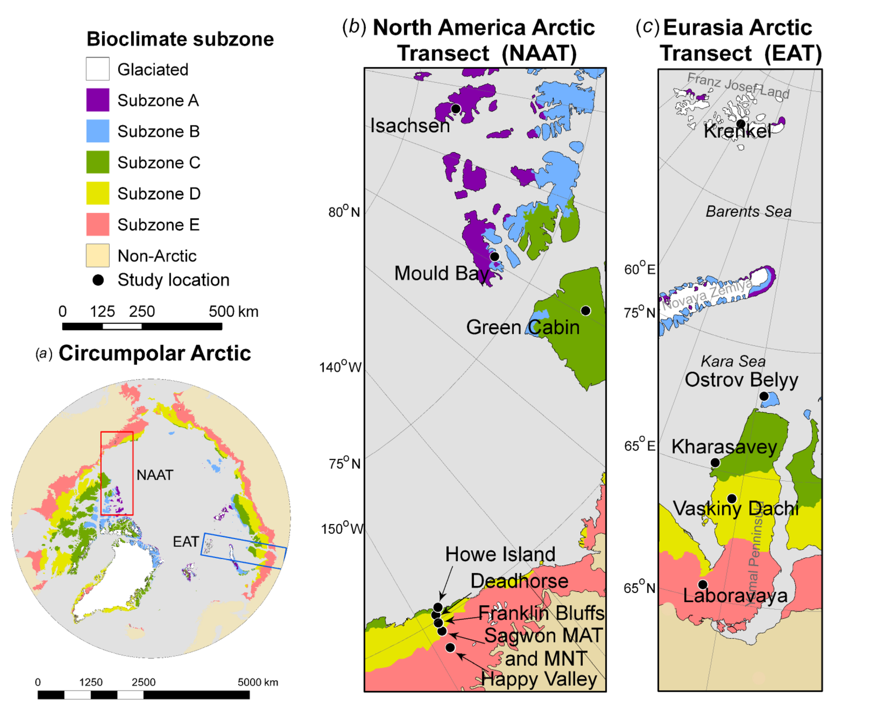
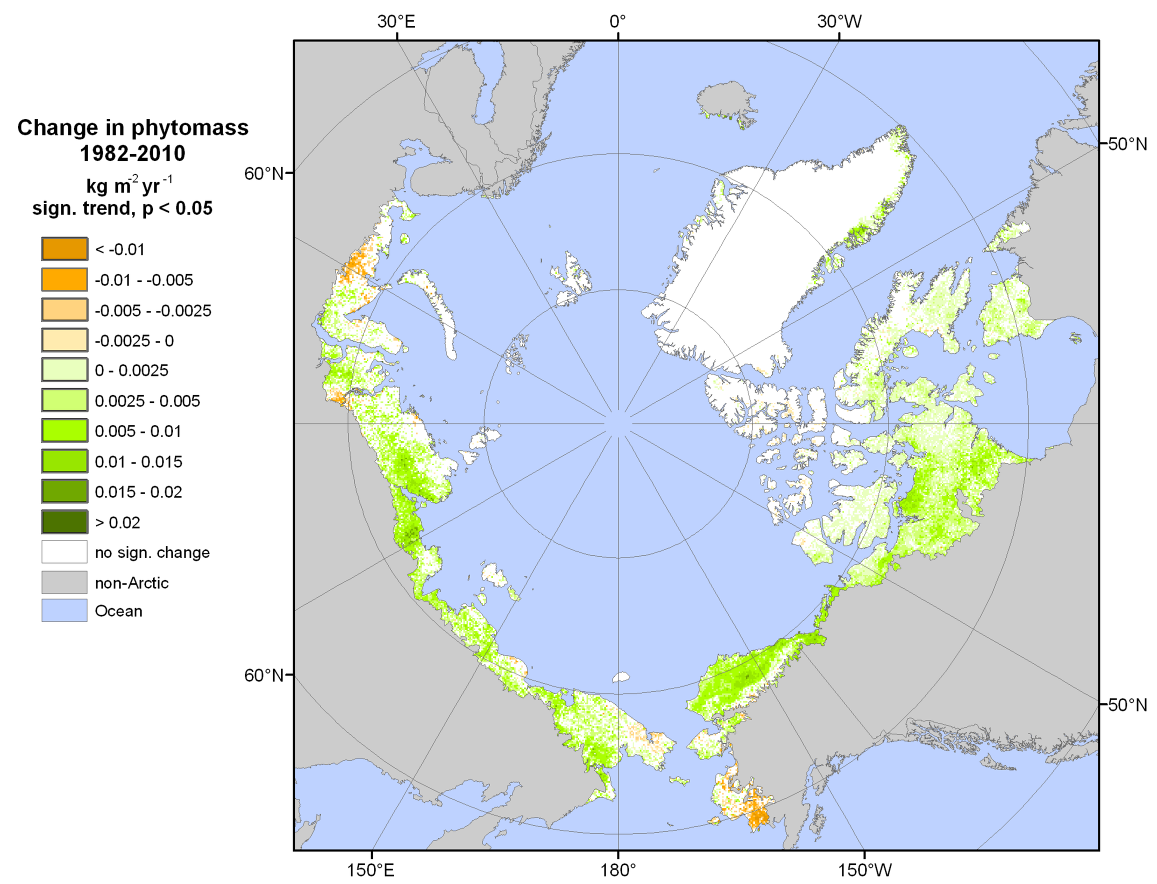
# Recent dynamics of arctic tundra vegetation: Remote sensing, field observations, and simulation modeling

