The Eurasia Arctic Transect: Vegetation-environment-permafrost relationships

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Abstract

The Eurasia Arctic Transect (EAT) is located in a key area of rapid change associated with dramatic sea-ice loss in the Barents and Kara seas and extensive gas development on the Yamal Peninsula. The EAT is 1500 km long, from Nadym, in the forest-tundra transition of northwest Siberia, to Krenkel hydro-meteorological station, Hayes Island, Franz Jozef Land **(Fig. 1)**. The major reasons to establish the transect were to (1) develop a set of ground-based data from zonal sites in each bioclimate subzone that could be used to help interpret remote-sensing spectral data of the region; (2) examine the interactions between zonal climate, permafrost, vegetation and soils along a continuous bioclimate gradient from treeline to the northernmost part of the Eurasian Arctic; and (3) compare this transect to a similar transect in North America (Walker et al. 2011a). The permafrost on the Yamal Peninsula is exceptionally sensitive to erosion by landslides. Vegetation protects the permafrost from erosion by both climate change and anthropogenic factors, so a primary interest was the relationship between summer temperature, aboveground biomass, active-layer thickness, vegetation composition, biomass, and soil texture. Here we present an update on the key vegetation-environment-permafrost information from the ongoing EAT synthesis studies.

I. The Eurasia Arctic Transect (EAT)

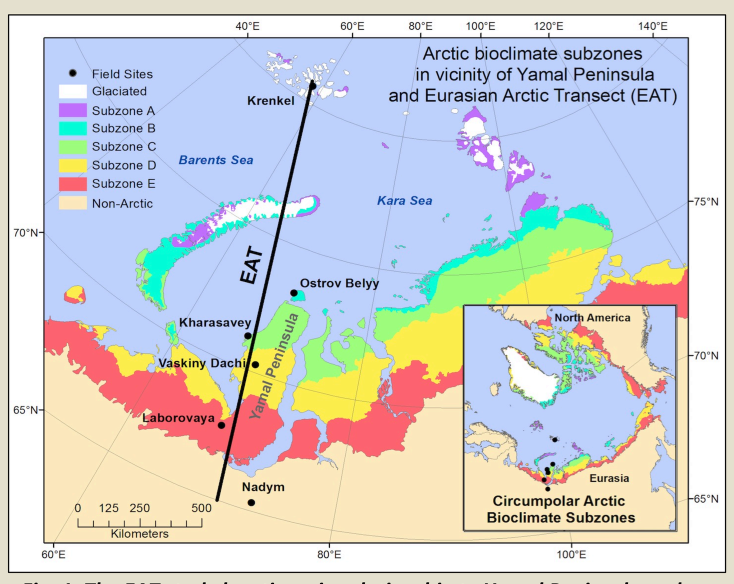


Fig. 1. The EAT study locations in relationship to Yamal Peninsula and Arctic bioclimate subzones.

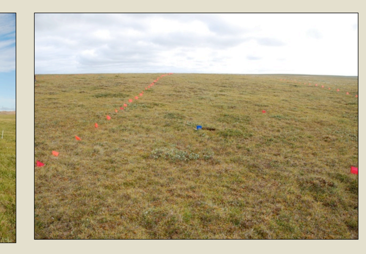
Table 1. Study locations, summer warmth index (SWI = sum of monthly mean temperatures >0 ˚C), geological setting, soil, and dominant vegetation for zonal sites at each location.

