Arctic Tundra Vegetation Dynamics under Changing Environmental Conditions

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Abstract

The Arctic is a system with strong interconnectedness among components and now is experiencing dramatic alterations due to climate change. With amplified climate warming and greater accessibility to the Arctic, anthropogenic factors such as industrial development, climate change, and animal husbandry have become increasingly important to arctic ecosystems. The objective of this dissertation is to use a vegetation model and remote sensing to better understand the dynamics of the arctic tundra biome in a chaning environment with emphasis on the effects of climate, soils, grazing and land use.

I examined the individual and interaction 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 dynamics model at regional and circumpolar scales. At the regional scale (on the Yamal Pensinula of northwestern Siberia), I found that grazing and warming affect tundra plant communities in opposite directions with significant interaction effects. The grazing impact can be the most important factor controlling tundra plant community composition and structure, aside from the latitudinal climate gradient. Grazing and warming can initiate shifts in tundra plant communities due to differential responses of different plant functional types. 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) on tundra plant communities.I also examined effects of climate change and grazing across the pan-Arctic and found that grazing can abate the tundra plant response to climate change and complicate our interpretation of the "greening" trend in the arctic tundra.

As land use has become a conspicuous factor that affects tundra plant communities, the magnitude of land cover and land use changes and the persistence of their effects remain unknown. I examined land use change effects on an oil/gas facility area at Nadym, Russia with multi-sensor and multi-temporal remotely sensed imagery. Exploration of oil/gas and associated development denuded surface vegetation and impacts of this development can last for several decades, although some recovery of vegetation was also found after extensive land use changes.

Changing climate interactions with grazing yielded complex responses in tundra vegetation. Additionally, land use as a controlling factor on tundra vegetation dynamics cannot be ignored in the Arctic, as vegetation recovers slower than in other parts of the world.

Table of contents

List of figures

List of tables

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Chapter 1: Introduction

Research background

The arctic tundra refers to a treeless region of the Northern Hemisphere where low temperatures and short growing season length limit growth of trees (ACIA 2004). The Arctic in general is a system with strong interconnectedness among components and now is experiencing dramatic changes due to climate warming (ACIA 2004; Walker, Epstein et al. 2008; Post, Forchhammer et al. 2009; Duarte, Lenton et al. 2012). Sea ice decline, permafrost thawing, and shrub expansion are examples of system dynamics that have made understanding the complexity of the Arctic in response to climate change rather challenging (Hinzman, Bettez et al. 2005; Tape, Sturm et al. 2006; Lawrence, Slater et al. 2008). Sea ice decline reduces albedo and may be a factor contributing to warming of arctic coastal areas, where vegetation has been increasing (Bhatt, Walker et al. 2010). Thawing permafrost can release CH_4 and CO_2 to the atmosphere as anaerobic and aerobic microbial decomposition of previously frozen organic carbon occurs -another positive feedback to the current positive temperature anomaly (Christensen, Johansson et al. 2004; Schuur, Bockheim et al. 2008; Tarnocai, Canadell et al. 2009). Expansion of shrubs in the arctic tundra region can result in surface albedo declines during periods of snow cover, concomitant surface energy budget changes, and increased CO_2 uptake by vegetation (Loranty, Goetz et al. 2011) - although there are still many unknowns about how shrub changes will affect soil and atmosphere at plot and regional scales (Blok, Heijmans et al. 2009; Lawrence and Swenson 2011). Terrestrial summer warming due to a lengthening of the snow-free season can also increase atmospheric heating, as exposed vegetation absorbs radiation otherwise reflected by snow (Bonan, Chapin et al. 1995). These changes and many others caused by climate warming have initiated feedbacks that make the understanding and prediction of arctic system dynamics extremely difficult.

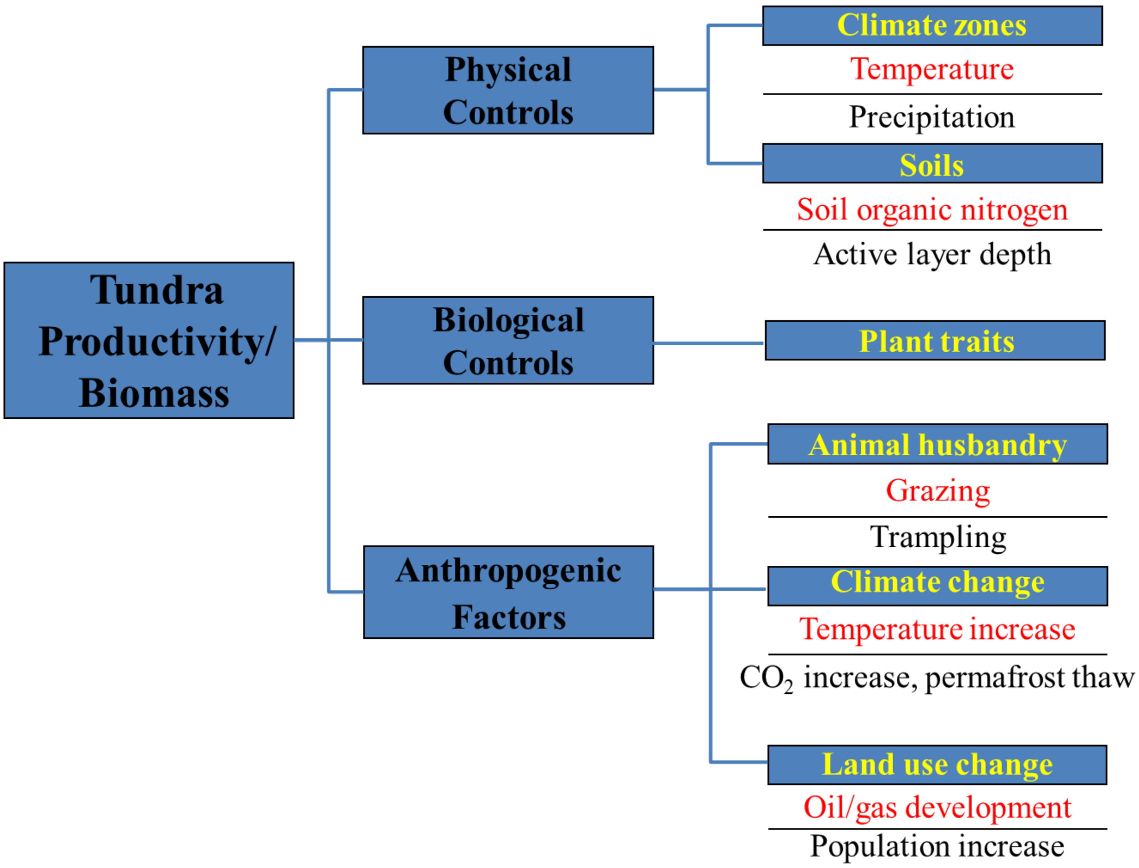
Anthropogenic footprints in the Arctic have added more complexity to our current efforts of better understanding the changing arctic environment (Forbes, Ebersole et al. 2001; Forbes, Stammler et al. 2009; Kumpula, Forbes et al. 2010; Walker, Forbes et al. 2010; Kumpula, Pajunen et al. 2011). Rapid population growth and increasing energy demand are prevalent in the once remote Arctic. Intense grazing of managed reindeer herds on tundra pastures, development of oil and gas fields, road networks, and associated activities have caused extensive land degradation (Forbes, Ebersole et al. 2001; Forbes, Boelter et al. 2006). These activities can either denude the land surface or cause dramatic vegetation decreases. The resultant land cover changes can alter surface albedo and other physical properties of the land surface, changing land-atmosphere interactions and energy budgets (Pielke 2002; Chapin, Sturm et al. 2005). Such feedbacks of land surface changes to the climate system may occur more rapidly in the Arctic than in other regions.

Arctic terrestrial ecosystems have been changing over the past several decades due to “amplified” climate warming. The decrease in sea ice extent has led to warming adjacent land (Serreze and Barry 2011) and is likely contributing to a general “greening” of the Arctic (Bhatt, Walker et al. 2010). Using the Normalized Difference Vegetation Index (NDVI) derived from Advanced Very

High Resolution Radiometer (AVHRR) data, a “greening” trend in arctic tundra vegetation consistent with increasing temperatures has been reported (Jia, Epstein et al. 2003; Jia, Epstein et al. 2009). Shrub expansion in the Arctic, presumably caused by warming, has been captured by studies using repeat aerial photographs (Sturm, Racine et al. 2001; Tape, Sturm et al. 2006). Changes in these ecosystems play a significant role in the regional energy balance and carbon budget (Foley, Levis et al. 2000; Chapin, Randerson et al. 2008). Interacting controls on arctic tundra vegetation dynamics are therefore crucial to understand.

Arctic tundra biomass and productivity are determined internally by plant biological traits and externally by physical and anthropogenic controls such as climate, nutrient availability and disturbances (Figure 1.1). Low temperatures and short growing season length strongly limit plant growth (Chapin 1992). Increasing temperature and lengthening of the growing season caused by climatic warming will promote vegetation growth directly and increase decomposition and nutrient availability to plants (Rustad, Campbell et al. 2001; Borner, Kielland et al. 2008). Tundra plant communities are strongly limted by nitrogen availability (Kielland 1994). Warming-induced early snow melt and shrub expansion can positively contribute to atmospheric heating (Chapin, Sturm et al. 2005). Disturbances such as grazing and land use change pose another threat to these plant communities (Forbes, Ebersole et al. 2001; Forbes, Stammler et al. 2009). However, the extent to which tundra will respond to changes in climate, land cover and land use and their interactions is unknown.

FIGURE 1.1 A subset of controls on tundra vegetation biomass and plant productivity. The factors highlighted in red are addressed in this dissertation.



Research objectives

The goal of this research is to evaluate effects of zonal bioclimate, climate change, soils, and grazing-associated land use on tundra vegetation dynamics on the Yamal Peninsula in northwestern Siberia, Russia and at the pan-arctic scale. I have also evaluated land use change effects on vegetation and surface properties focusing on northwestern Siberia. This research directly contributed to National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) funded projects, which aimed to understand “greening of the Arctic” at the pan-arctic scale and cumulative effects of rapid land-cover and land-use changes on the Yamal Peninsula, Russia (Walker, Forbes et al. 2010; Walker, H.E.

Epstein et al. 2010; Walker, Epstein et al. 2012). The main research questions of this disertation are:

1) How do individual and interaction effects of climate change and grazing on tundra vegetation in terms of total biomass, net primary production (NPP) and plant community structure across gradients of climate (summer warmth) and soil organic nitrogen (SON) at the regional scale on the Yamal Peninsula, Russia?
2) How do individual and interactiion effects of grazing and warming differ in respect to subzone, country and floral provinces at the circumpolar scale?
3) To what extent has land use changed and how does the change affect tundra ecosystems on the Yamal Peninsula, Russia?

Research approaches

Simulation modeling is a methodology that can combine data from observations and experiments, and can provide insights into understanding the processes behind observed changes (Bonan, Levis et al. 2003; Epstein, Kaplan et al. 2007; Sitch, McGuire et al. 2007). I use an arctic tundra vegetation dynamics model – ArcVeg- to investigate individual and interaction effects of bioclimate subzone, soils, climate change and grazing-associated land use on tundra plant community properties at regional and circumpolar scales.

Remote sensing monitors earth systems at various spatial scales and potentially over long time periods. Information from remote sensing and modeling can complement ground-based observations, which are often expensive and difficult in remote regions like the Arctic. The Yamal Peninsula is home to the Nenets people and is the largest area of reindeer husbandry in the world. This remote land was used only by the Nentsy indigenous group prior to 1964, when the first gas fields were discovered. I use both multi-sensor and multi-temporal remotely sensed imagery to understand how land use has changed and how the changes affect tundra vegetation and surface properties in terms of derivatives from remotely sensed images.

ArcVeg is a vegetation dynamics model simulating tundra plant types. It was originally developed by Epstein et al. in 2000 and has been applied in studies in North American arctic tundra. The current version of the model simulates 12 different plant functional types and is parameterized for five arctic subzones (Epstein et al. 2007). Tundra vegetation is strongly limited by plant available nitrogen (Chapin et al . 1992), which is adopted by ArcVeg as the main assumption. ArcVeg essentially simulates nitrogen mass balance, moving nitrogen among three main pools including soil organic matter, plant available nitrogen through nitrogen mineralization and nitrogen fixation (soil inorganic nitrogen), and plant nitrogen by functional type. The processes that control the nitrogen fluxes are climate and grazing. The model simulates plant growth on an annual time step with growing season divided into five distinct plant-growth periods. The plants are parameterized with a set of intrinsic plant traits such as nitrogen uptake efficiencies by plant-growth period, the biomass to nitrogen ratio, annual proportion of plant material senescing, probability of seedling establishment and cold tolerance for growth. For example, in High Arctic (subzone A) only certain non-vasular plants can grow due to their capability to endure cold growth periods. However, in Low Arctic, erect-dwarf shrubs can grow faster than these non-vasular plant types and outcompete them in the way of greater nitrogen uptake.

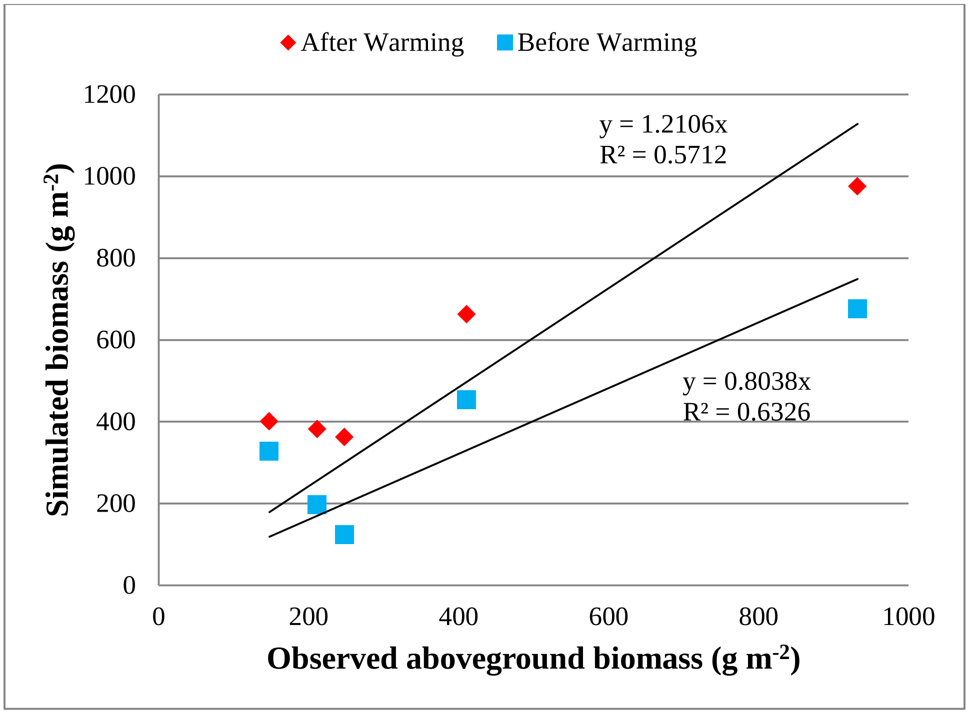
Model validation was conducted using field data from North American Arctic Transect. Since the model was originially developed for mesic tundra, I used the field-collected data in mesic sites including soil organic nitrogen, and latitude (subzone) to simulate aboveground total biomass (Table 1. 1). In total I simulated for 1500 years. At year 1000, a 2 °C warming was imposed and ramped linearly for 50 years, after that, the climate stayed at the warmer state for another 450 years.

TABLE 1.1 Input data to ArcVeg from mesic sites in North America Arctic Transect (NAAT).

Site	Vegetation Type	Subzone	Soil Organic Nitrogen (Active Layer) g m^{-2}	Summer Warmth Index (°C)
Isachsen	Mesic tundra	A	1110	4
Mould Bay	Mesic tundra	B	850	7
Green Cabin	Mesic tundra	C	1090	13
Deadhorse	Moist non-acidic tundra (MNT)	D	1010	19
Sagwon	Moist acidic tundra (MAT)	E	1160	31

Biomass from year 1000 and year 1050 as before and after warming scenarios was used respectively, and then was compared to the field collected aboveground biomass (Figure 1.2). Comparing model simulate biomass to field-measured biomass, the model overrestimated the aboveground biomass during before warming scenario while underestimated the biomass during after warming scenario.

FIGURE 1.2 Comparison of simulated biomass for before and after warming scenarios with field collected biomass in North America Arctic Transect.



Thesis structure

In chapter 2, I examine the individual and interaction effects of climatic subzones, soil organic nitrogen, grazing, and warming on the tundra vegetation of the mainland Yamal Peninsula. In chapter 3, I examined these effects on plant functional type biomass across all five tundra subzones of the Eurasian Arctic Transect (Walker, Epstein et al. 2012). For this chapter, I improved the grazing function in ArcVeg by incorporating both reindeer diet and foliar N concentration. In chapter 4, I examined grazing and climate change effects on aboveground tundra plant community biomass and NPP across the circumpolar Arctic. In chapter 5, I investigated land use change impacts in a region with a history of oil/gas development using multi-sensor and multi-temporal remotely sensed images.

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Chapter 2: Simulating the effects of soil organic nitrogen and grazing on arctic tundra vegetation dynamics on the Yamal Peninsula, Russia[1]

Abstract

Sustainability of tundra vegetation under changing climate on the Yamal Peninsula, northwestern Siberia, home to the world’s largest area of reindeer husbandry, is of crucial importance to the local native community. An integrated investigation is needed for better understanding of the effects of soils, climate change and grazing on tundra vegetation in the Yamal region. In this study we applied a nutrient-based plant community model -ArcVeg- to evaluate how two factors (soil organic nitrogen [SON] levels and grazing) interact to affect tundra responses to climate warming across a latitudinal climatic gradient on the Yamal Peninsula. Model simulations were driven by field-collected soil data and expected grazing patterns along the Yamal Arctic Transect (YAT), within bioclimate subzones C (High Arctic), D (northern Low Arctic) and E (southern Low Arctic). Plant biomass and NPP (net primary productivity) were significantly increased with warmer bioclimate subzones, greater soil nutrient levels and temporal climate warming, while they declined with higher grazing frequency. Temporal climate warming of 2 °C caused an increase of 665 gm^{-2} in total biomass at the high SON site in subzone E, while only 298 gm^{-2} in the low SON site. When grazing frequency was also increased, total biomass increased by only 369 gm^{-2} in the high SON site in contrast to 184 gm^{-2} in the low SON site in subzone E. Our results suggest that high SON can

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[1] **Yu, Q.**, H. E. Epstein, D.A. Walker. 2009. Simulating soil organic nitrogen and grazing effects on arctic tundra vegetation on Yamal Peninsula, Russia. Environmental Research Letters 4 (4): 045027.

support greater plant biomass and plant responses to climate warming, while low SON and grazing may limit plant response to climate change. In addition to the first order factors (SON, bioclimate subzones, grazing and temporal climate warming), interactions among these significantly affect plant biomass and productivity in the arctic tundra and should not be ignored in regional scale studies.