Howard E. Epstein[1], Martha K. Raynolds[2], Donald A. Walker[2], Uma S. Bhatt[3], Compton J. Tucker[4], Jorge E. Pinzon[4], Gerald V. Frost[1], Qin Yu[1], Gensuo J. Jia[5], and Heqing Zeng[5]

[1]Dept. of Environmental Science, University of Virginia, Charlottesville, VA 22904-4123; [2]Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775-7000; [3]Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775-7320; [4]NASA Goddard Space Flight Center, Greenbelt, MD 20771; [5]Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China 100029

## CIRCUMPOLAR TUNDRA BIOMASS DYNAMICS

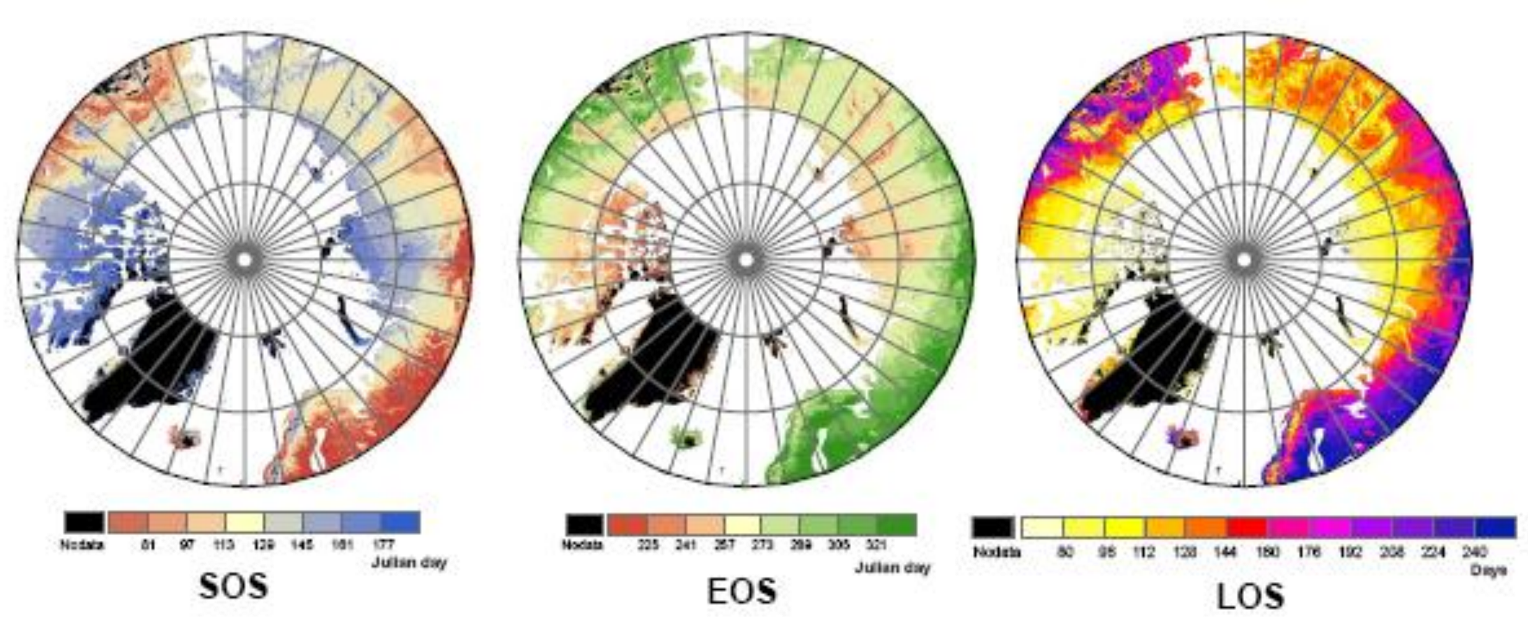


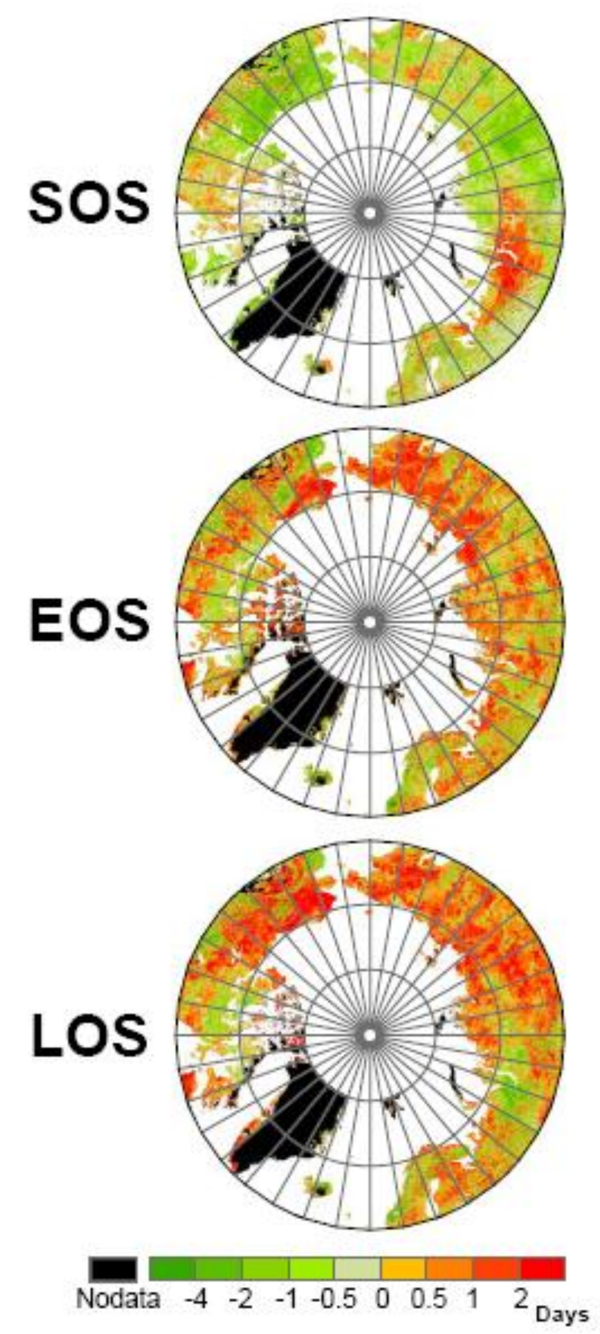