Location	Longitude, latitude	Bioclimate subzone	Summer Warmth Index (˚C mo)	Mean annual temperature (˚C)	Geological setting, slope, elevation (m), parent material, surface geomorphology of zonal site	Soil texture, pH	Dominant vegetation
Nadym	65.19° N, 72.53° E	Forest-Tundra	40	-6.5	Fluvial terrace II, Karga-age, (about 20-40 kya), alluvial sands	Sand 3.25	Lichen woodland: *Pinus sylvestris-Ledum palustre-Cladonia stellaris* (Walker et al. 2008a)
Laborovaya	67.71° N, 67.99° E	E	38	-7	Hill slope, 2° slope SW, 80 m, hillslope colluvium over glacial till (Ermakovsky-age, about 50-110 kya), no patterned ground.	Clay loam, 4.9	Sedge, dwarf-shrub, moss tundra: *Carex bigelowii-Betula nana-Aulacomnium palustre* (Walker et al. 2008b).
Vaskini Dachi	70.28° N, 68.89° E	D	22	-8.1	Stable hill crest in strongly eroded section of coastal plain with many landslides, flat, 45 m, marine terrace IV (Kazantsevskaya-age, about 130-117 kya), no patterned ground.	Silt loam, 4.5	Sedge, dwarf-shrub, moss tundra: *Carex bigelowii-Vaccinium vitis idaea-Hylocomium splendens* (Walker et al. 2008b).
Kharasavey	71.18° N, 66.98° E	C	15.5	-8.7	Coastal plain, marine terrace, flat, 16 m, alluvial-marine sediments, Marine terrace II, Karginsky-age, (about 20-40 kya), no patterned ground.	Silt loam, 4.5	Graminoid, prostrate dwarf-shrub, moss tundra: *Carex bigelowii-Calamagrostis holmii-Salix polaris-Dicranum elongatum-Cladonia spp.* (Walker et al. 2009a)
Ostrov Belyy	73.33° N, 70.08° E	B	11.5	-10.3	Coastal plain, gentle slope of marine terrace, 2° NE, 2 m, alluvial-marine sediments, marine terrace II (Upper Pleistocene to Holocene age), non-sorted circles (0.5-0.7 m diameter).	Loam, 4.8	Nonsorted circle complex: (Inter-circle areas) Graminoid, prostrate dwarf-shrub, moss tundra: *Carex bigelowii-Calamagrostis holmii-Salix polaris-Hylocomium splendens*. (Nonsorted circles) Prostrate dwarf-shrub, crustose-lichen barren: *Dryas integrifolia-Arctagrostis latifolia-Racomitrium lanuginosum-Ochrolechia frigida* (Walker et al. 2009b).
Krenkel	80.58° N, 57.90° E	A	1	-13.3	Hill backslope, 4° W, 30 m, hillslope colluvium derived from unconsolidated calcareous sandstone deposits (Mesozoic age), small nonsorted polygons (10-15 cm diameter).	Sandy loam, 6.2	Cushion-forb, lichen, moss tundra: *Papaver dahlianum spp. polare-Stellaria edwardsii-Cetrariella delisei-Ditrichum flexicaule*-black soil crust (Walker et al. 2011).

Nadym *Forest-tundra transition* | **Laborovaya** *Subzone E* | **Vaskini-Dachi** *Subzone D* | **Kharasavey** *Subzone C* | **Ostrov Belyy** *Subzone B* | **Krenkel** *Subzone A*