Key words: soil organic nitrogen, grazing, ArcVeg, modeling, multi-factor analysis

1. Introduction

Arctic tundra vegetation dynamics are affected by various environmental factors such as climate, soil nutrients, and animal grazing (Chapin 1992; Callaghan, Bjoern et al. 2004; Epstein, Walker et al. 2008). These controlling factors have been individually studied in the field (Arft, Walker et al. 1999; Hansen, Jonasson et al. 2006; Epstein, Walker et al. 2008; Gough, Shrestha et al. 2008). However, few studies have collectively examined the combinations of these factors and can provide insights as to how these factors may interact and affect tundra vegetation communities (Richardson, Press et al. 2002; Gough, Ramsey et al. 2007).

Temperature is a key factor that regulates plant community distribution and biomass in arctic tundra (Walker, Raynolds et al. 2005; Epstein, Walker et al. 2008). Across a climatic gradient, aboveground shrub biomass was found to increase substantially with summer warmth index (SWI–sum of mean monthly temperatures > 0°C) (Walker, Jia et al. 2003; Epstein, Walker et al. 2008). A global temperature increase of 0.76°C ± 0.19°C from 1850-1899 to 2001-2005 (IPCC, 2007) may be amplified in the Arctic (Serreze and Francis 2006) and be responsible for a recent increase in arctic vegetation in general as well as an increase in the abundance of shrubs (Myneni, Keeling et al. 1997; Sturm, Racine et al. 2001; Jia, Epstein et al. 2003; Forbes, Macias Fauria et al. 2009). Warming generally promote tundra plant growth but may vary across climatic zones over time (Arft, Walker et al. 1999).

Soil substrate and nutrient levels in arctic tundra are also determinants of species richness, vegetation growth and productivity (Nadelhoffer, Giblin et al. 1991; Gough, Shaver et al. 2000; Knoepp, Coleman et al. 2000; Walker, Jia et al. 2003; Walker, Epstein et al. 2003). In nitrogen limited arctic ecosystems, soil organic matter quality may be more important in controlling N mineralization rates than temperature, since during the growing season, temperatures typically stay between 0° and 10° C (Nadelhoffer, Giblin et al. 1991). Observations from N fertilization experiments in the Arctic have shown increases in plant biomass of several plant species as well as increases in litter decomposition with increasing available N (Shaver and Chapin 1995; Jonasson, Michelsen et al. 1999; Aerts, van Logtestijn et al. 2006; Shaver, Giblin et al. 2006; Kelley and Epstein 2009).

In the Arctic, herbivores can have positive or negative effects on plant growth and yield various tundra vegetation community shifts depending on the grazing intensity and frequency (Jefferies, Svoboda et al. 1992; Olofsson, Kitti et al. 2001; Herder, Kytoeviita et al. 2003; van der Wal 2006; Susiluoto, Rasilo et al. 2008). Grazing can also interact with soils to affect plant biomass. This was explored by Gough et al (2007) who manipulated soil nutrient levels in two arctic Alaskan tundra sites to study plant-herbivore interactions at the species level. Their results suggested that herbivores may cause reductions in plant biomass and shifts in competitive relationships in plant communities. Such relationships among soils, herbivores and vegetation can be further examined using vegetation modeling approaches.

Vegetation modeling has been widely used to improve our understanding of potential impacts of changing environmental variables on vegetation structure and function, e.g. (Clein, Kwiatkowski et al. 2000; Sitch, Smith et al. 2003; van Wijk 2007; Wolf, Callaghan et al. 2008). ArcVeg is a dynamic vegetation model of arctic tundra that has been applied to various tundra communities in Alaska and Canada (Epstein, Walker et al. 2000; Epstein, Chapin et al. 2001; Epstein, Calef et al. 2004; Epstein, Kaplan et al. 2007). Soils are parameterized essentially as the mass of soil organic nitrogen (SON), and grazing is an important disturbance parameterized in the model. Climate warming can be applied in the model simulation based on a subzonal approach. In other words, a summer warming of 2°C for an initial subzone is essentially a replacement by the climate at the adjacent southern subzone. Prior simulations using ArcVeg have shown increases in shrub biomass and reductions in moss biomass with summer warming of 2°C ramped over 50 years. This is consistent with field observations, indicating the applicability of this model for projecting vegetation responses to climate warming (Epstein, Calef et al. 2004; Epstein, Kaplan et al. 2007).

The Yamal Peninsula is a large area of arctic tundra in northwestern Siberia, Russia that encompasses landscape to regional gradients of each of these three environmental factors: climate, soil nutrients, and grazing (Forbes 1999).

The Yamal is not only the source of much of Europe’s current and future energy resources, and as a result is of enormous strategic importance to Russia, but it is also the world’s largest area of reindeer husbandry (Stammler 2005; Forbes and Kumpula 2009). Sustainability of tundra vegetation under changing climate is of special importance to the people who rely on reindeer husbandry for their livelihood (Forbes, Ebersole et al. 2001) and requires a good understanding of the interactions among soils, grazing, and warming (Kryazhimskii and Danilov 2000).

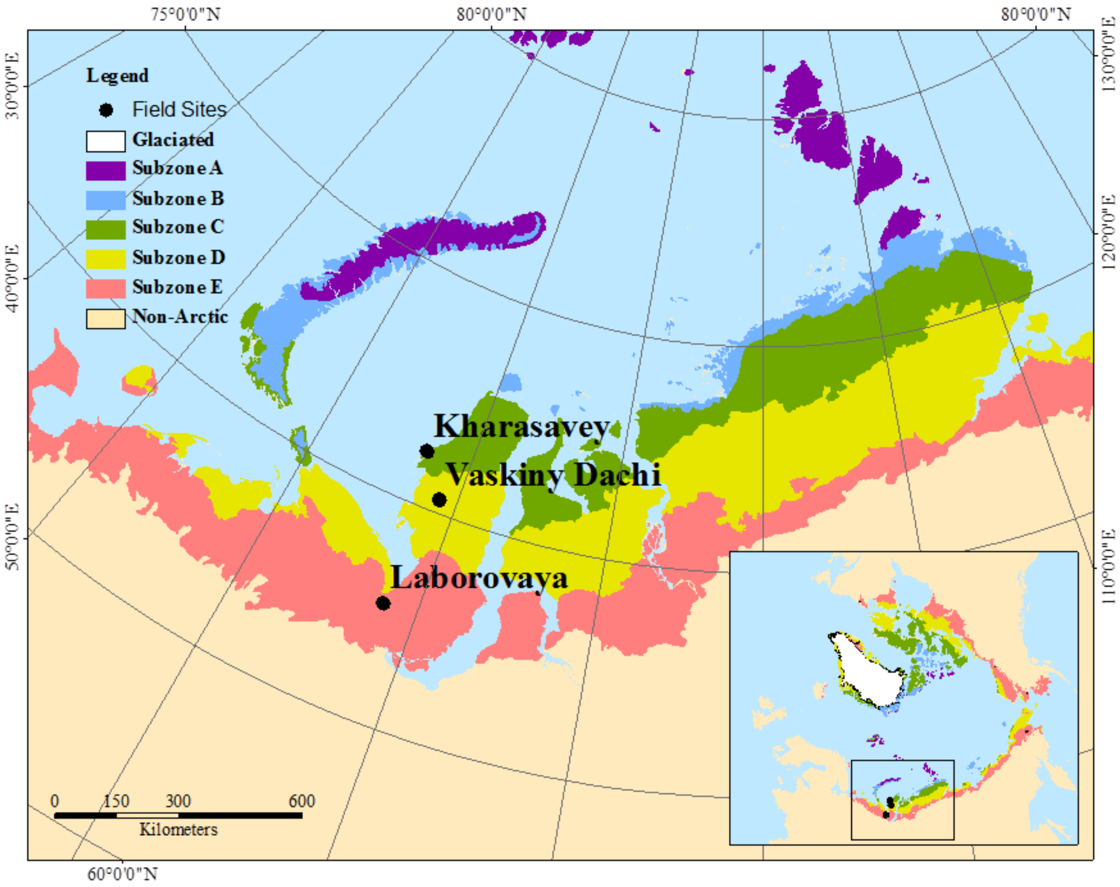
In this study, we use ArcVeg to address the effects of climatic subzones, soil organic nitrogen, grazing, and warming on the tundra vegetation of the Yamal Peninsula. We aim to answer the following research questions: 1) How do SON levels affect tundra vegetation in terms of total biomass and net primary productivity (NPP) responses to warming? 2) How does grazing affect tundra vegetation in terms of total biomass and NPP? 3) How do SON, grazing and climate interact to affect tundra vegetation?

2. Methods and Materials

2.1 Study area

The study encompasses locations along a bioclimatic transect on the Yamal Peninsula, northwestern Siberia. Figure 2.1 shows the relative locations of the field sites in this study: 2 sites near Laborovaya (67°42´N, 68°01´E), 3 sites near Vaskiny Dachi (70°17´N, 68°54´E), and 2 sites near Kharasavey (71°19´N, 66°95´E). The most southern site Laborovaya lies about 100km north of treeline within the southern tundra subzone, dominated by *Carex bigelowii*, *Betula nana*, *Aulacomnium palustre* sedge, moist dwarf-shrub, moss tundra on moist silt loamy soils (site 1) and *Betula nana*, *Vaccinium vitis-idaea*, *Sphaerophorus globosus*, *Polytrichum strictum*, prostrate dwarf-shrub, lichen tundra on more sandy site (site 2). Vaskiny Dachi is to the southeast of the main Bovanenkova gas field in the central part of the Yamal Peninsula. Soils in each site vary from silt loam (site 1), silt loam and sandy loam (site 2), and sand (site 3) and different soils are associated with different vegetation covers. For site 1, the dominant vegetation is *Carex bigelowii*, *Vaccinium vitis-idaea*, *Hylocomium splendens* sedge, dwarf-shrub, moss tundra; site 2 is dominated by *Betula nana, Calamagrostis holmii*, *Aulacomnium turgidum* dwarf shrub, graminoid, moss tundra; and site 3 is *Vaccinium vitis-idaea*, *Cladonia arbuscula*, *Racomitrium lanuginosum* prostrate dwarf-shrub, sedge, lichen, tundra. Kharasavey is the most northern region in this study and is located on the northwestern coast of the peninsula. Vegetation in this region includes *Carex bigelowii*, *Calamagrostis holmii*, *Salix Polaris*, *Dicranum elongatum*, *Cladonia spp*. graminoid, prostrate dwarf-shrub, and moss tundra on silt loamy soils (site 1) and *Carex bigeolowii*, *Salix nummularia*, *Dicranum spp*., *Cladonia spp*. graminoid, prostrate dwarf-shrub, and moss, lichen tundra on the sand loamy soils (site 2). These three regions are used as summer and autumn pasture for reindeer. More detailed information on each site can be found in the data report of the 2007 and 2008 Yamal expeditions (Walker, Epstein et al. 2009), and studies associated with the sites along the Yamal transect can be found in the following: (Goetz, H.E. Epstein et al. 2009; Walker, Leibman et al. 2009; Walker, U.S. Bhatt et al. 2009).

Figure 2.1 Field sites along the Yamal Arctic Transect (YAT) in mainland Yamal, Russia.



2.2 Model description

2.2.1 ArcVeg

ArcVeg is a nutrient-based, transient vegetation dynamics model, which was originally developed with a set of detailed plant functional types (PFT) to simulate how tundra vegetation represented by these PFTs responds to climate change. Since plant-available nitrogen can be a strongly-limiting nutrient for tundra plants (Chapin, Shaver et al. 1995; Shaver, Canadell et al. 2000), the model functions essentially with nitrogen mass balance, redistributing nitrogen among soil organic matter, plant available nitrogen, and plant pools. The current version of ArcVeg comprises 12 plant types, including mosses, lichens, forbs, and several categories of graminoids and shrubs (Epstein, Kaplan et al. 2007). ArcVeg has been parameterized for the five arctic bioclimate subzones (Walker, Raynolds et al. 2005) that range from the polar desert (Subzone A) to the Low Arctic tundra at the southern extent of the tundra biome (Subzone E). Soil conditions are expressed as different levels of soil organic nitrogen. A key assumption of the model is that with higher temperatures, decomposition rates increase, thus increasing the availability of soil nitrogen, which facilitates plant growth.

In addition, grazing as a major disturbance to tundra vegetation is parameterized as the removal of a specified percentage of plant biomass with different interannual frequencies. In other words, grazing intensity is represented by the combination of frequency and percent removal. For example, (0.1, 25) indicates that there is a 0.1 annual probability of a grazing herd (i.e. every 10 years frequency) and a maximum of 25% biomass will be removed. One of the model assumptions is that selectivity of grazing is determined by foliage nitrogen concentration.

2.2.2 Model input data and simulation procedures

Soil samples from each of the Yamal field sites have been collected and analyzed for bulk density, soil organic carbon, and soil organic nitrogen to the depth of the active layer. Each of the three field locations had two or three separate sampling grids to capture the variability of soil properties. The soil organic nitrogen data are used to drive the simulations in ArcVeg (Table 2.1).

Table 2.1 Site name, bioclimate subzone, and soil parameters on the Yamal Arctic Transect.

Subzone	sites	C%	N%	%Sand	%Silt	%Clay	Bulk Density (gm^{-3})	Active Layer Depth(cm)	SON (gm^{-2})
E	LV-1	1.72	0.06	18.00	59.32	22.68	1.21	81.20	570
E	LV-2	0.59	0.01	93.60	3.60	2.80	1.29	114.60	148
D	VD-1	1.25	0.03	28.90	60.80	10.30	1.34	71.75	271
D	VD-2	1.46	0.04	38.28	53.88	7.84	1.37	68.60	202
D	VD-3	1.31	0.05	92.80	4.64	2.56	1.18	113.80	498
C	KH-1	1.10	0.06	24.47	52.07	23.47	1.47	56.33	484
C	KH-2	1.18	0.07	65.60	26.60	7.80	1.22	75.50	599

Other input data include: bioclimate subzone, grazing intensity, and climate warming. Two sites near Laborovaya (LV-1, LV-2) are located in the southern low Arctic (subzone E). Three sites at Vaskiny Dachi (VD-1, VD-2 and VD-3) are within bioclimate subzone D, and two sites at Kharasavey (KH-1, KH-2) are in subzone C. The Yamal region is home to the indigenous Nenets people. Reindeer population increases have been documented by various authors (Golovnev and Osherenko 1999; Baskin 2000), and the drivers are quite complex as noted in Forbes and Kumpula (2009). Grazing patterns are quite heterogeneous and have been observed and modeled in various rangelands (Pickup and Chewings 1988; Stammler 2005). For managed reindeer herds on the Yamal, grazing is most intense near migratory Nenets camps and dissipates outward from the camps (Forbes and Kumpula 2009). We conducted a comparison study of grazing and soil effects across sites in different bioclimate subzones within a model simulation. The control grazing regime was set as (0.1, 25), indicating reindeer herds will graze on the same site every ten years and each visit a maximum of 25 percent of total biomass will be removed. A more frequent grazing regime is set as (0.5, 25), 25% of plant biomass will be removed every two years. These grazing scenarios are within the reasonable ranges that can be typically found in the Yamal region. Model simulations were conducted for 1500 years in total with a “spin-up” to equilibrium conditions for the first 1000 years. A warming scenario was implemented in the model by beginning a temperature increase of 2 °C (essentially a shift of one subzone) in year 1000, ramped linearly over a 50 year period. Then the system was simulated under the new warmer climate for another 450 years.

All parameter combinations (including subzone (3), SON (7), grazing regime (2) and warming or non-warming) were simulated with 20 replicate runs. Plant total biomass and NPP were compared and evaluated across all sites on the Yamal Peninsula under the different grazing regimes and one subzone climate warming as discussed above. We calculated the mean total biomass and NPP for 100 years before the warming (year 901 to year 1000) and for 100 years after warming (year 1401 to year 1500).

2.2.3 Statistical analyses

Simulated total biomass and NPP with 20 replicates were used as dependent variables in ANOVA (Analysis of Variance). The main effects were soil organic nitrogen (continuous variable), climate subzones, climate warming, and grazing (categorical variables). The interactions of the main effects were also included in the ANOVA. LSMEANS (Least Square Means) and Type III SS (Type III Sums of Squares) were used to account for the unbalanced data. All statistics were performed in SAS version 9.1 for Windows (SAS institute Inc.).

3. Results

The statistical analyses show that bioclimate subzones, SON, warming, and grazing have significant effects on total biomass and NPP individually (see Appendix). SON is the most important factor with the highest F value, suggesting the most significant effects on total biomass and NPP. All interactions were also significant.

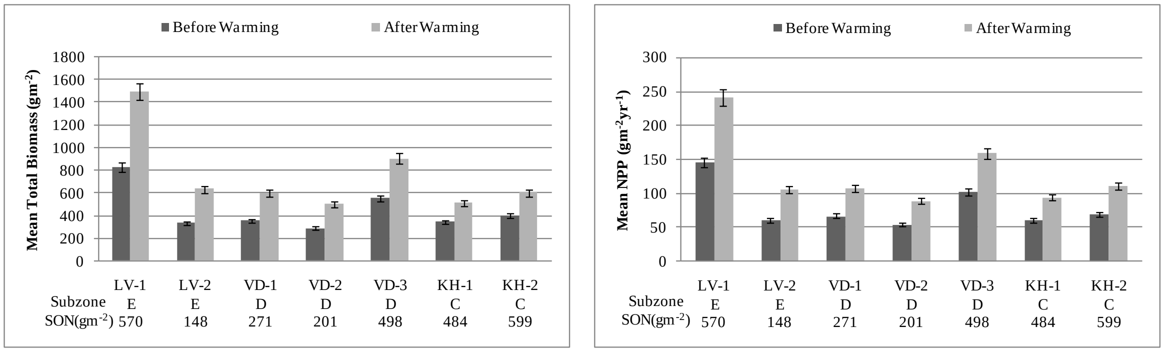
3.1 Soil organic nitrogen effects on biomass and NPP across climate subzones (Figure 2.2 – Before warming)

Soil organic N significantly affected plant total biomass and NPP. In each bioclimate subzone, lower soil organic N supported less vegetation than higher soil organic N (Figure 2.2). In particular, in the high SON site in subzone E (Laborovaya, LV-1), both total biomass and NPP were approximately 148% and 143% higher than those of the low SON site (LV-2) before warming. In LV-1 (SON = 570 gm^{-2}), the soil supported nearly 831 gm^{-2} biomass while only 336 gm^{-2} biomass was simulated in LV-2 (SON = 148 gm^{-2}). Effects of SON on total biomass and NPP changed with different climate subzones. With a similar amount of SON, warmer bioclimate subzones (e.g. subzone E) supported more vegetation and higher plant growth rates than colder subzones (e.g. subzone C) (Figure 2.2). For example, total biomass and NPP at LV-1 were around 831 gm^{-2} and 146 gm^{-2}year^{-1} whereas in KH-2 (SON = 599 gm^{-2}), total biomass and NPP were 554 gm^{-2} and 70 gm^{-2}year^{-1} respectively. With similar amounts of SON (LV-1 vs. KH-2), each gram of SON can support 0.79 gm^{-2} more biomass and 0.14 gm^{-2}year^{-1} greater NPP in subzone E than in subzone C.