| Bioclimate Subzone | Area (km²) | 1982 | SD | 2010 | SD | Change in mean biomass (g m⁻²) | Rate of change (g m⁻² y⁻¹) | 1982 | 2010 | Change | % change | Rate of change (% y⁻¹) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Greenland Ice Cap | 1,795,920 | 83.8 | 14.0 | 84.4 | 18.0 | 0.6 | 0.02 | 0.15 | 0.15 | 0.0011 | 0.70 | 0.025 |
| A | 200,964 | 98.3 | 39.2 | 100.3 | 53.4 | 2.0 | 0.07 | 0.02 | 0.02 | 0.0004 | 2.05 | 0.073 |
| B | 530,780 | 142.7 | 100.9 | 151.8 | 118.4 | 9.1 | 0.33 | 0.08 | 0.08 | 0.0048 | 6.39 | 0.228 |
| C | 1,380,760 | 199.6 | 116.6 | 241.2 | 148.7 | 41.6 | 1.49 | 0.28 | 0.33 | 0.0575 | 20.85 | 0.745 |
| D | 1,708,430 | 319.8 | 145.6 | 401.5 | 195.2 | 81.7 | 2.92 | 0.55 | 0.69 | 0.1396 | 25.56 | 0.913 |
| E | 2,027,020 | 467.5 | 142.5 | 563.6 | 153.1 | 96.1 | 3.43 | 0.95 | 1.14 | 0.1948 | 20.55 | 0.734 |