NA-1, Forest, sand, ungrazed

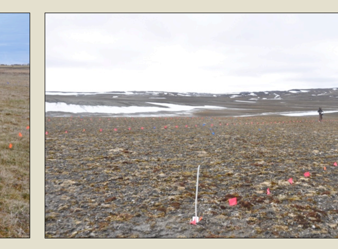
LA-1, zonal, loam, grazed



VD-1, zonal, loam, grazed

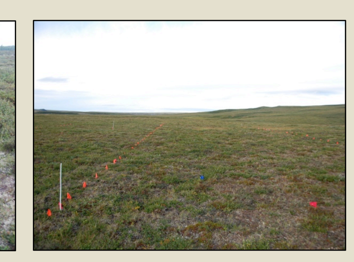
KH-1, zonal, clay-loam, grazed

OB-1, zonal, sandy clay loam, ungrazed

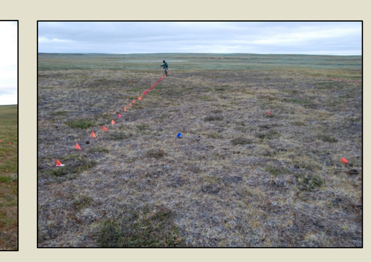


KR-1, zonal, sandy-loam, ungrazed

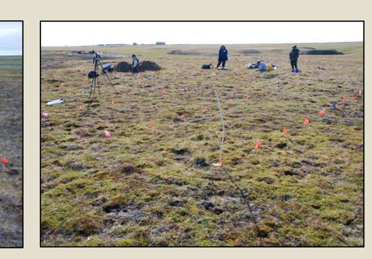
NA-2, Tundra, loamy sand, ungrazed



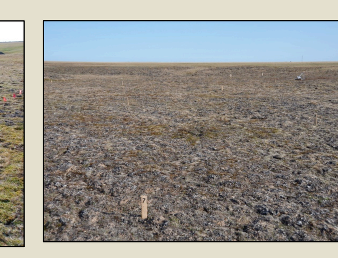
LA-2, loamy sand, grazed



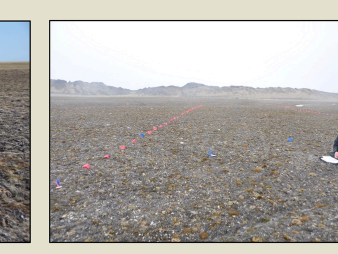
VD-3, sand, grazed



KH-2a, sand, grazed



OB-2, sand, ungrazed



KR-2, zonal, sand, ungrazed

Characterization of the study sites

Integrated geoecological and remote sensing studies were conducted at six general locations representative of the major substrate variation the five bioclimate subzones and the forest-tundra transition along the EAT (**Fig. 1**). Sampling was conducted at 17 study sites along transects and plots as shown in **Figure 2.**

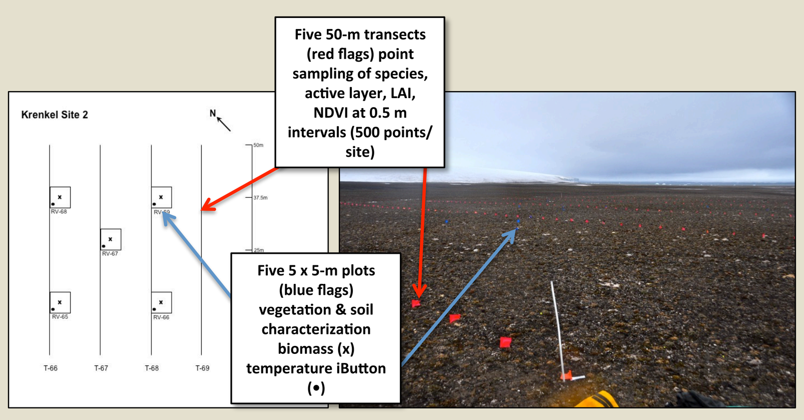


Fig. 2. Sample design at each site.

Integrated geoecoloigcal studies along transects and in study plots at each site

iButtons® for measuring ground surface temperature and n-factor

Soil pits

Thaw-depth measurements

Vegetation characterization: Point intercept along line transects; Braun-Blanquet phytosociology in plots

Clip harvests of aboveground biomass

Spectroradiometer and LAI measurements along line transects and at study plots

II. Vegetation-environment-permafrost relationships along the EAT

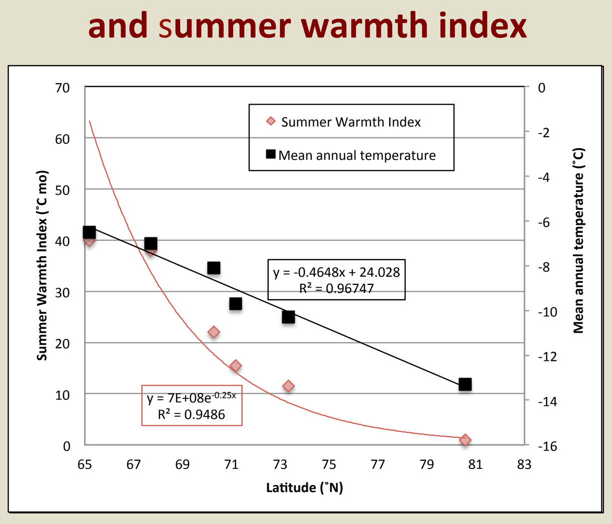
Overview

Vegetation plays a key role in protecting permafrost from thaw, but the relationships between vegetation and permafrost are generally poorly modeled because of complex environmental factors that affect the vegetation and permafrost and their interactions. The role of water for both vegetation and permafrost is particularly difficult to model because of its seasonal phase changes at the freezing point and the drastically different physical properties of water in its solid, liquid, and gaseous states during summer and winter. Our study simultaneously focused on a classical phytosociological description of the vegetation as well as the aspects of the vegetation that play a key role in permafrost dynamics. An earlier publication provided an overview of the zonal vegetation of the EAT in comparison with a similar transect in North America (Walker et al. 2012).