3.2 Warming effects on total biomass and NPP across sites (Figure 2.2- Before and after warming comparison)

Temporal warming from our simulations with low grazing frequency showed an absolute increase in total biomass of 665 gm^{-2} (absolute change will be shown following any relative change in parentheses: 80%) in the high SON site (LV-1) and about 298 gm^{-2} (89%) in the low SON site (LV-2). The absolute and relative increase in NPP in subzone E was found to be 95 $gm^{-2}year^{-1}$ (65%) in LV-1 and 46 $gm^{-2}year^{-1}$ (77%) in LV-2. For the set of sites in subzone D, the increases in biomass and NPP were 351 gm^{-2} (63%) and 57 $gm^{-2}year^{-1}$ (56%) in VD-3, 214 gm^{-2} (75%) and 35 $gm^{-2}year^{-1}$ (64%) in VD-2, and 246 gm^{-2} (70%) and 40 $gm^{-2}year^{-1}$ (61%) in VD-1 respectively, with higher relative increases in both total biomass and NPP in low SON sites compared to in high SON sites.

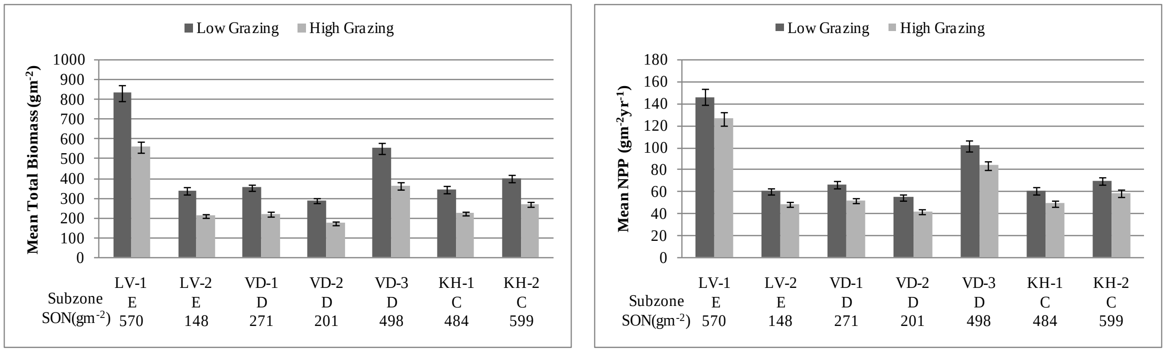
FIGURE 2.2 Comparison of mean total biomass (left) and NPP (right) (error bars show the 95% confidence intervals) before and after warming along the YAT for the low grazing frequency regime for each site. subzone and soil organic nitrogen (SON, g/m^2) are noted on the x-axis.



3.3 Grazing effects on total biomass and NPP (Figure 2.3)

Grazing generally caused total plant biomass and NPP to decrease. Under the same climate conditions (here we used the data before climate warming), the absolute decline in total biomass caused by increased grazing frequency varied with SON levels. For example, comparing the sites in Vaskiny Dachi (subzone D), declines in biomass were found when grazing frequency increased from every ten to every two years: a decline of 191 gm^{-2} in the high SON site (VD-3), 114 gm^{-2} in VD-2 (the low SON site) and 135 gm^{-2} in VD-1 (Figure 3.3). This was also true for NPP, where we simulated a decrease of 18 gm^{-2}year^{-1} in VD-3, 15 gm^{-2}year^{-1} in VD-1 and 13 gm^{-2}year^{-1} in VD-2.

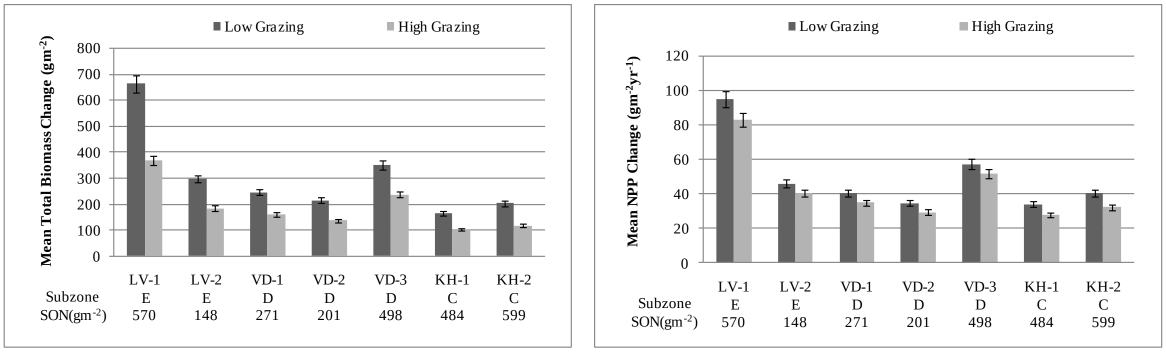
FIGURE 2.3 Comparison of change in mean total biomass (left) and NPP (right) (error bars show the 95% confidence intervals) for each site under two grazing regimes (low frequency grazing: (0.1, 25%) and high frequency grazing: (0.5, 25%)).



3.4 Grazing and warming interactions on total biomass and NPP (Figure 2.4)

Grazing also interacted with climate warming, suppressing plant biomass and NPP response to warming. The suppression was stronger in sites with higher SON content than in the sites with lower SON content. The positive response of total biomass to warming was reduced from 665 gm^{-2} in LV-1 to 369 gm^{-2} due to higher grazing frequency (Figure 2.4). In comparison, the total biomass increase due to warming in LV-2 site was decreased from 298 gm^{-2} to 194 gm^{-2}. The NPP response decreased from 95 gm^{-2} year^{-1} to 83 gm^{-2} year^{-1} in LV-1 and from 46 gm^{-2} year^{-1} to 41 gm^{-2} year^{-1} in LV-2. Greater response declines in the high SON site (KH-2 - 8 gm^{-2} $year^{-1}$) than the low SON site (KH-1 - 6 gm^{-2} $year^{-1}$) were also found in subzone C.

Figure 2.4 Comparison of absolute increase in mean total biomass (left) and NPP (right) (error bars show the 95% confidence intervals) caused by climate warming for each site under two grazing regimes (low frequency grazing: [0.1,25%] and high frequency grazing : [0.5,25%]).



4. Discussion

The results of this study demonstrate how tundra vegetation on the Yamal Peninsula in northwestern Siberia may respond to warming and grazing with different soil nutrient levels associated with different soil substrates across a climatic gradient. Climate and soil nutrient levels (especially nitrogen) in arctic soils determine how much vegetation a site can support. Our results of total biomass and NPP being intimately coupled with arctic temperature gradients are consistent with field studies, where above ground biomass increased exponentially or linearly across a temperature gradient (Walker, Jia et al. 2003; Epstein, Walker et al. 2008).

Soil organic nitrogen as a major limiting nutrient to arctic vegetation is found to be conspicuously important. High SON levels which tend to occur on clayey soils can facilitate plant growth and have a large impact on tundra vegetation (Chapin 1992). In high SON sites, simulated absolute increases in NPP with warming are greater than those in low SON sites (sandy soil substrates), which is consistent with N fertilization experiments (Chapin and Shaver 1996; Shaver and Jonasson 1999; Shaver, Giblin et al. 2006). However, with the same grazing regime, nutrient poor sites generally have higher SON efficiency (defined as model-simulated NPP divided by SON) than nutrient rich sites. For example, SON efficiency calculated before warming was about 0.26 in LV-1 (SON=570 gm^{-2}) and 0.40 in LV-2 (SON = 148 gm^{-2}). With climate warming, SON efficiency increased to 0.42 in LV-1 and to 0.72 in LV-2. The simulation results suggested that plants tend to make better use of SON in nutrient poor sites than nutrient rich sites, probably due to more intense resource competition in nutrient limited sites.

One of the assumptions of ArcVeg is that climate warming increases soil organic matter decomposition rates (Epstein, Walker et al. 2000). In the arctic, growth of tundra vegetation is limited by extreme low temperatures and short growing seasons, which result in low decomposition rates and low nutrient availability to plants (Chapin 1992; Hobbie and Chapin 1998). Increasing temperature may increase nitrogen mineralization rates in the Arctic and provide plants with more nutrients, thus increasing plant biomass and productivity (Nadelhoffer, Giblin et al. 1991; Hobbie 1996; Rustad, Campbell et al. 2001; Jonasson, Castro et al. 2006). A meta-analysis of the results from 32 research sites across the arctic region show an increase of net N mineralization rates by 46% (with a 95% confidence interval of 30-64%), and plant productivity by 19% (with a 95%

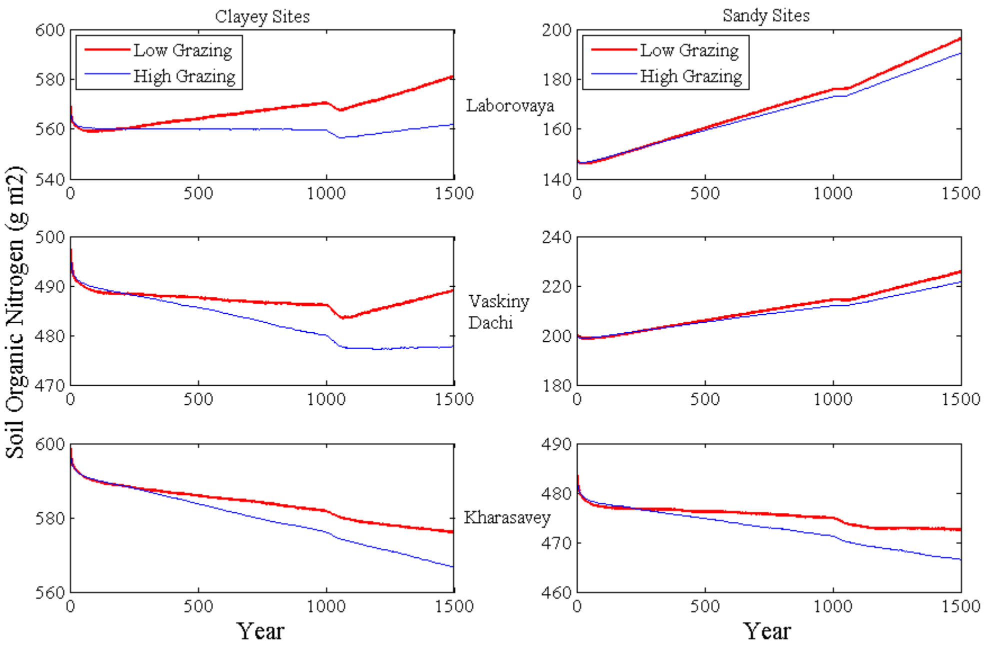
confidence interval of 15-23%) in response to experimental ecosystem warming in the range 0.3-6.0°C for 2-9 years (Rustad, Campbell et al. 2001). Toolik Lake in Alaska was included in the meta-analysis, and the responses of soil respiration to warming were found to be larger than the grand mean of the 32 sites. Some field warming experiments in the Arctic can however show an increase in net N immobilization rather than net N mineralization, but this may be due to the short observation period (Aerts, van Logtestijn et al. 2006).The climate gradient and warming scenarios were treated as separate factors that affect vegetation growth in ArcVeg. In both, temperature is positively related to total plant biomass and NPP. Climate warming effects on tundra vegetation communities have been addressed in several field experiments and the effect size of climatic warming is generally the greatest in the southern Low Arctic (Arft, Walker et al. 1999). Our model simulations are consistent with these results. The warming stimulation effects decrease for colder subzones. In LV-1 (Subzone E), the relative increase in NPP caused by warming is about 65%, while in KH-2 (Subzone C, SON = 599 gm^{-2}) the increase is only 58%.

Reindeer grazing was evaluated in this study by comparing a control grazing regime (0.1, 25) with an increased grazing frequency (0.5, 25). Soil nutrient conditions interact with grazing to yield complex effects on vegetation (Virtanen 2000; Gough, Ramsey et al. 2007; Eskelinen 2008). Sites with high SON levels were generally more susceptible to disturbance from higher grazing frequency than the low SON sites. For instance, the absolute difference in total biomass between low and high grazing frequency is about 271 gm^{-2} in LV-1

(SON=570 gm^{-2}) while only 125 gm^{-2} in LV-2 (SON = 148 gm^{-2}) in subzone E. The difference in NPP between low and high grazing frequency is 19 $gm^{-2}year^{-1}$ in LV-1 and 12 $gm^{-2}year^{-1}$ in LV-2. The interpretation can be that the site with high SON levels can support more vegetation, and hence more is eaten by grazing herds (Gough, Ramsey et al. 2007; Eskelinen 2008; Olofsson, Lauri Oksanen et al. 2009). A study conducted in northernmost Fennoscandia by Eskelinen et al (2008) showed that nutrient-rich sites are more intensively grazed than nutrient-poor sites. Gough et al (2007) measured weekly growth of dominant tundra plants under fertilized and unfertilized conditions. In their nine year manipulations, plants with herbivore exclusion grew better than those without exclusion, and plants were more grazed in fertilized sites than ambient sites without fertilization, indicating a negative effect of herbivory in the fertilized sites. Their results also corroborate our findings that absolute decrease in total biomass and NPP due to herbivory is significantly greater in sites with higher SON levels under the same grazing regime (Figure 2.3), in that animals tend to graze more on the abundant vegetation patches. This can also be interpreted as spatial effects of grazing due to soil heterogeneity, and as temporal effects of N fertilization; the fertile sites can support more vegetation and tend to be grazed more often than the control sites (Gough, Ramsey et al. 2007)**.**

Increasing grazing frequency caused a greater decline in plant response to climate warming (in terms of total biomass and NPP) in sites with higher SON levels, suggesting again that herbivory generally becomes more important under higher nutrient conditions. This is supported by recent work documenting long-term effects of herbivory on tundra plant growth (Virtanen 2000; Grellmann 2002; Olofsson, Hulme et al. 2004; Olofsson, Stark et al. 2004). A grazing suppression effect is evaluated in our model by comparing the absolute increases in total biomass and NPP between two grazing regimes. In subzone E, the suppression effect in terms of total biomass and NPP was 296 gm^{-2} and 12 gm^{-2} $year^{-1}$ in LV-1 vs. 113 gm^{-2} and 5 gm^{-2} $year^{-1}$ in LV-2 respectively. When comparing low grazing to high grazing effects on soil organic nitrogen pools over time (Figure 2.5), higher grazing frequency led to either slower SON accumulation rates or more rapid SON depletion rates. Warming accentuated these differences caused by grazing, suggesting the interaction between grazing and warming may yield greater differences in SON levels across sites.

Figure 2.5 Grazing effects on soil organic nitrogen pool in each site over time.



5. Conclusion

This study has offered insights into the interactions among soil nutrients, climate, and grazing on arctic tundra vegetation on the Yamal Peninsula. Soil nutrients are a limiting factor to plant growth, and also limit the plant responses to climate warming. Long-term projections of how SON levels affect tundra vegetation responses to warming and grazing can be assessed using the ArcVeg model. Numerous studies have suggested that climate warming is an essential factor for promoting tree and shrub expansion in arctic tundra, however grazing may limit this response (Olofsson, Lauri Oksanen et al. 2009). Research conducted in the neighboring Nenets Autonomous Okrug has shown that shrubs already above the reindeer browsing line have increased their growth significantly in response to current climate warming of the last few decades (Forbes, Macias Fauria et al. 2009). A better understanding of soil organic nitrogen and grazing effects on tundra vegetation growth is crucial for determination of the rate of shrub expansion in the Arctic.

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Appendix

Table 2.A.1 Statistics of Total Biomass and NPP as influenced by subzone, soil organic nitrogen, climate warming and grazing. Analysis of Variance (ANOVA) was applied to the simulated datasets, where subzone, warming, grazing are independent categorical variables. DF is the degrees of freedom. Type III Sum of Squares assesses at the unbalanced data, since our variables are of different DFs. Mean Square is the square root of Type III SS. F values measure the distance between individual distributions; as F values increase, P values decrease. P values < 0.05 indicate a statistically significant effect of that independent variable on the dependent variable.