Numerous studies have evaluated the dynamics of arctic tundra vegetation throughout the past several decades, using remotely sensed proxies of vegetation, such as the Normalized Difference Vegetation Index (NDVI). While extremely useful, these coarse-scale satellite-derived measurements give us minimal information with regard to how these changes are being expressed on the ground, in terms of tundra structure and function. In this analysis, we used a strong regression model between NDVI and aboveground tundra phytomass, developed from extensive field-harvested measurements of vegetation biomass, to estimate the biomass dynamics of the circumpolar arctic tundra over the period of continuous satellite records (1982-2010). We found that the southernmost tundra subzones (C-E) dominate the increases in biomass, ranging from 20-26 %, although there was a high degree of heterogeneity across regions, floristic provinces, and vegetation types. The estimated total sequestration of 0.40 Pg C over the past three decades is substantive, albeit quite small relative to anthropogenic C emissions. However, a 19.8% average increase in aboveground biomass has major implications for nearly all aspects of tundra ecosystems including hydrology, active layer depths, permafrost regimes, wildlife, and human use of arctic landscapes. While spatially extensive on-the-ground measurements of tundra biomass were conducted in the development of this analysis, validation is still impossible without more repeated, long-term monitoring of arctic tundra biomass in the field.

## SEASONALITY OF CIRCUMPOLAR TUNDRA VEGETATION



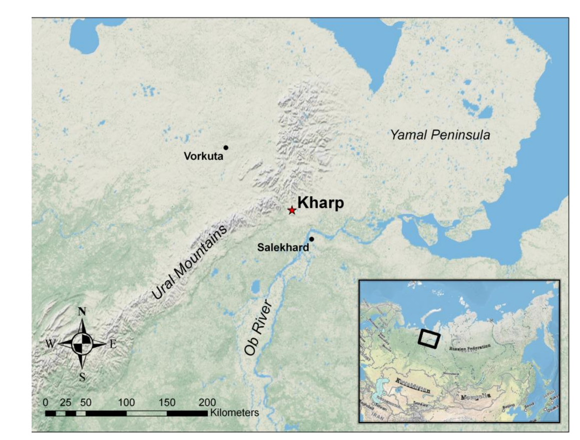




Phenology of vegetation is a sensitive and valuable indicator of the dynamic responses of terrestrial ecosystems to climate change. Therefore, it is important to reduce uncertainties in detecting phonological changes, to better understand and predict ecosystems dynamics. Here, changes in phenology over the past several decades across the northern high-latitude region ($\geq$ 60oN) were examined by calibrating and analyzing time series of the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometers (AVHRR). Over the past decade (2000-2010), an expanded length of the growing season (LOS) was detected by MODIS, largely due to an earlier start of the growing season (SOS) by 4.7 days per decade and a delayed end of the growing season (EOS) by 1.6 days per decade. There was a significant difference between North America and Eurasia in phenology based on MODIS data ($p < 0.01$). In Northern America, SOS advanced by 11.5 days per decade, and EOS was delayed by 2.2 days per decade. In Eurasia, SOS advanced by 2.1 days per decade, and EOS was delayed by 3.5 days per decade. SOS has likely advanced due to the warming Arctic during April and May. Our MODIS results suggest that in recent decades the longer vegetation growing seasons can be attributed to more advanced SOS rather than delayed EOS. However, AVHRR detected longer LOS over the past three decades, largely related to delayed EOS rather than advanced SOS. Further inter-calibration between the sensors is needed to resolve the inconsistency and to better understand long-term trends of vegetation growth in the Arctic.