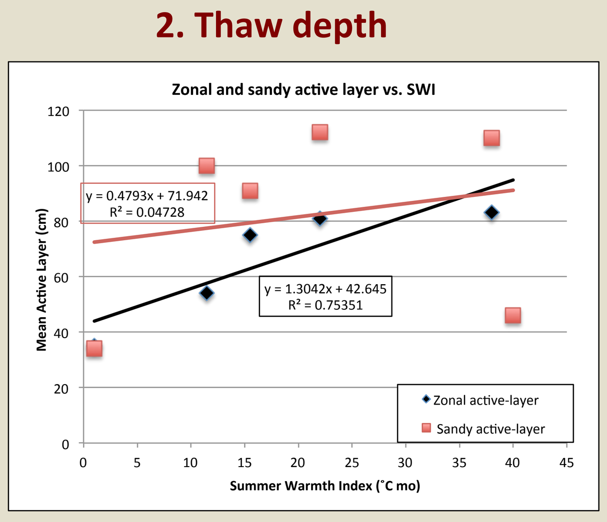
The synthesis of the EAT vegetation studies is still in progress. Here we focus on some of the contrasts within the EAT due to substrate/soil differences along the transect. The photos in the above panel (**I**) show the contrast in vegetation on loamy vs. sandy sites at each of six major study locations along the EAT, and some of the sampling approaches used to examine vegetation-environmental relationships.

The figures to the right describe the major geomorphological and soil controls on the plant-species composition and biomass of the vegetation. Numerous other factors not described here also affect the vegetation and permafrost. For example, reindeer grazing has a major effect on the structure and composition of the vegetation and consequently to the permafrost, but could not be studied adequately because of the lack of long-term reindeer-exclusion studies.