Source of Variations	DF	Type III SS	Mean Square	F Value	P>F
Total Biomass					
Subzone	2	109625.712	54812.856	471.08	<.0001
SON	1	3572898.163	3572898.163	30706.5	<.0001
Warming	1	28548.129	28548.129	245.35	<.0001
Grazing	1	25105.281	25105.281	215.76	<.0001
SON*Subzone	2	531677.655	265838.828	2284.70	<.0001
Subzone*Warming	2	14999.054	7499.527	64.45	<.0001
Subzone*Grazing	2	872.427	436.213	3.75	0.0242
SON*Warming	1	178326.428	178326.428	1532.59	<.0001
SON*Grazing	1	124979.964	124979.964	1074.11	<.0001
Warming*Grazing	1	10964.736	10964.736	94.23	<.0001
SON*Subzone*Warming	2	55304.044	27652.022	237.65	<.0001
SON*Subzone*Grazing	2	47219.928	23609.964	202.91	<.0001
SON*Subzone*Warming*Grazing	3	191960.578	63986.859	549.92	<.0001
NPP					
Subzone	2	3112.0345	1556.0172	1634.69	<.0001
SON	1	128213.4283	128213.4283	134696	<.0001

Warming	1	1126.0711	1126.0711	1183.00	<.0001
Grazing	1	495.5042	495.5042	520.56	<.0001
SON*Subzone	2	16647.3388	8323.6694	8744.51	<.0001
Subzone*Warming	2	554.2940	277.1470	291.16	<.0001
Subzone*Grazing	2	21.0443	10.5222	11.05	<.0001
SON*Warming	1	5786.5652	5786.5652	6079.13	<.0001
SON*Grazing	1	262.6218	262.6218	275.90	<.0001
Warming*Grazing	1	70.7726	70.7726	74.35	<.0001
SON*Subzone*Warming	2	998.1921	499.0961	524.33	<.0001
SON*Subzone*Grazing	2	75.8446	37.9223	39.84	<.0001
SON*Subzone*Warming*Grazing	3	157.0791	52.3597	55.01	<.0001

Chapter 3: Modeling dynamics of tundra plant communities on the Yamal Peninsula, Russia, in response to climate change and grazing pressure[2]

Abstract

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 interaction 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 lichen, deciduous shrub and graminoid plant functional types (PFTs) caused by grazing 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

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[2] **Yu, Q.**, H.E. Epstein, D.A. Walker, G.V. Frost, B.C. Forbes. 2011. Modeling dynamics of tundra plant communities on the Yamal Peninsula, Russia, in response to climate change and grazing pressure. Environmental Research Letters 6 (4): 045505.

result in different shrub responses to grazing pressure. Heavy grazing caused plant communities to shift from shrub tundra towards moss, graminoid-dominated tundra in tundra in subzones C and D when evergreen shrub growth rates were decreased in the the model. The response of moss, lichen and forbs to warming varied across the different subzones. 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) within tundra plant communities.

1. Introduction

The Arctic is a complex system with strong interconnectedness among system components (Walker, Epstein et al. 2008; Post, Forchhammer et al. 2009). Climate and vegetation interactions have been studied extensively. From a vegetation perspective, the effects of climate change on such a complex system may be challenging to predict, as shifts in tundra plant communities affect ecosystem processes including net primary production, nutrient cycling and trophic interactions (Walker, Wahren et al. 2006; Post, Forchhammer et al. 2009). Repeat photography has documented expansion of shrubs, particularly deciduous shrubs such as Salix and Alnus spp. over the past 50 years in northern Alaska, likely caused by a warming of the arctic climate (Tape, Sturm et al. 2006). Assessing the responses of tundra vegetation at the plant functional type level is challenging using remote sensing (which includes aerial photography) and has most often been accomplished with field experiments. Post and Pedersen (2008) revealed that graminoid-dominated tundra shifted to dwarf birch-dominated tundra in five years within enclosures with passive warming using open-top chambers (OTCs) in the inland area of

Kangerlussuaq Fjord, West Greenland. In meta-analyses of tundra warming experiments, warming increased height and cover of deciduous shrubs and graminoids and decreased cover of mosses and lichens, however individual studies show that the responses differed among sites (Henry and Molau 1997; Arft, Walker et al. 1999; Walker, Wahren et al. 2006).

Grazing exists in most ecosystems and, with concomitant trampling, constitutes a regular disturbance regime to which some plants are more or less adapted (Milchunas, Sala et al. 1988). The reindeer (*Rangifer tarandus*) is a ruminant of the family Cervidae, which is distributed circumpolarly and has long been a key component of high latitude ecosystems (Forbes and Kumpula 2009). Reindeer grazing and trampling effects on arctic plant species have been studied relatively extensively (Bråthen and Oksanen 2001; Moen and Danell 2003; Olofsson, Hulme et al. 2004; Bråthen, Ims et al. 2007; Gough, Ramsey et al. 2007; Pajunen, Virtanen et al. 2008; Kitti, Forbes et al. 2009). However, grazing interactions with climate warming and the effects on plant community structure have received less attention (Post and Pedersen 2008; Olofsson, Lauri Oksanen et al. 2009). Post and Pedersen (2008) found that grazing mitigated long-term warming effects on tundra plant communities, as was also suggested in a study where herbivores were found to inhibit shrub expansion (Olofsson, Lauri Oksanen et al. 2009). These results are consistent with a recent modeling study which found that grazing caused tundra community biomass to decline, and that grazing interacted with warming to buffer plant responses (Yu, Epstein et al. 2009). In contrast, when erect willows (*Salix lanata*), that would otherwise constitute an important source of forage for reindeer in areas of heavy grazing, are already above the limit of browsing (≈180 cm), their growth increases significantly in response to decadal warming (Forbes, Fauria et al. 2010). Further investigation of the responses of the major tundra plant functional types (PFTs) is needed to improve understanding of warming and grazing interactions on tundra plant community biomass and composition.

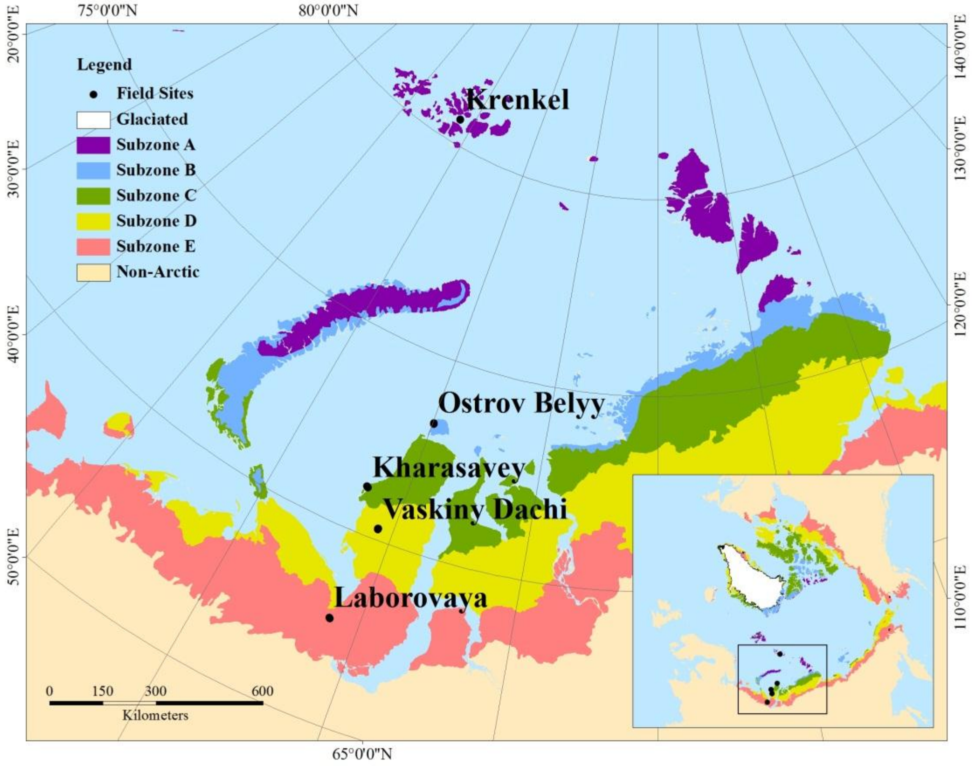
Different plant species may respond individualistically to changes in temperature, nutrients, and herbivory, and these responses may differ over time (Hollister, Webber et al. 2005). Short-term experiments, however, are not able to provide an understanding of how tundra plant communities may reorganize over long-term trajectories. 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, Epstein et al. 2009). Our objective is to investigate the effects of the tundra climate gradient, climate warming, soil nutrients and grazing on tundra vegetation dynamics at the PFT level. Our research questions are: 1) How does climate warming affect PFTs across the five latitudinal subzones (Walker, Raynolds et al. 2005) of the Arctic tundra biome (i.e. from polar desert to Low Arctic)? 2) How does grazing affect each PFT across this latitudinal gradient? 3) How do grazing and climate warming effects differ for PFTs along the latitudinal gradient, and how do these factors interact?

2. Methods

2.1 Study region

The Yamal Peninsula, in northwest Siberia, Russia, is a region with many environmental impacts including nomadic reindeer herding by indigenous Nenets, gas development and variable climatic change (Forbes and Kumpula 2009; Walker, Leibman et al. 2009; Walker, Forbes et al. 2010). Our study region stretches from southern Low Arctic tundra at Laborovaya on the Peninsula (67º 42’ N) to the polar desert at the Krenkel station (80º 38’ N) on Hayes Island, Franz Josef Land, and consists of study locations along a transect spanning the five arctic bioclimate subzones (Figure 3.1).

Figure 3.1 The tundra bioclimate subzones in northwest Russia, including the Yamal Peninsula. Inset map shows the circumpolar distribution of the subzones. Locations of the Yamal studies are shown. (Map based on CAVM Team, 2003).



Yamal soils consist of nutrient-poor marine sands and nutrient-rich clays. The loamy sites tend to have greater soil organic nitrogen contents than the sandy sites. Comparable sandy and loamy sites were established in each location, and different vegetation cover is associated with each site (Table 3.1). On mainland Yamal, we have study sites in subzones C, D and E located near Kharasavey, Vaskiny Dachi and Laborovaya respectively. For the loamy sites, dwarf shrub, moss tundra is often dominant, while for sandy sites, prostrate dwarf-shrub, lichen tundra dominates. Study sites north of the Yamal include Ostrov Belyy (subzone B) and Krenkel station (subzone A). Ostrov Belyy is an island north of the Yamal Peninsula and includes two study sites: one on a mesic loamy landscape (OB-1) and the other on a drier sandy landscape (OB-2). The dominant plant communities at OB-1 include graminoid, prostrate-dwarf-shrub, moss tundra on inner-circle areas and prostrate dwarf-shrub, crustose-lichen barrens on non-sorted circles. The communities at OB-2 are moss, prostrate dwarf-shrub tundra. These sites are used for summer and autumn pasture for migrating reindeer. Two study sites were established at Krenkel station on Hayes Island (subzone A) with one zonal sandy loam site (KR-1) and one drier sandy loam site (KR-2) in 2010. These sites are within the polar desert geobotanical subregion, and the vegetation is characterized by lichens, mosses, and cushion-forbs at KR-1, and less moss but more cryptogamic crusts at KR-2.

Table 3.1 Study sites and dominant plant types. Summer Warmth Index is the sum of mean monthly temperatures > 0 °C.

Location and sites	Longitude, latitude	Summer Warmth Index (°C mo)	parent material	Dominant vegetation
Krenkel-1 (Subzone A)	80.593˚ N, 57.903˚ E	1.9	colluvial slope, sandy loam site	Cushion-forb, lichen, moss tundra: *Papaver dahlianum* spp. *polare-Stellaria edwardsii-Cetrariella delisei-Ditrichum flexicaule*-black soil crust.
Krenkel-2 (Subzone A)	80.607˚ N, 57.907˚ E	1.9	marine terrace, sandy site	Cushion-forb, lichen, moss tundra: *Papaver dahlianum* spp. *polare-Stellaria* edwardsii-*Cetrariella delisei*-black soil crust.

Ostrov Belyy-1 (Subzone B)	73.329˚ N, 70.078˚ E	11.5	marine terrace II, loamy site	Non-sorted circle complex: (Inter-circle areas) Graminoid, prostrate dwarf-shrub, moss tundra: *Carex bigelowii-Calamagrostis holmii-Salix polaris-Hylocomiuim splendens.* (Nonsorted circles) Prostrate dwarf-shrub, crustose-lichen barren: *Dryas integrifolia-Arctagrostis latifolia-Racomitrium lanuginosum-Ochrolechia frigida.*
Ostrov Belyy-2 (Subzone B)	73.309˚ N, 70.129˚ E	11.5	marine terrace I, sandy site	Moss, prostrate dwarf-shrub tundra: *Racomitrium lanuginosum-Salix nummularia.*
Kharasavey-1 (Subzone C)	71.178˚ N, 66.980˚ E	28.7	marine terrace II, clay site	Graminoid, prostrate dwarf-shrub, moss tundra: *Carex bigelowii-Calamagrostis holmii-Salix polaris-Dicranum elongatum-Cladonia* spp.
Kharasavey-2 (Subzone C)	71.194˚ N, 66.889˚ E	28.7	marine terrace I, sandy site	Graminoid, prostrate dwarf-shrub, moss, lichen tundra: *Carex bigelowii-Salix nummularia-Dicranum spp., Cladonia* spp.
Vaskiny Dachi-1 (Subzone D)	70.276˚ N, 68.891˚ E	29.6	marine plain, clay site	Sedge, dwarf-shrub, moss tundra: *Carex bigelowii-Vaccinium vitis idaea-Hylocomium splendens.*
Vaskiny Dachi-2 (Subzone D)	70.296˚ N, 68.884˚ E	29.6	fluvial-marine terrace, sandy loam site	Dwarf-shrub, graminoid, moss tundra: *Betula nana-Calamagrostis holmii-Aulacomnium turgidum.*
Vaskiny Dachi-3 (Subzone D)	70.301˚ N, 68.842˚ E	29.6	fluvial-marine terrace, sandy site	Prostrate dwarf-shrub, sedge, lichen, tundra: *Vaccinium vitis-idaea-Cladonia arbuscula-Racomitrium lanuginosum.*
Laborovaya-1 (Subzone E)	67.707˚ N, 67.999˚ E	36.4	glacial terrace III, clay site	Sedge, dwarf-shrub, moss tundra: *Carex bigelowii-Betula nana-Aulacomnium palustre.*
Laborovaya-2 (Subzone E)	67.695˚ N, 68.037˚ E	36.4	alluvial sands, sandy site	Prostrate dwarf-shrub, lichen tundra: *Betula nana-Vaccinium vitis-idaea-Sphaerophorus globosus-Polytrichum strictum.*

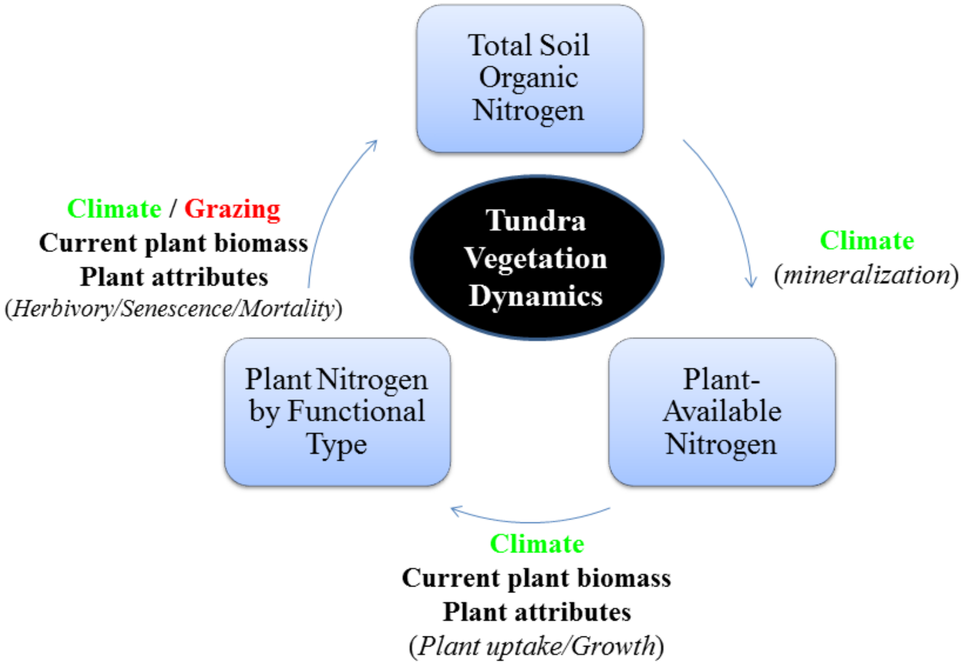
More detailed site descriptions and sampling methods can be found in the data reports of the 2007, 2008, 2009 and 2010 Yamal expeditions (Walker, Epstein et al. 2009; Walker, Orekhov et al. 2009; Walker, Carlson et al. 2011), and several published studies associated with the sites along the Yamal transect (Goetz, H.E. Epstein et al. 2009; Walker, Leibman et al. 2009; Yu, Epstein et al.

2009; Walker, Forbes et al. 2010; Kumpula, Pajunen et al. 2011; Leibman, Moskalenko et al. 2011).

2.2 ArcVeg model

ArcVeg is a nutrient-based dynamic vegetation model (see Epstein et al., 2000 for model description) that has been applied extensively for North American tundra (Epstein, Chapin et al. 2001; Epstein, Calef et al. 2004; Epstein, Kaplan et al. 2007). Arctic tundra vegetation in the model is grouped into 12 plant functional types including mosses (MOSS), lichen (LICH), forbs (FORB), tussock sedges (TUSS), non-tussock sedges (SEDG), rushes (RUSH), grasses (GRAS), evergreen prostrate dwarf shrubs (<5cm, EPDS), evergreen erect dwarf shrubs (15-40cm, EEDS), deciduous prostrate dwarf shrubs (<5cm, DPDS), deciduous erect dwarf shrubs (15-40cm, DEDS) and low shrubs (40-200cm, LOWS). The model essentially runs with nitrogen mass balance equations, moving nitrogen among three major pools (total soil nitrogen, plant available nitrogen and plant biomass nitrogen by PFT) (Epstein, Kaplan et al. 2007). Climate and grazing control nitrogen fluxes among these pools (see Figure 3.2). The twelve plant functional types compete for the limited nitrogen and use the acquired nitrogen to generate new biomass. Climate subzone, soil organic nitrogen levels and grazing regime dictate the simulated plant functional type composition and biomass for a particular tundra system. The model is parameterized for the five arctic bioclimatic subzones that range from the polar desert (subzone A) to the Low Arctic tundra at the southern extent of the tundra biome (subzone E) (Walker, Raynolds et al. 2005). Soil organic nitrogen levels were taken from field data for each site, and extrapolated to account available nitrogen in active layer. Climate warming in the model alters the available nitrogen for plants, assuming greater mineralization rates with higher temperatures (Epstein, Walker et al. 2000; Cornelissen, van Bodegom et al. 2007). Additionally, the length of the growing season in the models is affected by climate change.

Figure 3.2 Diagram of the simulation of tundra vegetation dynamics in ArcVeg (adapted from Epstein *et al*. 2000).