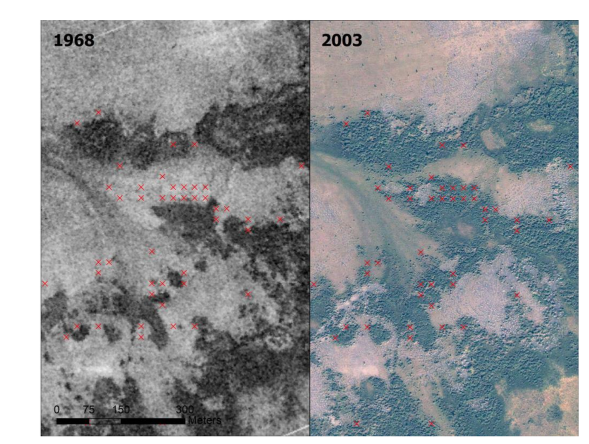
## SHRUB EXPANSION IN NORTHWESTERN SIBERIA

Numerous experimental and simulation modeling studies have indicated that expansion of deciduous shrubs is one of the most likely land-cover changes to accompany climate-warming in Low Arctic tundra. Observational studies have corroborated these findings, particularly in the North American Arctic. However, the Eurasian Arctic has received less attention. Shrubification of tundra-dominated regions has the potential to strongly influence a range of biophysical attributes of Arctic landscapes, including vegetation structure, albedo, surface energy balance, and hydrology.

We conducted field-studies within a tundra ecotone in the northwest Siberian Low Arctic, near the town of Kharp. Comparisons of high-resolution satellite imagery indicated that cover of alder shrubs (*Alnus fruticosa*) increased by ~10% in the Kharp study area between 1968 and 2003. Additionally, an NDVI time-series derived from Landsat data for the period 1985-2009 indicated a strong "greening" across much of the site, especially in association with alder shrublands. We were primarily interested in identifying important soil- and geomorphic site characteristics related to recent alder proliferation and increases in vegetation productivity at Kharp.




Map showing southern Yamal region and location of Kharp study site in northwest Siberia.



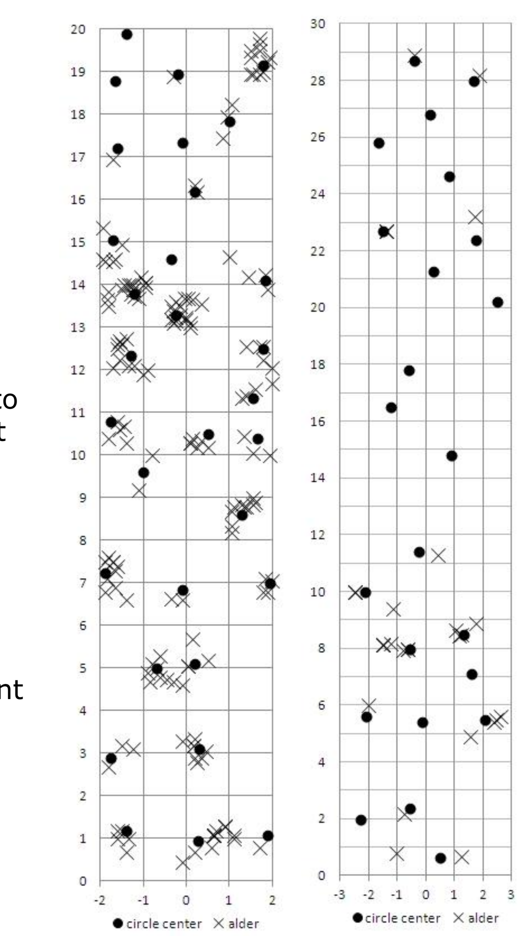

Comparison of 1968 (Corona) and 2003 (QuickBird) showing area of recent alder expansion. Areas with new shrub cover are marked in red.

### *Facilitation of shrub recruitment on patterned ground*

Field observations at Kharp revealed that virtually all of the recent alder expansion was closely linked to circle microsites in areas of patterned ground. Circles are widespread in Arctic landscapes; they develop due to repeated freeze-thaw cycles and feedbacks with the development of vegetation, resulting in annual disturbance of the circle center. Circles are characterized by regularly-spaced, circular patches of mineral soil within a matrix of vegetated inter-circles.

We established a series of transects in alder shrublands of varying stand-age to test if alder expansion is facilitated by circle microsites, and to evaluate likely impacts of shrubland development on permafrost thermal regime. We recorded soil organic depth, mineral horizon thickness, soil temperature profiles, and Leaf Area Index (LAI) systematically along the transects and at alders. We learned that circles are "hotspots" of alder recruitment, and that the soil conditions and distribution of alders in older shrublands—where circles are obscured by vegetation—was consistent with initial recruitment on circles.