1. Mean annual temperature and summer warmth index



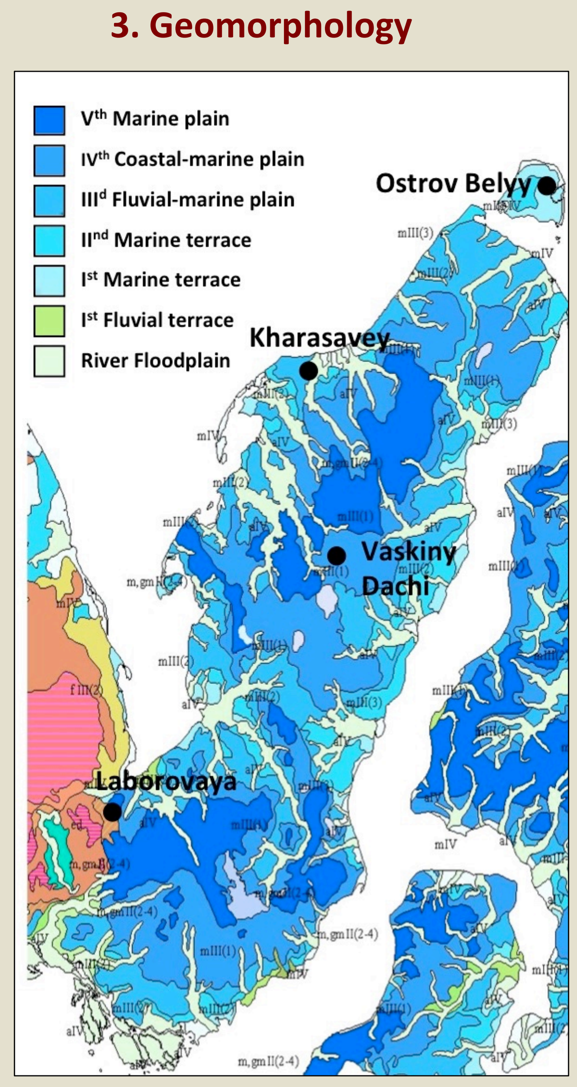
2. Thaw depth



Climate and thaw depth

Mean annual air temperature strongly affects the development of permafrost and is highly correlated with latitude along the EAT. The mean annual air temperature drops 8 ˚C in the 1500 km between the Nadym (Forest-Tundra transition) and Krenkel (bioclimate subzone A) weather stations **(1, black line)**. Vegetation, most biological processes, and the active layer, however, are most strongly affected by summer air temperatures above the freezing point. The *Summer Warmth Index* (SWI) is the sum of the monthly mean air temperatures above freezing. At these extreme latitudes, SWI has an negative exponential relationship to latitude. There is approximately a 40-fold increase in the SWI between Krenkel and Nadym **(1, red line)**. At the northern end of the gradient, a small change in total summer warmth has dramatic effects on species composition and vegetation structure. Air temperature only partially controls the seasonal thaw depth because thaw is affected by many other environmental factors, namely soil texture, drainage, and the composition, thickness, and insulative properties of the vegetative and organic soil layers (Walker et al. 2003). There was generally good correspondence between SWI and active-layer thickness on zonal sites, and poor correspondence on sandy sites **(2)**.

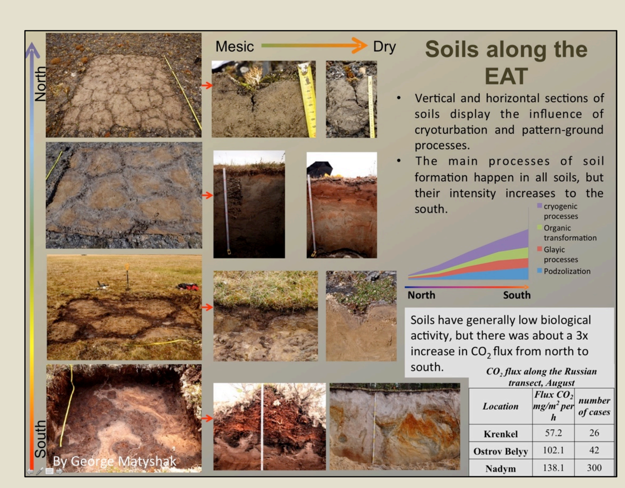
3. Geomorphology



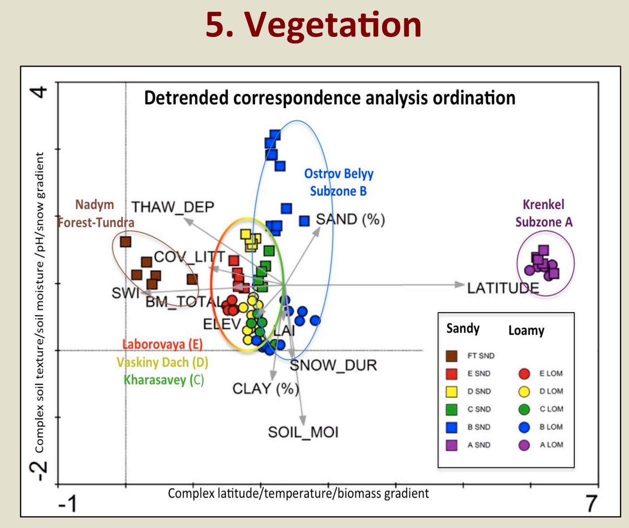
Substrate controls

The range of lithologies across the EAT is wide. The southern part of Yamal is in the Ural foothills with low-mountain terrain and bedrock located close to the surface. The Yamal, where four of the six EAT study locations are situated, is covered by thick layers of Quaternary deposits **(3)**. Hilltops with vast barren areas of wind-blown sands are widely distributed. The large variety of surface deposits contributes to the unusually wide range of seasonal thaw depths. Additional complications are associated with saline marine sediments in the area north of the Yuribey River, which did not undergo thawing during the Holocene climatic optimum. Moreover, the upper washed layers are continuously moved down slopes, bringing the saline sediments to the surface as a result of slope processes. Saline soils cause difficulties in measuring thaw depths with standard methods and in the determination of the notion of the thaw depth itself. For example, the difference between the depth of positive ground temperatures and the depth of the first ice lens occurrence can be 50-80% in saline clays (Leibman et al. 2013). For this reason, we focused on zonal sites and areas with sandy soils, and excluded sites with saline clay.

