster of vectors in the centers of the plots) show relative direction and strength of* ***(a)*** *original latitudinal gradient and treatment factors (climate change, grazing, and soil organic nitrogen (SON, a function of soil texture);* ***(b)*** *trends in relative biomass of plant functional types; and* ***(c)*** *trends in absolute biomass of plant functional types. Axis 2 is strongly correlated with the latitudinal summer temperature gradient (~12 °C MJT) (42% of total variance), Axis 1 is strongly correlated with the grazing gradient (13% of total variance.* ***(d)*** *Total biomass for each simulation scenario; each point represents one model simulation; color indicates different grazing intensities, size of dot is relative total biomass). Grazing is parameterized with two components: frequency of each grazing event and percent biomass removal. For example, (0.1, 25%) indicates the grazers will graze the same area every ten years and each time a maximum of 25% biomass will be removed. Percent biomass removal matters more than frequency of visit: (0.1, 50%) is of greater grazing intensity than (0.5, 25%) through this analysis. Side plots show trend in biomass along each axis. The biomass trend is strongest along the latitudinal gradient.*

Results: Nonmetric Multi-Dimensional Scaling (NMDS) ordination is used to the display the results of the modeling **(Fig. 17)**. For mainland Yamal (subzones C, D and E) before warming, on average deciduous shrub biomass declined from 249 gm^-2 when grazing was (0.1, 25%) to 198 gm-2 when grazing was (0.1, 50%), and to 111 gm^-2 when grazing was (0.5, 25%) and 17 gm^-2 when grazing was (0.5, 50%). Grazing caused total plant community biomass to decrease, but PFTs were affected differently by grazing. Lichen, forb, graminoid, and deciduous shrub biomass declined in response to increased grazing frequency and percentage. Lichen and deciduous shrubs were affected the greatest by grazing.

III. Major conclusions and key publications from this research

I. Hierarchical analysis of Arctic land-cover changes:

a. **Panarctic change:** Between 1982 and 2011, there were large significantly positive and temporally correlated trends in the amount of coastal summer and fall ice-free open water, summer land temperatures, and NDVI across most of the Arctic **(Bhatt et al. 2010, Walker et al. 2011)**. The trends in North America and Eurasia have, however, recently diverged. Large areas of negative summer-temperatures trends and some negative NDVI trends now occur, particularly in western Eurasia. This appears to be due to delayed freeze-up of the seas north of Russia, leading to more atmospheric moisture content, more snow, and colder winters reported in recent years (Cohen et al. 2012, Liu et al. 2012, Muskett 2012). This is causing later snow melt, delayed phenology, decreased accumulation of thawing temperatures during summer and reduced NDVI in several areas of the Arctic.

b. **Differences between North America and Eurasia Arctic climate gradients, soils and vegetation:** The contrast between the relatively continental NAAT and more maritime EAT helps explains some of the temporal differences in temperature and NDVI seen at the panarctic scale **(Walker et al. 2011, 2012)**. Although the EAT and NAAT have broadly similar summer-temperature regimes and overall vegetation physiognomy, there are major differences in the soil pH, disturbance regimes, and precipitation (especially snow) that cause important differences in the relative abundance of the major plant functional types and total aboveground plant biomass. These differences have important implications for ecosystem response to a warmer climate in continental versus more maritime parts of the Arctic. Despite the differences in species composition and vegetation structure, there is a remarkably similar relationship between harvested total aboveground biomass and MaxNDVI along the two transects (**Raynolds et al. 2012, Epstein et al 2012**).

c. **Detailed observations of shrub expansion:** Separate studies of shrubs on landslides near Vaskiny Dachi and an old burned area near Kharp, combined with observations from many sites using high-resolution satellite imagery indicate the strongest greening trends are occurring in local parts of landscapes with abundant disturbances of several kinds, including those related to fire, landslides, thermokarst, differential frost heave in areas of patterned ground, and areas of anthropogenic change **(**Leibman and Kizyakov 2007**,** Ukraintseva 2008, **Walker et al.. 2009, Munger et al. 2009, Frost et al. 2012, in press, Kumpula et al. 2010, 2011, 2012 in press).** Paludification and accumulation of organic soil horizons on cold permafrost soils following shrub establishment eventually leads to slower shrub growth and the reduction of sites with warm bare soils that are conducive to shrub establishment. Shrub growth in relatively warm and/or more maritime portions of the Arctic with deep active layers and or deep snow, is however, strongly related to regional air temperatures **(Forbes et al. 2010).**

II. Land-use change related to hydrocarbon development and reindeer grazing: Remote sensing and GIS technology are being used to trace the history of development on the Yamal **(Kumpula et al. 2010, 2011)** and at Prudhoe Bay, AK **(Raynolds et al. 2012).** These methods are important tools for monitoring the pace of change in the Arctic and their effects on local people. Interviews with the local people are using maps and satellite images to document local peoples perceptions of the changes **(Forbes et al. 2009)**. Gas-field infrastructure is increasingly affecting summer pastures used by reindeer herds of the Nenets people, and will increase more rapidly with transportation and pipelines linking the field to the south.