Maps showing locations of alders and circle-centers along two transects in alder expansion zones at Kharp. Squares are 1x1 m on both figures. Among small, densely-spaced circles, young alders are highly clumped about the margins of sorted-circles. Alders are also closely associated with large, widely-spaced circles.




## SIMULATING EFFECTS OF CLIMATE CHANGE AND GRAZING ON TUNDRA VEGETATION

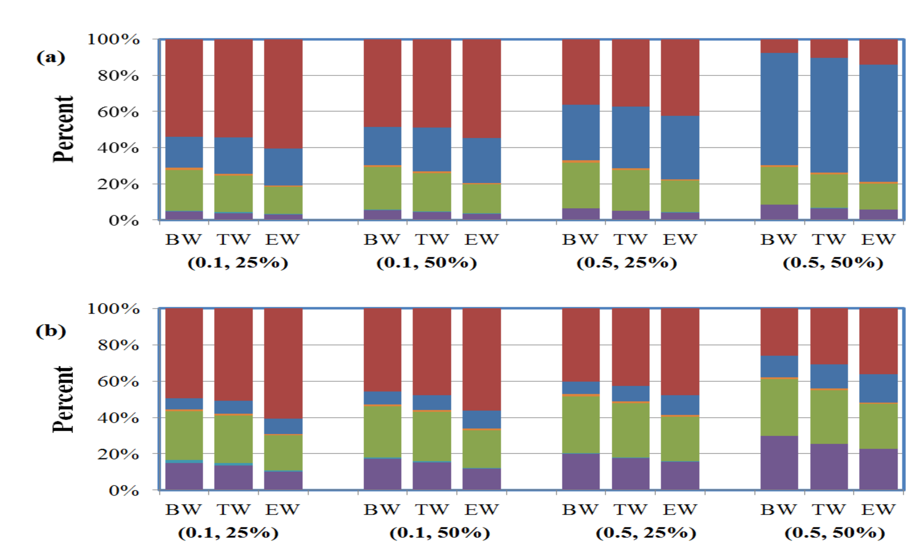
### Model setting

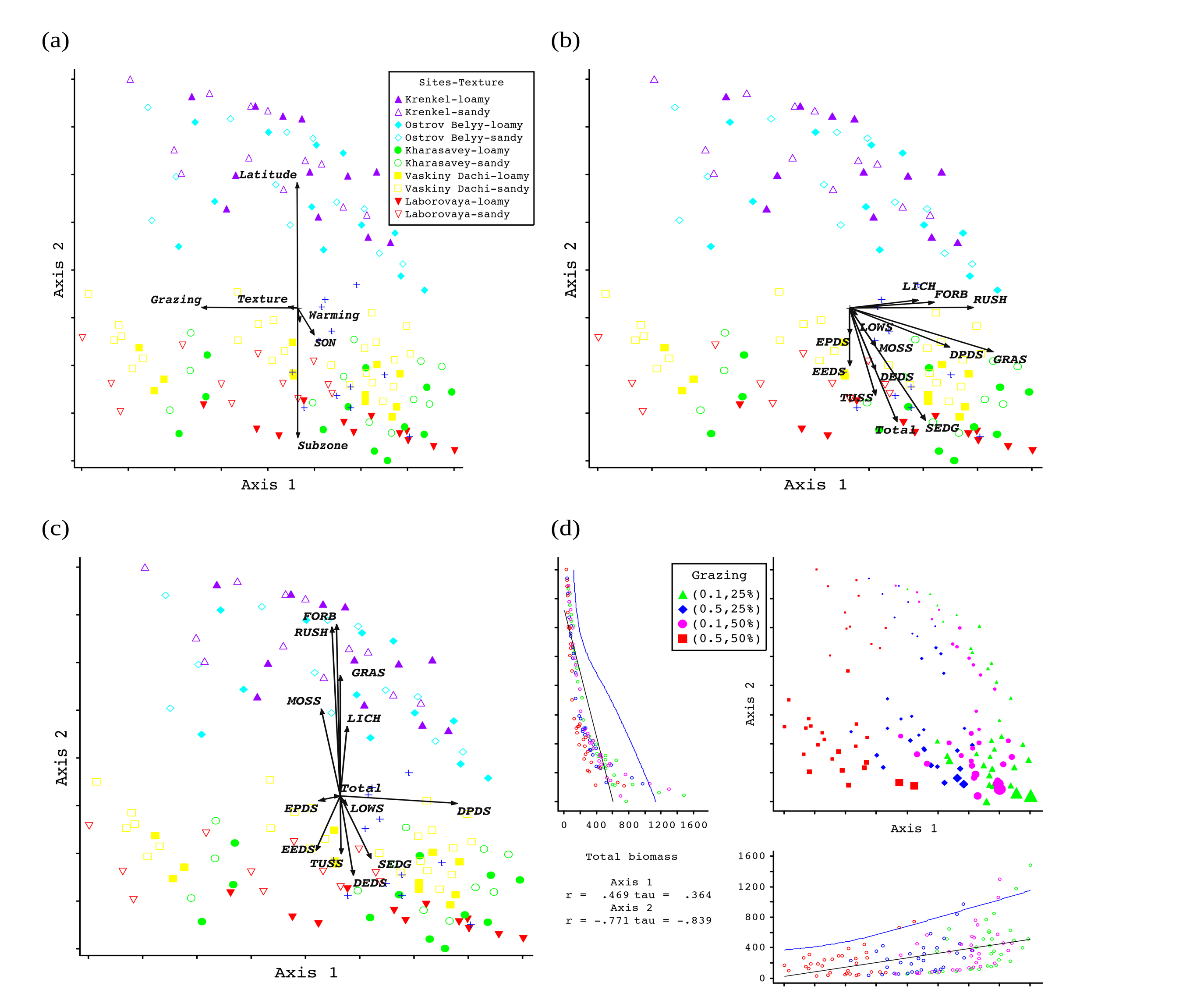
**ArcVeg simulations were conducted with field collected parameters:**