4. Soils



5. Vegetation



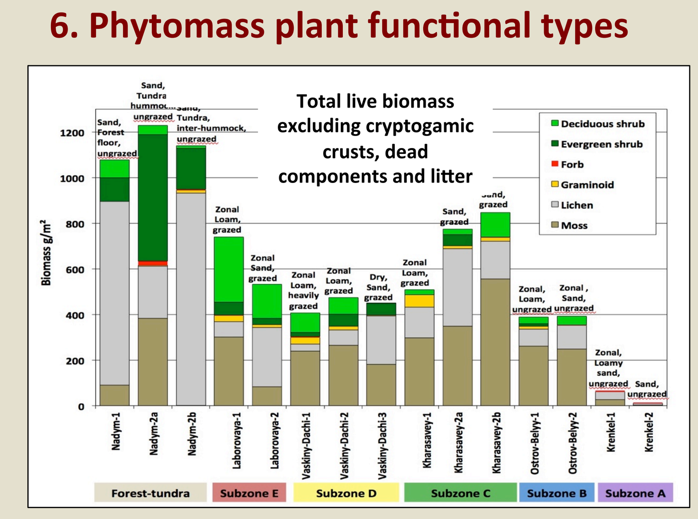
Soils

The sampling at each location included sites with zonal, primarily loamy to clayey soils, and sites with sandy soils (except for Nadym where the soils were all sandy). Soil pits examined variation in the horizontal and vertical planes **(4)**. The horizontal plane revealed the effects of small-scale patterned-ground features on carbon distribution. Generally the size of the patterned–ground features and the intensity of soil processes, including cryoturbation, organic transformation, gleyic processes, and podzolization, increased toward the south. Overall soil biological activity was low along the entire transect compared to more southerly locations, but CO_2 flux showed about a 3-fold increase from north to south (Matyshak et al. 2012).

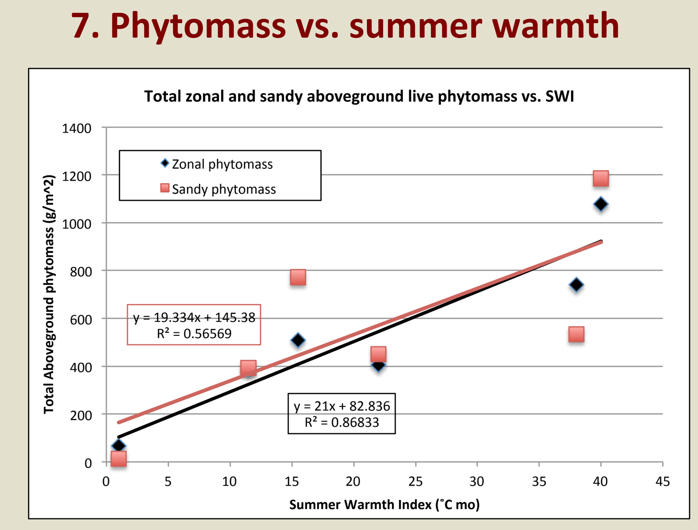
Vegetation

An ordination of plots based on their floristic similarity uses Sorenson's coefficient of similarity **(5)**. Plot symbols are colored according to bioclimate subzone, and the shapes of the symbols correspond to soil texture. The extreme High Arctic sites at Krenkel are most distant geographically, climatically, and floristically from the other sites. The subzone E, D, and C sites are all on the Yamal Peninsula and floristically quite similar, but with clear south-north floristic trends. The primary axis is correlated with latitude, temperature, and biomass, while the secondary axis is correlated with a complex of soil factors (texture, moisture, pH) and snow cover. Plant communities on loamy (zonal) soils are clearly separated from communities on sandy soils at all locations, except Nadym (which had no loamy sites) and Krenkel, where all plots showed high floristic similarity to each other due to low overall species diversity (12 vascular species, 25 bryophytes, 22 lichens) (Chasnikova et al. 2016 in prep.).