2.3 Model adjustment for selective grazing

Grazing, as a major disturbance in ArcVeg, is characterized using two parameters: frequency of grazing and percentage of biomass eaten. For example, a grazing regime of (0.1, 25%) means that there is 0.1 probability of a grazing herd each year, and a maximum of 25% biomass is removed with grazing. Grazing is selective as herbivores generally prefer forage with a high content of nutrients and a low level of structural and chemical defenses (Hanley 1997). To study plant-herbivore interactions, diet selection is important for inclusion in model simulations. Reindeer are ruminants with a highly selective forage strategy to adapt to cold weather, short growing seasons and small plants. Grazing selectivity considered in ArcVeg is a function of both foliar nitrogen concentration and reindeer diet preference. The diet preference used in this paper is based on studies by the Reindeer Research Program in Fairbanks, Alaska, and reflects the selectivity of reindeer diet in general (Bucki, Finstad et al. 2004; Flenniken 2007). The data show a high reliance on lichen with a seasonal spike in use of vascular plants during the growing season. Salix spp., Eriophorum spp., and Carex spp., make a big proportion of reindeer diet during the growing season (Podkorytov 1995; Kitti, Gunslay et al. 2006; Forbes and Kumpula 2009).

2.4 Simulation design and model input data

Our model simulations were driven by bioclimatic subzones and field collected soil organic nitrogen (calculated based on N%, bulk density and active layer depth) (Table 3.2). Input data include soil organic nitrogen (SON), climate subzone, grazing regimes [(0.1, 25%), (0.1, 50%), (0.5, 25%) and (0.5, 50%)] and climate warming manipulations (before warming, during warming [transient], and after warming [equilibrium]). All parameter combinations (including eleven sites – which span the five subzones and have different SON levels, four grazing regimes and three climate scenarios) were simulated with 20 replicate runs for each scenario. The three climate change scenarios included control/before warming, transient warming and equilibrium/after warming, and the four grazing regimes included: (0.1, 25%), (0.1, 50%), (0.5, 25%) and (0.5, 50%). The (0.1, 25%) scenario was assumed to be the control grazing regime or low grazing, and (0.5, 50%) was the highest grazing intensity, indicating reindeer herds will graze on the same site every two years, and each visit a maximum of 50% total biomass will be removed. These are reasonable grazing scenarios on the Yamal Peninsula, where the Nenets may set up camp, and herds will graze essentially around the camp for several days. The Nenets normally migrate across the peninsula every year with designated migration routes for each brigade (Stammler 2005), but there are also a large number of privately owned herds grazing on the same territories (Forbes, Stammler et al. 2009). Although there are no managed reindeer herds at Krenkel station on Hayes Island, for this study, we simulated grazing effects in subzone A for zonal vegetation dynamics comparison.

Plant functional type biomass values were compared and evaluated across all sites on the Yamal Peninsula under the different grazing regimes with one subzone climate warming (essentially 2 °C). In total we simulated for 1500 years. 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).

Table 3.2 Site name, bioclimate subzone, and soil parameters on the Yamal Arctic Transect.

Subzone	sites	C%	N%	%Sand	%Silt	%Clay	Bulk Density (gm^{-3})	Active Layer Depth(cm)	SON (gm^{-2})
A	KR-1	1.32	0.11	60.08	32.92	7.00	1.27	33.60	449
A	KR-2	0.80	0.10	81.40	16.20	2.40	1.30	32.80	277
B	BO-1	0.83	0.03	36.50	46.25	17.25	1.39	49.98	227
B	BO-2	0.62	0.01	83.76	12.16	4.08	1.26	77.60	145
C	KH-1	1.10	0.06	24.47	52.07	23.47	1.47	56.33	844
C	KH-2	1.18	0.07	65.60	26.60	7.80	1.22	75.50	599
D	VD-1	1.25	0.03	28.90	60.80	10.30	1.34	71.75	271
D	VD-2	1.46	0.04	38.28	53.88	7.84	1.37	68.60	202
D	VD-3	1.31	0.05	92.80	4.64	2.56	1.18	113.80	135
E	LV-1	1.72	0.06	18.00	59.32	22.68	1.21	81.20	570
E	LV-2	0.59	0.01	93.60	3.60	2.80	1.29	114.60	148

2.5 Statistical analysis

Nonmetric Multidimentional Scaling (NMS) was used to assess simulated biomass of 12 plant functional types and their relationships to the environmental controls including subzone, soil organic nitrogen, grazing, and climate change. NMS was developed by Kruskal (1964) and is widely used for ecological applications (Urban, Goslee et al. 2002). It is based on ecological distance and essentially produces a low-dimension ordination space in which sample separation in this space reflects sample separation in a multi-dimensional ‘species’ space. The algorithm ranks correlation between ordination distance and ecological distance. NMS makes no assumptions about the nature of species response to underlying gradients, and it is well suited for non-normal data (McCune, Grace et al. 2002). Any similarity or dissimilarity (distance) matrix (e.g. Jaccard, Bray-Curtis or Euclidean) can be used. A total of 132 ArcVeg simulated plant communities (as a multivariate of PFT biomass values) and their relationships to environmental variables (latitudinal climate gradient or five climate subzones, eleven soil organic nitrogen levels, three temporal climate scenarios, and four grazing intensities) were analyzed. We used PC-Ord (version 5.0) for NMS with a Bray-Curtis distance matrix for this study. The NMS was run randomly with 250 runs with real and randomized data respectively. The final stress was 6.7 for a 3-dimension solution, and the instability was 10-5, which suggests a good ordination with no real risk of drawing false inferences (McCune, Grace et al. 2002).

The simulated biomass values of 12 PFTs were grouped into 6 growth forms (moss [MOSS], lichen [LICH], forbs [FORB], graminoids [SEDG, TUSS, RUSH and GRAS], evergreen shrubs [EPDS and EEDS], and deciduous shrubs [DPDS, DEDS and LOWS]) and were analyzed as dependent variables using multi-factor ANOVA (analysis of variance). The main effects were climate subzone, SON, warming, and grazing (all categorical variables except for SON). The interactions of the main effects were also included in the ANOVA. Least square means and Type III sum of squares were used to account for the unbalanced data. This analysis was performed in SAS version 9.3 for Windows (SAS institute Inc.).

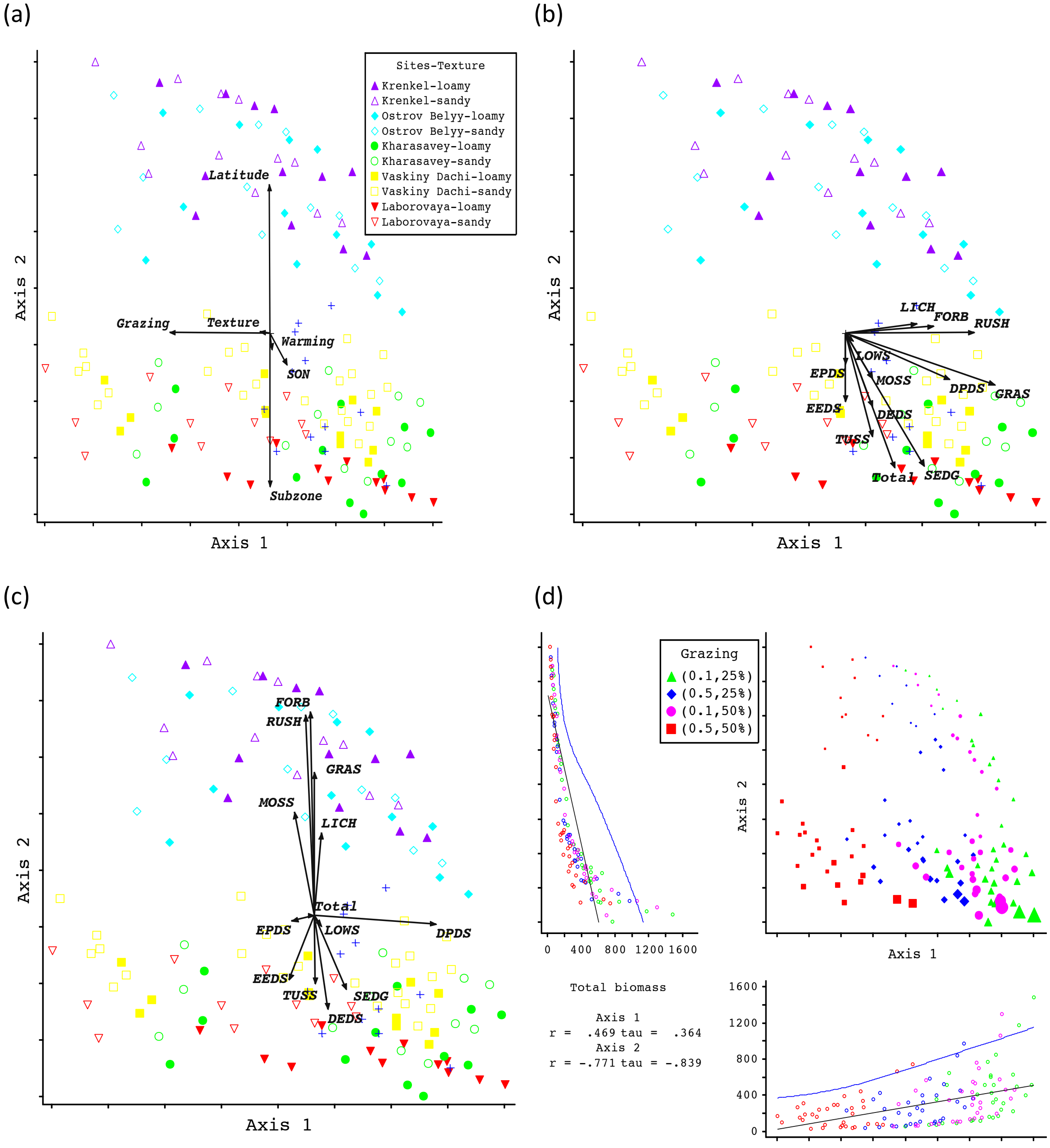
3. Results

3.1 Overall results in ordination

NMS ordination was applied to assess controls on simulated tundra plant community properties (Figure 3.3). Each point in Figure 3.3 represents one model scenario, and the colors indicate the five subzones. We used the biplot function in

PC-Ord to show the direction and strength of correlations of environmental variables (Figure 3.3a) within the ordination space, which are shown with the red arrows. In Figure 3.3a the vertical axis is strongly correlated with the latitudinal temperature gradient (~12 °C) and summer warmth (42% of total variance in model simulations for all arctic tundra subzones), the horizontal axis is strongly correlated with the grazing gradient (13% of total variance), and the rest of the variance is explained by SON, soil texture, warming and the interaction effects. Sites at Krenkel and Ostrov Belyy (subzones A and B) formed one cluster in the north of the ordination space and sites at Kharasavey, Vaskiny Dachi and Laboravaya (subzones C, D and E) clustered together probably because they have similar community properties which are determined by SON and SWI. The biplot in Figure 3.3b illustrates the absolute value of PFT biomass. Most plant functional types, except evergreen shrubs, were negatively affected by grazing, especially lichen, forbs, rushes, grasses and deciduous prostrate-dwarf shrubs (Figure 3.3b). Relative abundance of each PFT for each simulation was calculated and shown in Figure 3.3c. Relative abundances of mosses, lichen, forbs, rushes and grasses were greater to the north, in the polar desert (northern High Arctic), while relative abundances of tussock sedges, non-tussock sedges, evergreen and deciduous shrubs were the greatest in the southern subzones. Relative abundance of evergreen shrubs (Figure 3.3c) correlated positively with grazing, suggesting minimal grazing impact on evergreen shrubs. Total biomass in Figure 3.3d increased towards the low latitudes or south subzones (represented by the size of each dot, which increased towards south), but decreased towards the high grazing intensity.

Figure 3.3 NMS ordination shows the effects of environmental controls on simulated tundra plant community properties (figure rotated 115º for better visual interpretation). Biplot of environmental controls (a), PFT biomass (b) and relative abundance of each PFT (c) in ordination space are shown. Colors represent five sites, and hollow shapes represent sandy sites. Ordination of total biomass and correlation with each axis (d) where colors represent grazing pressure and the sizes correspond to the magnitude of total biomass of each scenario.

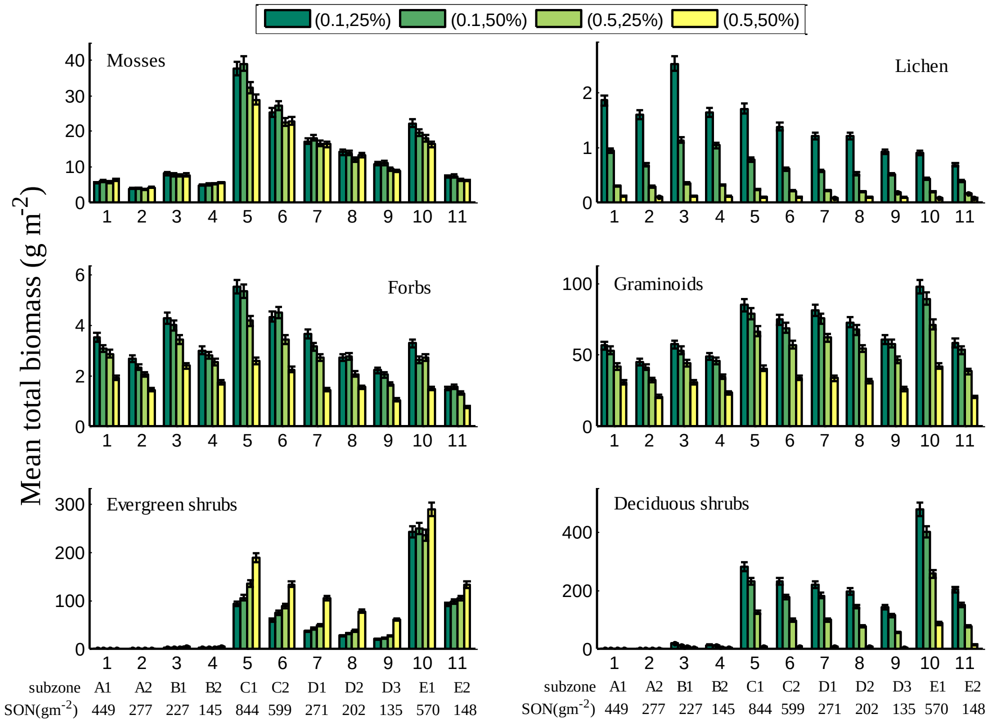


Multi-factor ANOVA was conducted to test the individual and interaction effects and the results are presented in the supplemental materials (Table 3.A.1.). Each individual effect (subzone, SON, warming and grazing) and interaction effects (subzone*SON, subzone*warming) on our grouped plant functional types were significant ($p<0.01$).

3.2 Grazing effects

Overall, grazing caused total plant community biomass to decrease, but PFTs were affected differently by grazing (Figure 4). 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. 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%). Evergreen shrub biomass increased as grazing intensity increased, and the increase was most substantial (about 29 gm^{-2}) when grazing was most intense (0.5, 50%). Moss biomass responded to grazing nonlinearly, increasing 1% (before warming) and 2% (after warming [equilibrium]) when grazing percentage increased from 25% to 50% and then declining (-11% and -13%) when grazing frequency increased from 0.1 to 0.5 (every ten years to every two years); this response was consistent under transient warming and equilibrium warming scenarios.

Figure 3.4 Effect patterns of increased grazing on 6 growth forms (before warming scenario)



3.3 Temporal climate warming effects on tundra plant communities

Climate warming affected PFTs differently across our study sites (Figure 3.5). Shrubs responded to warming with increased biomass at all study sites. The responses of moss, lichen and forbs to warming varied across the different subzones. In addition, some PFT responses during the transient warming period were different from their responses following the transient warming period.

3.3.1 Warming period effect (transient vs. equilibrium warming)

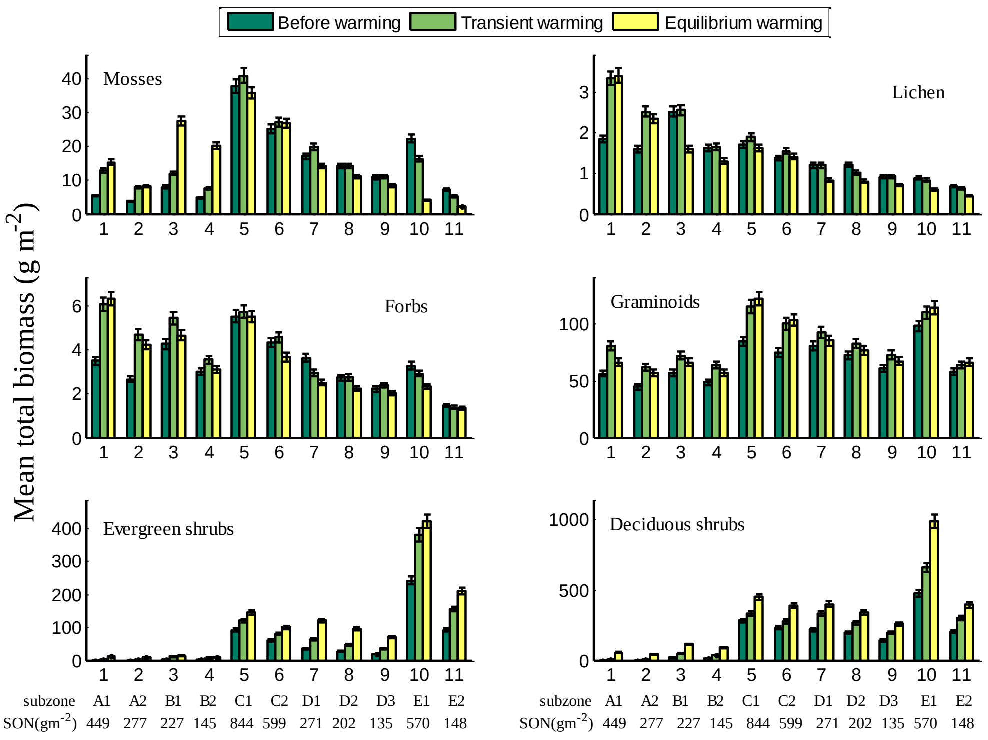
Different PFTs responded to transient warming and equilibrium warming differently. Evergreen and deciduous shrubs responded to both warming scenarios with continued positive responses, and these responses were consistent across both latitudinal and soil nutrient gradients, although the magnitude varied slightly.

Evergreen and deciduous shrub biomass increased from 64 gm^{-2} and 93 gm^{-2} to 100 gm^{-2} (54% increase) and 132 gm^{-2} (42% increase) respectively during transient warming, and to 126 gm^{-2} (96% increase) and 188 gm^{-2} (102% increase) during equilibrium warming. Graminoids also had a positive response to warming at all sites but responded to transient warming with greater biomass increase (13 gm^{-2} or 26% increase) than equilibrium warming (10 gm^{-2} or 19% increase). Lichens responded to transient warming with only a 16% biomass increase and had a 3% biomass decrease during equilibrium warming when grazing was (0.1, 25%). Forbs responded with greater biomass increase during transient warming (15%) than during equilibrium warming (7%), although these responses differed across the latitudinal gradient and with different soil nutrient levels.