The ArcVeg tundra succession model was used to explore the possible consequences of climate warming, and different reindeer grazing scenarios along the full Arctic climate gradient and in different soil textures **(Yu et al. 2009, 2011)**. Initial vegetation responses to climate change during transient warming are different from the long term equilibrium responses due to shifts in the controlling mechanisms (nutrient limitation vs. competition). Generally, warming promotes the growth of shrubs and graminoids. Moss biomass had a nonlinear response to grazing, and such responses were stronger when warming was present. Further analyses with inclusion of trampling effects are strongly needed to better understand the interactions between shrub dominance and grazing.

Key publications:

Bhatt, US et al. 2010. Circumpolar Arctic tundra vegetation change is linked to sea-ice decline. *Earth Interactions*, 14:1-20.
Epstein HE et al. 2012. Dynamics of aboveground phytomass of the circumpolar arctic tundra during the past three decades. *Environmental Research Letters*, 7: 015506.
Forbes BC et al. 2009. High resilience in the Yamal-Nenets social-ecological system, West Siberian Arctic, Russia. *Proceedings of the National Academy of Sciences*,106: 22041.
Forbes B.C and Stammler, F. 2009. Arctic climate change discourse: the contrasting politics of research agendas in the West and Russia. *Polar Research* **28**: 28–42.
Forbes BC, et a. 2010. Russian Arctic warming and greening are closely tracked by tundra shrub willows. *Global Change Biology,* 16:1542-1554.
Frost GV et al. 2012 (in press). Linkages between patterned ground, alder shrubland development, and active layer temperature in the northwest Siberian Low Arctic. *Proceedings of the Tenth International Conference on Permafrost*.
Kumpula T, Forbes BC, Stammler F. 2010. Remote sensing and local knowledge of hydrocarbon exploitation: the case of Bovanenkovo, Yamal, West Siberia. *Arctic* 63:165–178.
Kumpula T. et al. 2011. Land use and land cover change in Arctic Russia: Ecological and social implications of industrial development. *Global Environ. Change*, 21: 550-562.
Kumpula T. et al. 2012. Dynamics of a coupled system: social-ecological responses during 25 years of gas field development in Arctic Russia. *Remote Sensing* (revision submitted)
Munger CA. 2009. Spatial and temporal patterns of vegetation, terrain and greenness in the Toolik Lake and Upper Kuparuk River region. MS thesis. University of Alaska Fairbanks.
Raynolds MK et al. 2012a. A new estimate of tundra-biome phytomass from trans-Arctic field data and AVHRR NDVI. *Remote Sensing Letters*, 3:403-411.
Raynolds MK et al. 2012b. Integrated geobotanical and historical disturbance map (IGHDM) for monitoring landscape changes in the Prudhoe Bay oil field (1:6000 scale). Circumpolar Remote Sensing Symposium, Levi, Finland, 14-18 May 2012.
Walker DA et al. 2011. The Arctic: Land: Vegetation. [In: State of the Climate in 2010]. *Bulletin of the American Meteorological Society* 92:S150-S152.
Walker DA et al. 2012. Environment, vegetation and greenness (NDVI) along the North America and Eurasia Arctic transects. *Environmental Research Letters*. 7:015504.
Walker DA et al. 2011. Vegetation of zonal patterned-ground ecosystems along the North American Arctic Transect. *Applied Vegetation Science*, 14:440-463.
Walker DA et al. 2009. Spatial and temporal patterns of greenness on the Yamal Peninsula, Russia: interactions of ecological and social factors affecting the Arctic normalized difference vegetation index*. Environmental Research Letters*. 4:16.
Yu Q et al. 2009. Simulating the effects of soil organic nitrogen and grazing on arctic tundra vegetation dynamics on the Yamal Peninsula, Russia*. Environmental Research Letters* 4: 045027.
Yu Q et al. 2011. Modeling dynamics of tundra plant communities on the Yamal Peninsula, Russia, in response to climate change and grazing pressure*. Environmental Research Letters* 4: 045505.

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