6. Phytomass plant functional types



7. Phytomass vs. summer warmth

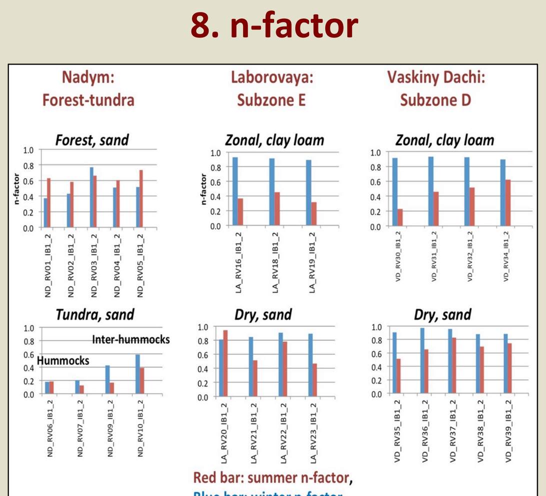


Vegetation structure and phytomass

Clip harvests from five plots within each 50 x 50-m study site were sorted according to plant functional types and weighed to determine phytomass on zonal and sandy sites at each EAT location **(6)** (Walker et al. 2011b). The histogram here shows the total live phytomass, but excludes the trees in the forested site at Nadym, which add approximately another 4400 g m^2 to the Nadym-1 biomass, cryptogamic soil crusts, which added 95-218 g m^2 to the Krenkel sites but were unmeasured at the other locations, and dead components of the vegetation, including standing dead and litter, which were highly variable (litter alone contributed 35-571 g m^2). By far the largest part of the biomass at all study sites was in the moss-lichen layer. An even larger, unmeasured component of the total biomass was in the dead moss and lichen layer that graded into the mineral soil. The structure of the aboveground vascular-plant canopy and its distribution between various plant functional types and between foliar and woody components strongly affect the shading and the total cooling capacity of the vegetation.

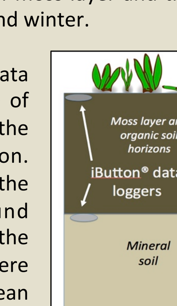
All of this plant material contributes in complex ways to the insulation capacity of the soil. The distribution of the biomass in the different layers of the plant canopy between different plant funtional types, foliar and woody components, and live and dead components, all affect the total insulative value of the vegetation mat. Interestingly, however, the overall biomass on both loamy and sandy soils increased with summer warmth (SWI) along the EAT at about the same rate **(7)**.

8. n-factor



Insulative value of the moss mat

The n-factor has been used as an index of the insulative value of the vegetation layer (Klene et al. 2002, Kade et al. 2006). The diagram below shows how Onset iButton® temperature data loggers were placed to measure the insulative value of moss layer and the organic soil horizons in summer and winter.



Onset iButton® temperature data loggers were placed at the base of live vegetation and at the top of the uppermost mineral soil horizon. Thawing degree-day sums at the base of the live aboveground vegetation (TDD_v) and top of the mineral soil surface (TDD_m) were calculated by summing daily mean temperatures from the first to the last day of the season when the mean soil-surface temperature rose above 0 ˚C. Similarly, freezing degree-day sums were determined for the same positions (FDD_v and FDD_m) by summing daily mean temperatures from the first to the last day of the season that the mean soil-surface temperature dipped below 0 ˚C. The n-factor value of the organic moss and soil was calculated for summer and winter:

- Summer moss and organic layer n-factor: $n_s = TDD_m/TDD_v$
- Winter moss and organic layer n-factor: $n_w = FDD_m/FDD_v$

Data loggers were placed at all vegetation study plots along the EAT, but to date we have only retrieved those from the southern three sites shown above.

The iButton® data from the southern three EAT locations **(8)** reveal the differences in the insulative properties of the organic layer in summer and winter for a forest site vs. a tundra site with the same macroclimate. The forest site had no permafrost and, in contrast to areas with permafrost, had generally higher summer n-factors than winter n-factors. The data from Laborovaya and Vaskini Dachi show the generally lower summer n-factors for loamy sites with relatively thick organic layers. The winter n-factors at all tundra locations are close to 1.0, possibly because of small temperature differences between the two sensors due to overlying snow.

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Poster presentation

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