3.3.2 Interaction with latitudinal gradient and soil properties

In general, warming caused most PFTs to increase biomass, but this response interacted with the latitudinal gradient and soil properties including soil texture and soil organic nitrogen levels. Multi-factor ANOVA showed that interaction effects between subzone and warming on most plant types were significant ($p<0.01$, Table 3.A.1.). For example, moss responded to warming positively in subzones A (136% increase) and B (171% increase), and negatively in subzone E (52% decrease). In subzones C and D, moss biomass increased during transient warming but decreased during the equilibrium warming period. Lichen responded to warming positively with increased biomass in subzone A, but the response to warming was negative in subzones B, C, D and E. Essentially, warming affected moss and lichen negatively where shrubs became largely dominant. Graminoids had a positive response to warming at all sites but responded during transient warming with a greater biomass increase than equilibrium warming in subzones A (40% vs. 22% increase), B (28% vs. 16% increase), and D (16% vs. 7% increase), yet had a smaller biomass increase during transient warming than during equilibrium warming in subzones C (35% vs. 41% increase) and E (11% vs. 13% increase). The interaction effect of SON and warming significantly affect deciduous and evergreen shrubs ($p<0.05$, Table 3.A.1.). Across all sites, deciduous and evergreen shrubs responded to warming consistently, but with less biomass increase in sandy sites or low SON sites (85 gm^{-2} and 33 gm^{-2}) than in loamy sites or high SON sites (139 gm^{-2} and 53 gm^{-2}).

Figure 3.5 Warming effects on PFTs at low grazing regime (0.1, 25%).



3.4 Warming and grazing interactions

Compared to climate change, grazing had a more substantial effect on plant communities (Figure 3.7a). We found that plant responses to grazing were different during the control climate, transient and equilibrium warming, indicating interactions of climate change with grazing. The interaction effects between subzone and grazing, and warming and grazing on deciduous shrubs and lichen were significant ($p<0.01$, Table 3.A.1.). Deciduous shrub, lichen, forb, and graminoid biomass decreased continually with increased grazing intensities. However, since warming may promote greater plant growth, such a decline due to grazing is mediated by climate warming, particularly for deciduous shrubs already above the browse limit for reindeer. For example, grazing caused about 21%, 56% and 93% deciduous shrub biomass decline before warming when grazing regimes were (0.1, 50%), (0.5, 25%) and (0.5, 50%) respectively. However, the decline was 19%, 52% and 90% during the transient warming period and 21%, 55% and 89% during the equilibrium warming period. Lichen had a greater biomass decline during the transient warming period (57%, 86% and 95%) than both control (52%, 84% and 94%) and equilibrium warming period (51%, 84% and 94%) with increased grazing. In response to grazing, evergreen shrub biomass increased less during transient warming (8%, 18% and 63%) and equilibrium warming (6%, 10% and 48%) compared to the control climate scenario (9%, 19% and 75%), when grazing regimes were (0.1, 50%), (0.5, 25%) and (0.5, 50%) respectively. In other word, warming suppresses the positive effects of grazing on evergreen shrubs, probably due to enhanced deciduous shrub growth under warming.

4. Discussion

According to the presented data and analyses, we found that grazing can be important in addition to the latitudinal temperature gradient (~12 ºC) in controlling tundra plant community properties. The NMS results of this study showed that grazing, as one of the controlling factors in addition to climate change (2 ºC) and soil organic nitrogen, explained about 13% of total data variance in model simulations for all arctic tundra subzones, while latitude explained about 42%. This can have important implications for reindeer husbandry across the Arctic. The interactions of warming and grazing are potentially complicating our understanding of tundra vegetation dynamics and need to be taken into account in future research efforts.

4.1 Grazing effects

Grazing may cause total plant community biomass to decrease as indicated in our previous modeling study (Yu, Epstein et al. 2009). But, understanding how major plant functional types may respond, especially the types that compose the reindeer diet, is critical for projecting future changes in tundra vegetation cover affected by grazing and trampling. Our results suggest that as lichen and deciduous shrubs are preferred by reindeer, they can be the plant functional types that are most affected by grazing management patterns. This finding is in line with remote sensing data from along the Finnish-Norwegian border where a reindeer fence has been visible due to higher reindeer lichen coverage in Norway; the fence prevented lichen being grazed by reindeer in Norway in comparison to Finland (Kumpula 2006; Forbes and Kumpula 2009). Study conducted in Brøggerhalvøya, Svalbard also found that lichen and vascular plants declined with increased grazing (Staaland, Scheie et al. 1993). Moss, which is not preferred as much by reindeer (Flenniken 2007), showed a nonlinear response to increased grazing in High Arctic. For example, the biomass in subzone C increased by 6%

when grazing scenarios shifted from (0.1, 25%) to (0.1, 50%) and then declined by 12% and 19% respectively when grazing intensity continued to increase to the (0.5, 25%) and (0.5, 50%) scenarios. Increased grazing may favor moss growth by reducing species competition and changing the soil moisture regime, possibly causing the tundra plant community to shift from lichen-dominated tundra to moss-dominated (van der Wal 2006). But with continual increase in grazing, moss may also be foraged (Staaland, Scheie et al. 1993) and negatively affected by trampling.

Grazing interacts with soil nutrients, which can contribute to more complicated tundra plant responses to warming. For example, forb biomass generally decreased with increased grazing intensity, but there are exceptions in nutrient poor sites or sandy sites (KH-2, VD-2 and LA-2). In these sites, forbs responded positively when grazing increased from (0.1, 25%) to (0.1, 50%) and negatively with further grazing increases. This may due to the fact that in nutrient poor sites, grazing affected deciduous shrubs substantially and thus there may be nutrients available to other plant functional types such as forbs.

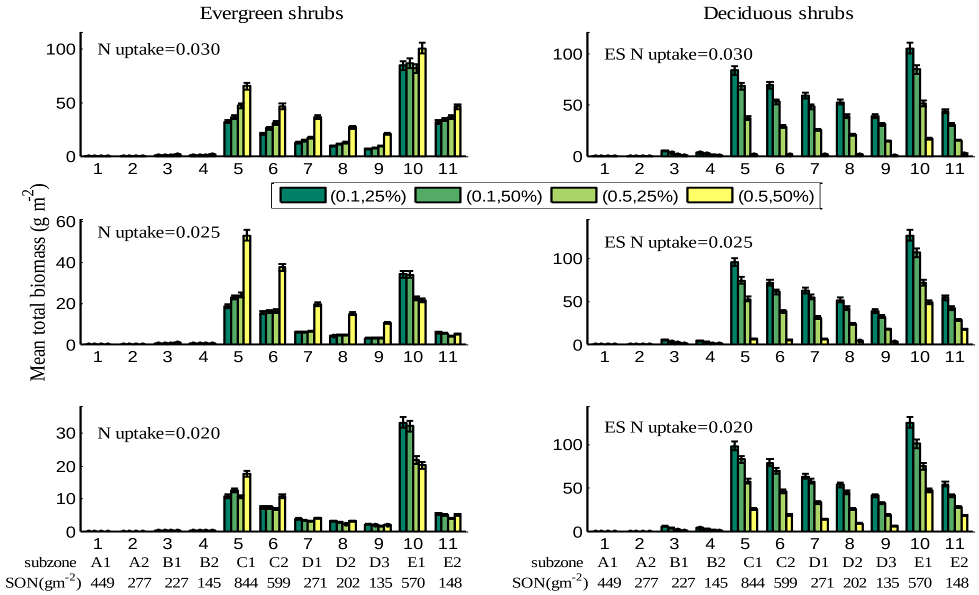
Evergreen shrubs in our current model simulations respond to increased grazing intensity with continual increase of biomass. This is due to the fact that they are least preferred by reindeer in the diet data used by ArcVeg. Moderate grazing has been shown to cause evergreen shrubs to increase albeit not always (Olofsson, Hulme et al. 2004; Bråthen, Ims et al. 2007). The increase of evergreen shrubs in this model study may not represent the situation that we see in the field on the Yamal (Walker, H.E. Epstein et al. 2010); one reason may be that the susceptibility of vegetation to reindeer trampling has not been taken into account in the model. Additionally, the rapid cycling of nutrients in the model over time through grazing may not be accurately represented in the model as reindeer expedite decomposition and relocate nutrients through feces and urine (Olofsson, Kitti et al. 2001). While trampling during intense grazing can affect all taxa, and cause both deciduous and evergreen shrubs to be damaged (Forbes, Stammler et al. 2009), deciduous shrubs may have an advantage over some other plant types in that they have higher photosynthetic rates and higher reproductive capacity as mechanisms of resilience to disturbance. The more common prostrate deciduous shrubs on the Yamal (e.g., Salix polaris, S. arctica, S. nummularia) are fairly resilient to grazing (Walker, Epstein et al. 2009; Walker, Orekhov et al. 2009).

4.2 Resilience and palatability

We tested how the resilience of evergreen shrubs affected their response to grazing to help us understand how growth rates may affect the responses of evergreen shrubs to different grazing regimes. Evergreen shrubs are less palatable in comparison to deciduous shrubs due to their low nitrogen concentration and their poor digestibility, which contribute to their low percentage in reindeer diet throughout the year. Evergreen shrubs also have slower growth rates than deciduous shrubs in our model; however this did not prevent evergreen shrubs from becoming dominant with increased grazing intensity. Based on observations from the Yamal, deciduous shrubs still have greater abundance than evergreen shrubs on the Yamal, which is a heavily grazed system compared to other places in northern Russia and North America (Walker, Epstein et al. 2009). We examined this phenomenon by altering evergreen shrub growth rates (nitrogen uptake: biomass ratio) to see how responses differed under the four grazing regimes.

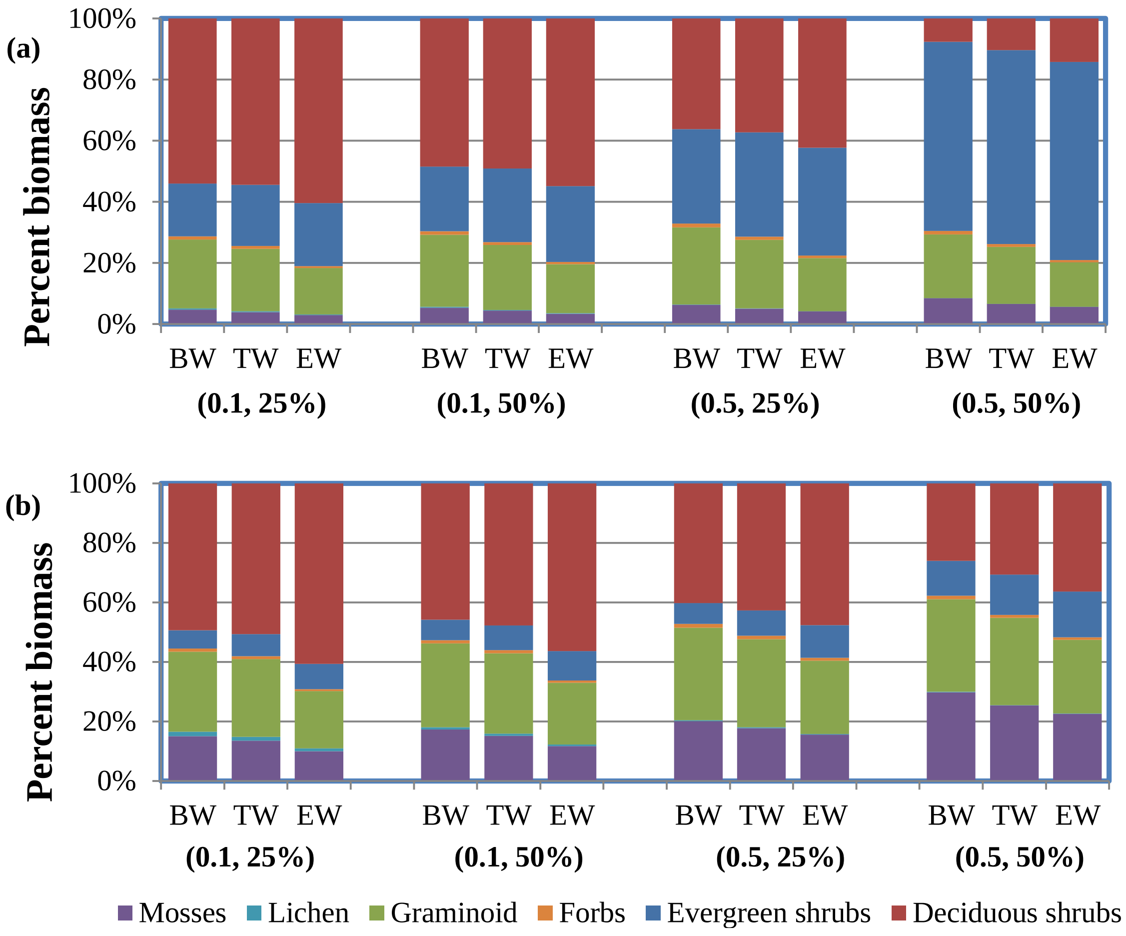
The response of evergreen shrubs to grazing changed along a small gradient of evergreen shrub growth rates under different grazing scenarios. Slower growth rates limited evergreen shrubs, and thus there was substantially less biomass when growth rates decreased for evergreen shrubs from 0.030 g N uptake per biomass to 0.020 g N uptake per biomass, and the response to increased grazing became negative in subzones D and E (Figure 3.6). Moreover, as the growth rates of evergreen shrubs decreased, the negative effect of increased grazing pressure on deciduous shrubs became reduced.

Figure 3.6 Resilience test of evergreen shrubs (evergreen shrub growth rates included 0.030 g N uptake per biomass, 0.025 g N uptake per biomass, and 0.020 g N uptake per biomass) shown on the left column. Deciduous shrub biomass was compared without change of deciduous shrub growth rates (right column).



Heavy grazing may cause plant communities to shift. When evergreen shrub growth rate was reduced to 0.020 g N uptake g biomass^{-1}, the proportional abundance of moss and graminoids increased with continual increase in grazing pressure. Figure 3.7b shows the plant community transition from shrub-dominated tundra towards moss, graminoid-dominated tundra when grazing intensity increased. We tested this grazing effect with before-warming biomass data for shrubs (both evergreen and deciduous shrubs) using a single factor ANOVA (Table 3.A. 2). When evergreen shrub nutrient uptake rate was 0.02 g N uptake g biomass^{-1}, heavy grazing caused subzones C and D to shift significantly from shrub-dominated to graminoid-moss dominated tundra. Decrease in shrubs may be beneficial for understory plants, since there will likely be more light and nutrients available. Heavy trampling however may negatively affect moss growth and reduce the moss layer depth (Van der Wal and Brooker 2004), but this is not included in current model version. Altered or expedited nutrient cycling by reindeer digestion appears most advantageous for graminoids, according to field nutrient addition manipulations (Olofsson, Kitti et al. 2001; Van der Wal, Bardgett et al. 2004). Tundra plant communities tend to be altered by grazing and trampling, and have been suggested to shift towards graminoid-dominated systems under these conditions (Zimov, Chuprynin et al. 1995). Transition towards graminoid-dominated tundra caused by heavy grazing has been observed on the Yamal at the local scale (Forbes, Stammler et al. 2009).

Figure 3.7 Proportional abundance of the main functional groups across all sites. (a) illustrates how warming affects the responses of PFTs to grazing (BW - before warming, TW- transient warming and EW - equilibrium warming). Proportional abundance was calculated when evergreen shrub growth rate was 0.030 g N uptake per biomass. (b) illustrates the change in dominant plant types caused by grazing when evergreen shrub growth rate changed from 0.030 g N uptake per biomass to 0.020 g N uptake per biomass.



4.3 Warming effects

Shrub expansion in the Arctic, presumably caused by warming, has been captured by studies using repeat aerial photographs (Sturm, Racine et al. 2001; Tape, Sturm et al. 2006). Other remotely sensed imagery such as from AVHRR has documented greening trends in the tundra region (Jia, Epstein et al. 2003; Goetz, Bunn et al. 2005; Bhatt, Walker et al. 2010). Shrub dendrochronology has also been used in the Arctic (Forbes, Fauria et al. 2010; Hallinger, Manthey et al. 2010). Forbes et al (2010) explored the chronology of Salix lanata L. (sensu latu), an abundant erect deciduous shrub in the Yamal region and an important source of reindeer forage throughout the Low Arctic.

They found a significant increase in shrub willow growth over the last six decades, and a strong correlation with the Normalized Difference Vegetation Index (NDVI), corroborating the ‘greening’ trend detected by remote sensing studies. Our model results also suggest that shrubs may respond to warming with a continual biomass increase, at least under a consistent grazing regime (Figure 3.5). This may be highly applicable to Alaskan tundra where caribou grazing dominates, and grazing pressure is generally low. This study expands our understanding of shrub growth under different grazing regimes, including the Yamal Peninsula, Russia, where large herds of reindeer managed by the Nenets can graze and trample extensively at relatively high levels and, in many places, quite intensively.

Our model-simulated warming responses are consistent with field studies, such as experimental warming studies from the International Tundra Experiment (ITEX) using open-top chambers (OTCs), which can increase mean growing season air temperature by 1-3 °C. Our modeled warming was a 2 °C increase linearly ramped over a 50 year period, thus the rate of temperature increase was not as great as in the ITEX studies (Henry and Molau 1997), however we simulate for a longer period of time. Moss and lichen biomass measured in ITEX-associated studies declined in response to warming in Low Arctic sites, while deciduous shrubs and graminoids increased (Chapin, Shaver et al. 1995; Henry and Molau 1997; Walker, Wahren et al. 2006). This is consistent with our modeling results in the Low Arctic. Moreover, our results provide insights as to how these plants respond differently in soils of different organic nitrogen contents.

Limitation of soil organic nitrogen may constrain plant responses to warming (Henry and Molau 1997). Additionally, graminoids and forbs responded with greater biomass increase on average during transient warming (26% and 14%) than during equilibrium warming (19% and 7%), and this may be due to shifts in controlling mechanisms from direct warming response to species competition for nutrients (Epstein, Walker et al. 2000). Species competition, essentially for limited nutrients, may cause some PFTs to decline in biomass after transient warming. Such responses cannot be detected with short term experiments (Chapin, Shaver et al. 1995). Shifts in controlling mechanisms need to be considered to understand and predict how arctic systems will respond over the long term to changing climate.