- **Bioclimate subzones**
- **Soil nutrients – soil organic nitrogen**
- **Grazing**: (0.1, 25%), (0.1, 50%), (0.5, 25%), (0.5, 50%)
- **Climate warming**: 2°c transient warming and equilibrium warming


| Subzone | sites | N% | %Sand | Active Layer Depth(cm) | SON (g/m^2) |
|---|---|---|---|---|---|
| A | KR-1 | 0.11 | 60.08 | 33.60 | 449 |
| A | KR-2 | 0.10 | 81.40 | 32.80 | 277 |
| B | BO-1 | 0.03 | 36.50 | 49.98 | 227 |
| B | BO-2 | 0.01 | 83.76 | 77.60 | 145 |
| C | KH-1 | 0.06 | 24.47 | 56.33 | 844 |
| C | KH-2 | 0.07 | 65.60 | 75.50 | 599 |
| D | VD-1 | 0.03 | 28.90 | 71.75 | 271 |
| D | VD-2 | 0.04 | 38.28 | 68.60 | 202 |
| D | VD-3 | 0.05 | 92.80 | 113.80 | 135 |
| E | LV-1 | 0.06 | 18.00 | 81.20 | 570 |
| E | LV-2 | 0.01 | 93.60 | 114.60 | 148 |

Table 1. Field collected data for model input




Understanding the responses of the arctic tundra biome to a changing climate requires knowledge of the complex interactions among climate, soils, and the biological system. This study investigates the individual and interactive effects of climate change and reindeer grazing across a variety of climate zones and soil texture types on tundra vegetation community dynamics using an arctic vegetation model that incorporates reindeer diet, where grazing is a function of both foliar nitrogen concentration and reindeer forage preference. We found that grazing is important in addition to the latitudinal climate gradient in controlling tundra plant community composition, explaining about 13% of the total variance in model simulations for all arctic tundra subzones. The decrease in biomass of caused by grazing such as lichen, deciduous shrub and graminoid plant functional types (PFTs) is potentially dampened by climate warming. Moss biomass had a nonlinear response to increased grazing intensity, and such responses were stronger when warming was present. Our results suggest that evergreen shrubs may benefit from increased grazing intensity due to their low palatability, yet a growth rate sensitivity analysis suggests that changes in nutrient uptake rates may result in different shrub responses to grazing pressure. Heavy grazing caused plant communities to shift from shrub tundra towards moss, graminoid-dominated tundra when evergreen shrub growth rates were decreased in the model. In response to warming, moss, lichen and forb biomass increased in High Arctic sites and declined in Low Arctic sites. Initial vegetation responses to climate change during transient warming (TW) are different from the long term equilibrium responses (EW) due to shifts in the controlling mechanisms (nutrient limitation vs. competition) within tundra plant communities.

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