4.4 Interaction effects

PFT responses to grazing varied under the three climate scenarios. As grazing may cause most PFTs to decline in biomass, more substantially at higher intensity grazing regimes, warming interacts with grazing and may contribute to more complicated plant responses. Lichen and deciduous shrubs were significantly affected by warming and grazing interactions ($p<0.001$, Table 3.A.1.). In general, grazing negated plant biomass increases in response to warming. Shrub biomass increased under warming scenarios alone, yet responses were buffered when grazing pressure increased (Figure 3.7). Deciduous shrubs responded to warming with increased biomass, and the increases were profound at lower intensity grazing regimes. This is consistent with what has been found in northern Fennoscandia, where the abundance of the dominant shrub (Betula nana) has increased, and the increase has been more pronounced when grazing was absent from the study site (Olofsson, Lauri Oksanen et al. 2009). The responses to grazing under different climate change conditions were different. Graminoid and forb biomass declined with increased grazing, and this decrease became greater under the equilibrium climate state due to enhanced shrub growth and thus competition for nutrients despite that warming can accelerate nitrogen mineralization and provide more nutrients for vegetation. Large scale surveys in regions of Finnmark and northern Norway with reindeer herds of high densities found that high grazing substantially reduced large dicotyledons and grasses in fertile sites (Bråthen, Ims et al. 2007). Long term grazing, trampling and feces deposition may cause the plant community state to shift from woody dominated tundra to clonal rhizomatous graminoids (Forbes, Stammler et al. 2009). Although our model provides understanding of long-term tundra vegetation dynamics, the current version does not include either trampling or rigorous nutrient recycling routine for reindeer waste and thus need further improvement and investigation to better understand plant community state shifts.

5. Conclusion

Simulation results in this study suggest that grazing can be important in addition to the latitudinal temperature gradient (12 ºC) for tundra plant communities, explaining about 13% of the total variance. Plant functional types (PFTs) such as lichen, deciduous shrubs and graminoids responded to grazing with decreasing biomass. However, such a decline is potentially mediated by climate warming since generally warming promotes the growth of shrubs and graminoids, particularly when erect deciduous shrubs are above the browse line.

Moss biomass had a nonlinear response to grazing, 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 may cause plant communities to shift from shrub tundra towards moss, graminoid-dominated tundra in subzones C and D. Further analyses with inclusion of trampling effects are strongly needed for better understanding of the interactions between shrub dominance and grazing. In response to climate warming alone, moss, lichen and forbs varied across the different subzones. Deciduous and evergreen shrubs responded positively to warming consistently across all subzones, but with less biomass increase in low SON sites than in high SON sites. 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) on tundra plant communities.

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Chapter 4: Circumpolar arctic tundra responses to grazing pressure and projected climate change

Abstract

Aim We aim to examine how impacts of climate change and grazing cause the variation in tundra plant community biomass and net primary productivity (NPP) across arctic regions. We examine the effects of (1) projected climate change only (2) observed grazing only (3) combined effects of projected climate change and grazing on tundra plant community properties.

Location Pan-arctic tundra

Methods We apply an arctic tundra vegetation dynamics model – ArcVeg- to estimate the changes in vegetation biomass and NPP caused by climate change and grazing in the Arctic. We performed model simulations for 2000-2099 at a 0.5 by 0.5 degree spatial resolution across the arctic tundra, encompassing all five tundra bioclimate subzones. We first assessed effects of climate change and grazing individually on plant community biomass and net primary productivity (NPP). Then we compared and evaluated these two individual effects by region and by bioclimatic subzone. We compared the simple difference between grazing and climate change effects in addition to the coupled effects within the ArcVeg model.

Results Climate change and grazing caused tundra plant community biomass and NPP to change in opposite directions, but regions with different magnitudes of climate change and grazing result in different responses to these two forcings. Both climate change and grazing caused greater absolute aboveground biomass change in southern subzones and the Russian arctic tundra than northern subzones and other tundra regions. For areas with grazers, the effects of grazing dominated the relative changes of aboveground biomass in northern subzones (A, B and C). When averaged across all study areas, warming dominated the relative changes in aboveground biomass in all subzones.

Main conclusions This study provides a novel analysis of the potential climate change and biotic disturbance controls on arctic tundra vegetation dynamics. The main finding is that grazing can abate the tundra plant response to climate warming in terms of aboveground biomass and NPP. Grazing therefore complicates our interpretation of the "greening" trend across the Arctic.

Keywords: arctic tundra, aboveground biomass change, CCSM, climate change, grazing, NPP, vegetation dynamics modeling

1. Introduction

Arctic tundra ecosystems have long been limited by low temperatures and low rates of nutrient turnover and availability (Chapin 1992). Several processes (e.g. warming temperatures, animal excretions, and atmospheric nitrogen deposition) can alter nutrient availability to these strongly nitrogen-limited plant communities (Nadelhoffer, Giblin et al. 1991; Hobbie, Nadelhoffer et al. 2002; Shaver, Giblin et al. 2006). Temperature increases are greater in the Arctic than other regions of the world, due to amplification effects through global circulation patterns (Serreze and Francis 2006; Screen and

Simmonds 2010; Serreze and Barry 2011). Based on a set of coupled models included in Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4), mean annual Arctic warming is approximately 1.9 times greater than the global mean warming with doubling CO_2 simulation scenario (Winton 2006; Serreze and Barry 2011). This degree of warming is likely to be beneficial to much of the tundra vegetation, promoting plant growth due to increased nutrient availability from increased decomposition rates (Chapin 1983; Epstein, Raynolds et al. 2012). Long term climate warming experiments across the Arctic have found that most plants responded to warming positively (Walker, Wahren et al. 2006; Elmendorf, Henry et al. 2012); although responses of plant types differed across regions (e.g. shrubs increased in warm arctic regions, but graminoids can increase in colder arctic regions), according to Elmendorf et al (2012), based on a synthesis of 61 experimental warming research projects across arctic tundra sites. Patch dynamics of vegetation in circumpolar arctic ecosystems can be attributed to both natural (temperature, precipitation, soils, and wild grazers) and anthropogenic (land use, human-induced climate warming, and animal husbandry) factors (Forbes, Ebersole et al. 2001). Studies of these are limited in space and time, although they can provide an understanding of tundra vegetation dynamics across the arctic region. As temperatures are predicted to further increase (IPCC 2007; Overland, Wang et al. 2011), the effect on tundra vegetation biomass across the Arctic remains unknown.

Satellite remote sensing and repeat photography have documented “greening” and “shrubification” in the arctic tundra (Tape, Sturm et al. 2006; Bhatt, Walker et al. 2010). Epstein et al. (2012) estimated the aboveground biomass change for circumpolar arctic tundra vegetation over the period of continuous satellite records (1982-2010), using a strong regression model between NDVI (Normalized Difference Vegetation Index, a spectral metric related to plant productivity and photosynthetic biomass) and field measured phytomass. Southern tundra subzones (C-E; defined by the Circumpolar Arctic Vegetation Map, Walker et al 2005) exhibited approximately 20 to 26% biomass increases, with heterogeneity across regions, floristic provinces and vegetation types. Such "greening" trends across the arctic tundra biome are generally believed to be caused by increased surface temperatures (Fraser, Olthof et al. 2011), with spatial differences in magnitude that likely reflect regional trends in climate and weather driven by summer sea-ice extent (Bhatt, Walker et al. 2010; Walker, Bhatt et al. 2011). Bhatt et al (2010) examined the link between sea-ice decline and increases in tundra productivity, and found a nearly ubiquitous greening of the coastal tundra, but with regional differences in magnitude: a 9% increase in the peak NDVI for arctic North America from 1982-2008, versus only a 2% increase for the Eurasian Arctic. However, it is difficult to interpret the actual warming-induced "greening" simply based on satellite analyses, since remote sensing captures in totality all of the factors that influence the vegetation on the ground. There can be numerous factors explaining differences in "greening" magnitudes across North American and Eurasian regions, such as magnitudes of temperature change, soil nutrient status, and disturbance regimes (Walker, Epstein et al. 2012).

Disturbance regimes in the Arctic are strong controls on resource availability and plant community dynamics (Hu, Higuera et al. 2010; Virtanen, Luoto et al. 2010; Walker, Epstein et al. 2012). Grazing is one important disturbance that can play a crucial role in regulating plant community dynamics and also affect the cycling of essential nutrients, such as nitrogen. Grazers that have adapted to harsh tundra environments and can cause substantive vegetation change are for example caribou/reindeer (*Rangifer tarandus*), lemmings (*Lemmus*), and muskoxen (*Ovibos moschatus*). Heavy grazing can reduce tundra plant community biomass and net primary productivity (Virtanen 2000; Grellmann 2002; Yu, Epstein et al. 2009). Grazing impacts can be the most important factor controlling tundra plant community composition and structure, aside from the latitudinal arctic climate gradient (~12 °C) (Yu et al. 2011). A ubiquitous decline in reindeer/caribou populations across the Arctic has been found coincident with increases in arctic temperatures, extreme weather events and changes in precipitation (Vors and Boyce 2009). Brown lemmings have also been found to affect tundra plant communities, oscillating with population cycles, but these impacts are generally limited to local scales (Johnson, Lara et al. 2011).

Changes in vegetation biomass are important with regard to the global carbon cycle and budget (Houghton, Hall et al. 2009). Although the carbon sink associated with increased aboveground vegetation in arctic tundra over the past three decades is not large from a global perspective (Epstein et al. 2012), it can represent a substantial change in the high latitude carbon budget (McGuire, Wirth et al. 2002; McGuire, Chapin et al. 2006). Also, dynamics of tundra vegetation can strongly affect above- and belowground trophic systems (Gough et al. 2012, in press). Variations in aboveground biomass and plant community shifts can affect caribou and reindeer grazers directly. Wild caribou and semi-domestic managed reindeer herds in turn have different impacts on tundra vegetation. Domesticated reindeer tend to use the same pasture more frequently and more intensely than wild caribou. Reindeer have been herded for centuries and have been used to provide meat, antlers and, to a lesser extent, milk and transportation (Stammler 2005).

The reindeer has an important economic role for many polar peoples, including Nenets, Saami, Khants, Evenks, Yukaghirs, Chukchi, and Koryaks in Eurasia. Understanding interactions between tundra plant biomass/ productivity and reindeer grazing is crucial for regional economics and indigenous people.

Field observations and modeling studies suggest that intense pasture use with increased reindeer populations in some arctic regions (e.g. RussianYamal and Lapland) may have caused either pasture degradation or plant communities to shift from shrub-dominated tundra to moss, graminoid-dominated tundra (Forbes, Stammler et al. 2009; Riseth and Vatn 2009; Yu, Epstein et al. 2011). The overall effects of grazing on arctic tundra suggest that increases in vegetation productivity due to climate warming may be abated by heavy grazing. However, there is no study yet that examined climate change and grazing effects at large spatial scales.

Pan-arctic tundra vegetation dynamics in response to climate change can be important to regional herders of reindeer as well as migrating wild herds of caribou. In this study, we investigate how changes in climate and current grazing regimes can impact tundra vegetation at the pan-arctic scale. We hypothesize that vegetation will be affected by climate change and grazing in opposite directions and by different grazer management patterns. Heavy grazing and trampling can cause biomass to be removed to an extent that vegetation cannot recover easily (Olofsson et al. 2009), and we hypothesize that heavy grazing by reindeer in certain regions will attenuate the arctic vegetation greening trend.

2. Methods

2.1 Overview

We apply an arctic tundra vegetation dynamics model – ArcVeg – to estimate the changes in vegetation biomass and NPP caused by climate change and grazing in the Arctic. We performed model simulations for 2000-2099 at a 0.5 by 0.5 degree spatial resolution across the arctic tundra, encompassing all five tundra bioclimate subzones as displayed on the Circumpolar Arctic Vegetation Map (CAVM) (Walker, Raynolds et al. 2005). The subzonal concept classifies tundra vegetation based on climate and the dominant shrub type on undisturbed, loamy soils in mesic landscapes.

2.2 ArcVeg model

ArcVeg is a nutrient-based dynamic vegetation model, suitable for this study in that it simulates the dynamics of 12 tundra plant functional types. The model simulates nitrogen-limited tundra plant communities and can incorporate how climate change and grazing affect these plant types over time. To drive the model, we prepared climate, soil, and grazing input datasets (see Epstein et al. 2000, Yu et al. 2011 for model details).

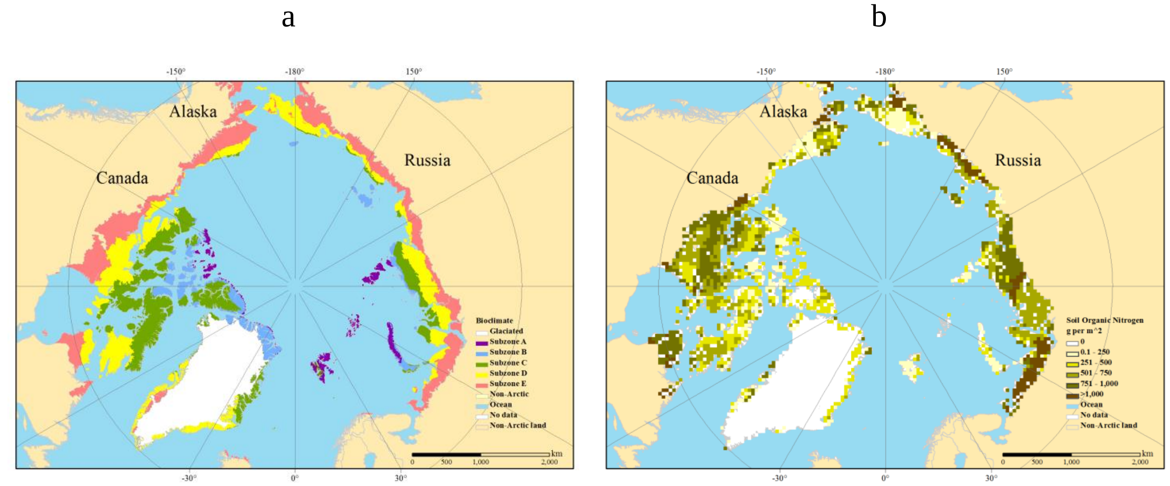
2.3 Input data

We collected and computed input data to drive ArcVeg, including bioclimate subzones, soil organic nitrogen output from the Terrestrial Ecosystem Model (TEM) (Clein, Kwiatkowski et al. 2000; McGuire, Clein et al. 2000), grazing intensity estimated by the CircumArctic Rangifer Monitoring &Assessment Network (CARMA, http://www.carmanetwork.com/) and Arctic Portal (http://arcticportal.org/), and surface temperature anomalies averaged across Community Climate System Model (CCSM 3.0) runs for Phase 3 of the Coupled Model Intercomparison Project (CMIP3), coordinated by the Program for Climate Model Diagnosis and Intercomparsion (PCMDI) (Meehl, Covey et al. 2007). These climate datasets were developed in response to a proposed activity of the World Climate Research Programme's (WCRP) Working Group on Coupled Modeling (WGCM). We derived climate change magnitudes based on the ensemble mean of surface temperatures from CCSM3.0 runs under the Intergovernmental Panel on Climate Change (IPCC) A1B scenario (720 ppm CO_2 stabilization experiment according to Special Report Emissions Scenarios -A1 balanced or SRESA1B).

2.3.1 Subzone and soil organic nitrogen data

The study region encompasses five tundra bioclimate subzones (Figure 4.1a) ranging from subzone A in the north, where shrubs are absent, non-vascular plants (mosses and lichens) are dominant, and bare or crusted ground is common, to subzone E in the south which is completely vegetated and often dominated by tall, low and erect dwarf shrubs. Data on soil organic nitrogen are currently sparse across the Arctic (Tarnocai, Canadell et al. 2009); thus we used soil organic nitrogen simulated by TEM which spans from 55 °N to 90 °N (Figure 4.1b).

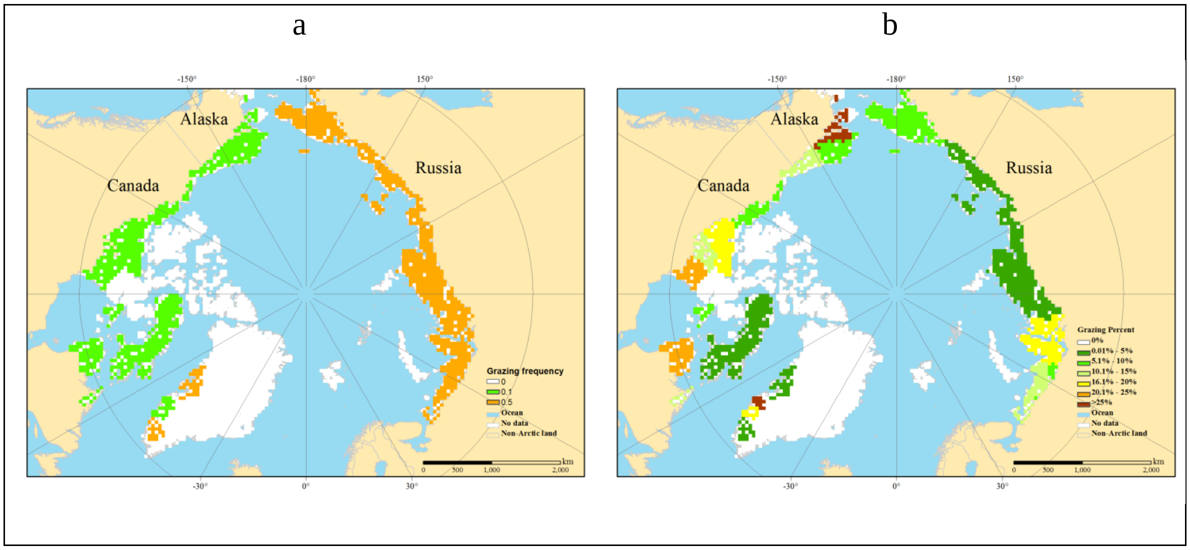
Figure 4.1 a. Bioclimate subzone map (CAVM Team, Walker et al. 2005); b. Soil organic nitrogen (g m^{-2}) to 2 meters depth across the arctic tundra, output from TEM model.



2.3.2 Reindeer/caribou populations and relation to grazing parameters

Two sets of field data from both a North American Arctic Transect and a Eurasian Arctic Transect (Walker, Epstein et al. 2012) have facilitated our parameterization of the model across circum-arctic regions. Caribou and reindeer population information was collected from both CARMA and Arctic Portal. CARMA is a network that collects and updates wild caribou herd information, while Arctic Portal focuses more on managed reindeer herds. Wild caribou and managed reindeer tend to be different in their migration patterns and thus have different levels of grazing intensity (Figure 4.2a). To parameterize grazing intensity for different herds, we made two assumptions. First, we assume wild caribou use the same landscapes less frequently than managed reindeer. In ArcVeg we parameterize caribou herds to have a grazing frequency probability of 0.1, meaning they may graze the same landscapes on average every ten years. Managed reindeer herds are parameterized with a grazing frequency probability of 0.5 (they may use the same landscapes about every two years). Although semi-domesticated reindeer herds have been managed in brigades, particularly in the European Arctic, the indigenous herders migrate along with reindeer herds, and thus we believe grazing the same pasture about every two years is reasonable. Then, we parameterize grazing percent – another important grazing parameter in ArcVeg – based on herd population information. We processed grazer population information in a GIS and calculated population density for each region. Grazing pressure or grazing intensity (percent biomass removal for each visit) was estimated based on grazer population density (Figure 4.2b) using a linear equation (percent biomass removal = 20*herd population density). The estimated biomass removal was therefore 20% in areas with population density of 1 animal km^2, which represents areas with moderate grazing pressure. This is within the range of about 48-61% of leaf biomass eaten during a maximum grazing period (Vakhtina 1963). Averaging across woody and non-woody tundra plants, we estimated that this is approximately 20% of total biomass.

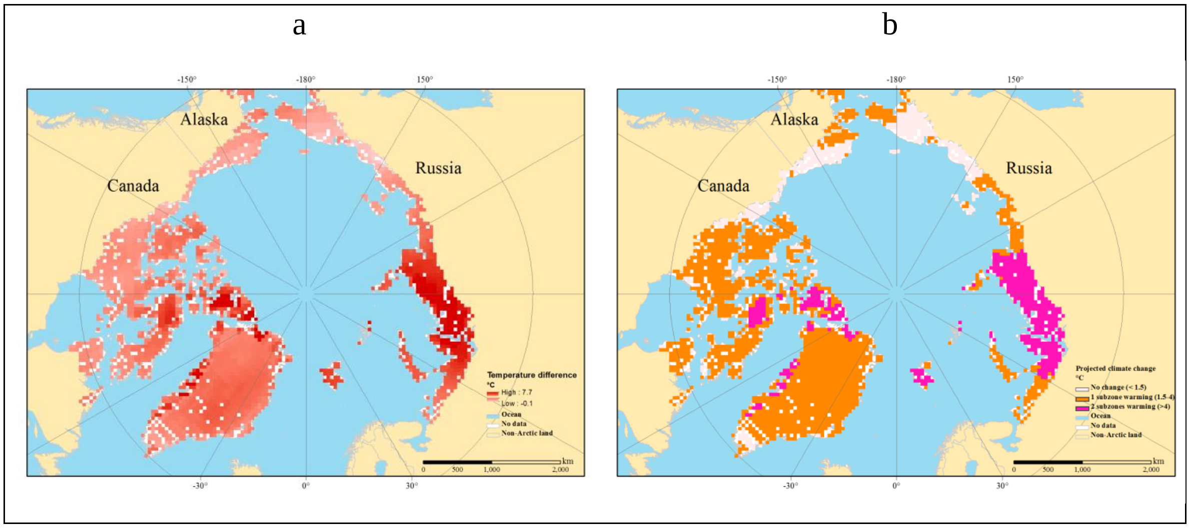
Figure 4.2 Input grazing parameters to ArcVeg: a) caribou (frequency = 0.1) and reindeer (frequency = 0.5) distribution across the Arctic based on CARMA and Arctic Portal respectively; b) grazing intensity is calculated based on reindeer and caribou population density in each region.



2.3.3 Temperature difference derived from IPCC simulations

We used the CCSM3.0 SRES-A1B emission scenario model output from the PCMDI ftp site. We extracted and calculated ensemble mean July temperatures from 2000 to 2099. Then we calculated temperature differences between 2000 and 2099 (Figure 4.3a). Climate change was parameterized in ArcVeg using a subzonal approach. In total there are five tundra subzones ranging from polar desert (subzone A) in the north to southern Low Arctic tundra (subzone E). A 2 °C temperature increase in the model is equivalent to a one-subzone warming. With warming temperature in the model, certain plant functional types that could not establish due to temperature limitation could now start to grow in response to the warming. The mean projected temperature increase circumpolarly from 2000 to 2099 is 2.8 °C. The minimum and maximum temperature changes are -0.1 °C and +7.7 °C respectively. Mathematically, if temperature increases > 6 °C, this would be equivalent to a three subzone change. However, in order to constrain the warming response (assuming that plant community shifts due to warming could take centuries to occur in the Arctic), we allowed a maximum of two subzones of warming, even the temperature difference was greater than six degrees Celsius. We binned the temperature change into three categories: 1) no subzonal change when the difference was less than 1.5°C; 2) one subzone warming when the difference was between 1.5 and 4°C and two subzones warming when the difference was > 4°C (Figure 4.3b).

Figure 4.3 July surface temperature change from 2000 to 2099 across the arctic tundra. a) shows the July temperature difference calculated from mean July temperature between 2000 and 2099; b) shows the same temperature change but binned to a number of bioclimate subzones.



2.4 Simulation setup

We processed the input data in ArcGIS 10.0 (ESRI Inc.), and all data were intersected with the bioclimate subzone map. We simulated plant biomass data for a total of 600 years. The simulation in the first 500 years was to allow biomass and plant communities to “spin up,” i.e. to reach some stochastic equilibrium values. Then in year 500 we prescribed climate change with the change calculated based on CCSM 3.0 projected temperature changes across the Arctic. Warming was ramped up linearly for the next 100 simulation years. Community level aboveground biomass and NPP were compared across all arctic regions. For warming effects, we calculated simulated biomass and NPP differences by subtracting mean biomass/NPP between years 400 - 500 as the before-warming scenario from mean biomass/NPP between years 500 - 600 as the during-warming scenario. For grazing effects, we calculated simulated biomass and NPP differences between with and without grazing scenarios for years 400 - 500. Simulation scenarios are summarized in Table 4.1.

Table 4.1 Simulation scenarios for this study

Simulation scenario	Climate	Grazing
Control	Before climate change	No grazing
Grazing effects	Before climate change	Current grazing regimes
Warming effects	Projected climate change	No grazing
Combined effects	Projected climate change	Current grazing regimes

2.5 Statistics

We compared aboveground biomass and NPP changes caused by warming and grazing across all regions, subzones and floristic provinces. We calculated both absolute and relative biomass and NPP changes. Since there are areas with and without grazing, we examined grazing effects exclusively for grazed areas and examined warming effects for all tundra areas. We used Proc Means in SAS 9.3 (SAS Institute Inc.) to calculate the descriptive statistics across regions, subzones and floristic provinces.

3. Results

We evaluated tundra plant community biomass and NPP changes due to grazing or warming and analyzed the difference in these two effects on plant biomass and NPP. Generally, grazing and warming affected plant community biomass in opposite directions, with grazing abating the increase in biomass due to warming (Figure 4.5). We also compared the difference in biomass and NPP changes due to grazing and warming individually with the simulated combined effects on biomass and NPP changes. The combined effects resulted in more homogenous biomass change across the study area, where climate change masked the effects of grazing, than the simple difference between grazing and climate change effects where these two effects were of generally similar magnitude (Figure 4.6).

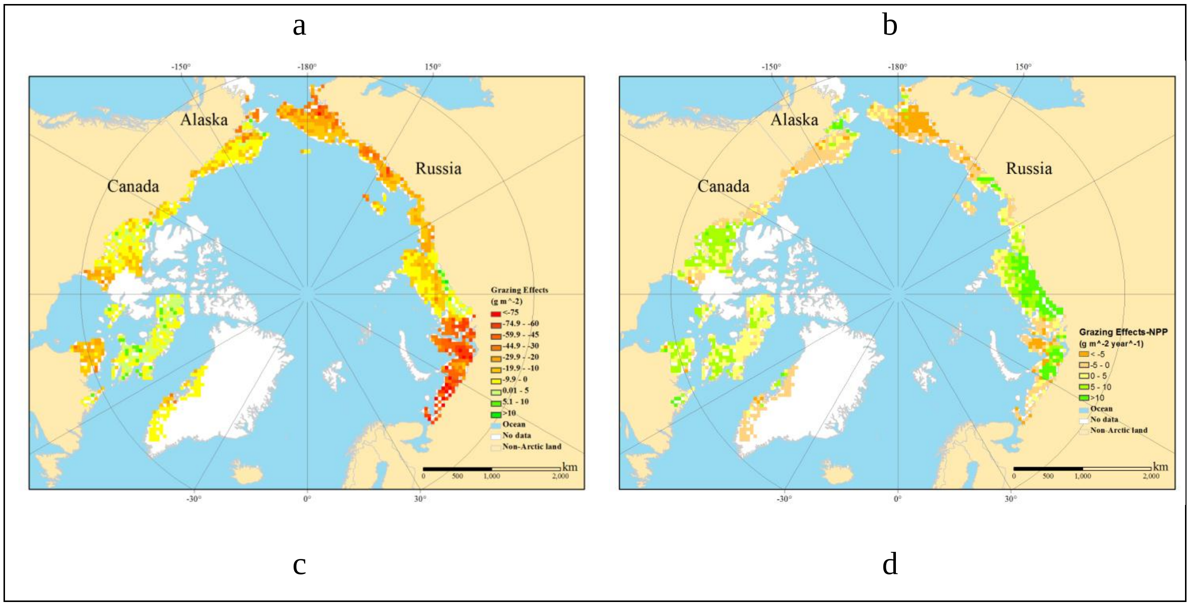
3.1 Grazing effects without climate change

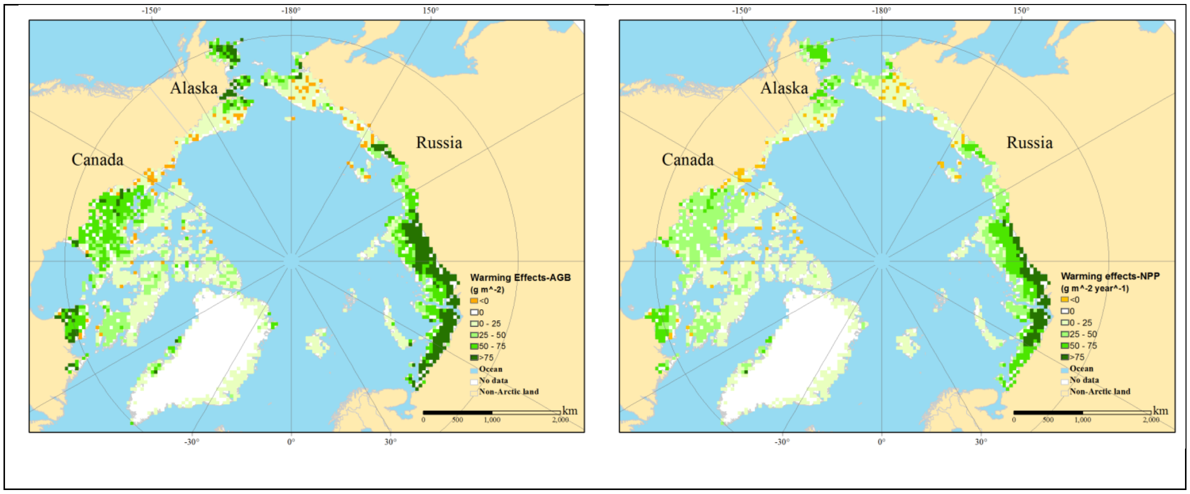
Grazing in general caused biomass to decline compared to the no-grazing scenario. In grazed areas, grazing caused approximately -2 gm^{-2}, -11 gm^{-2}, -8 gm^{-2}, -19 gm^{-2} and -23 g m^{-2} changes in subzones A, B, C, D and E (Figure 4.5a). Regionally grazing caused approximately -38 gm^{-2}, -15 gm^{-2} and -9 gm^{-2} aboveground biomass change in Russia, United States and Canada respectively (Figure 4.5e). The most dramatic decline in biomass was in western Siberia (Figure 4.4a), where soils tend to be richer in organic nitrogen content (Figure 4.1b). In these regions, there are greater reindeer populations, and thus reindeer density may affect tundra biomass substantially. For example, in Kanin-Pechora and Yamal-Gydan regions, grazing caused biomass to decline about -80 gm^{-2} and -68 gm^{-2} respectively. In comparison, wild caribou dominated areas in the United States had smaller biomass declines. Interestingly, high soil organic nitrogen along with high grazing intensity caused NPP to be comparatively high in northwestern Siberia (Taimyr and southern Yamal). For the Yamal Peninsula in northwest Siberia, NPP decreased due to grazing when compared to the no-grazing regime in the northern subzones but increased in southern subzones (Figure 4.4b).

3.2 Climate change effects without grazing

In general, climate change scenarios caused aboveground biomass (Figure 4.4c) and NPP (Figure 4.4d) to increase in most regions, particularly in northwestern Russian tundra. This is likely due to greater projected temperature increases in northwestern Siberia compared to other regions (Figure 4.3). Russian arctic tundra has the greatest response to warming in terms of above ground biomass increase (~ 60 g m^{-2}) for all subzones. Regionally, arctic tundra biomass increases in Canada (30 g m^{-2}) and the United States (29 g m^{-2}) were substantially less than the Russian tundra (Figure 4.5). Changes in aboveground biomass increased exponentially with increasing Summer Warmth Index (SWI) (Figure 4.7, r^2=0.97).

Figure 4.4 Changes in aboveground biomass (a) and NPP (b) caused by grazing only across the arctic tundra. Changes in aboveground biomass (c) and NPP (d) caused by projected climate change only across the arctic tundra between 2000 and 2099.

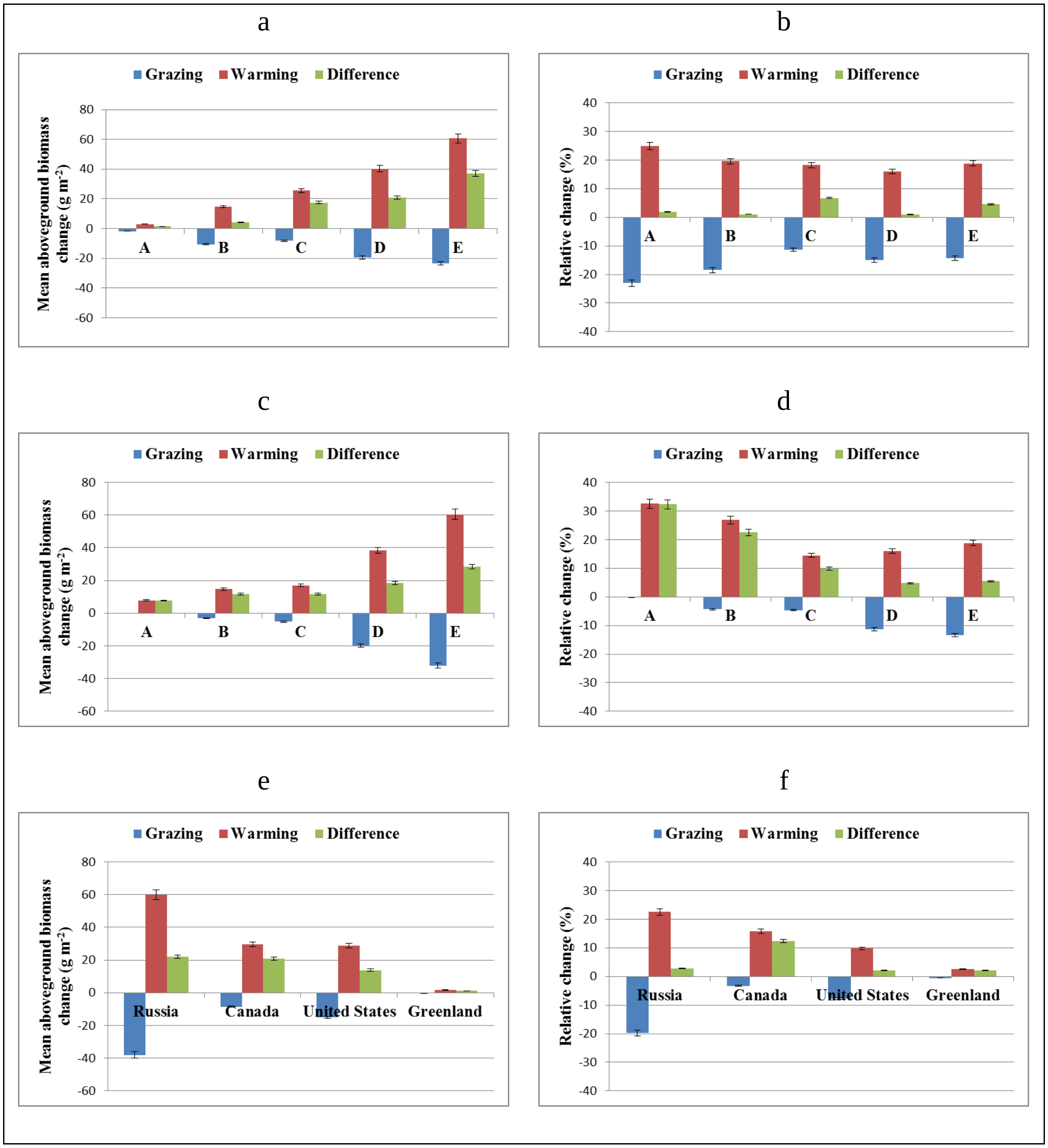




3.3 Difference between effects of grazing and climate change

Grazing and warming in general drove tundra vegetation to change in opposite directions in terms of total biomass (Figures 4.4, 4.5). The differences in absolute change in biomass due to grazing or warming were greater in subzones D and E than in subzones A, B and C (Figure 4.5a, 5c). The differences in relative biomass change due to effects of grazing or climate change were greatest in subzones C and E for areas with grazing (Figure 4.5b). Across all study areas, the differences in relative biomass change were the greatest in subzones A and B, where warming contributed to the majority of biomass change (Figure 4.5d). Grazing and warming caused the greatest absolute aboveground biomass increase in southern subzones (Figure 4.5a, 4.5c) and Russian tundra (Figure 4.5e). On average biomass decreased due to grazing about -20 g m^{-2} and -32 g m^{-2} in subzones D and E respectively. Warming caused biomass to increase about 38 g m^{-2} and 60 g m^{-2} in subzones D and E across all regions.

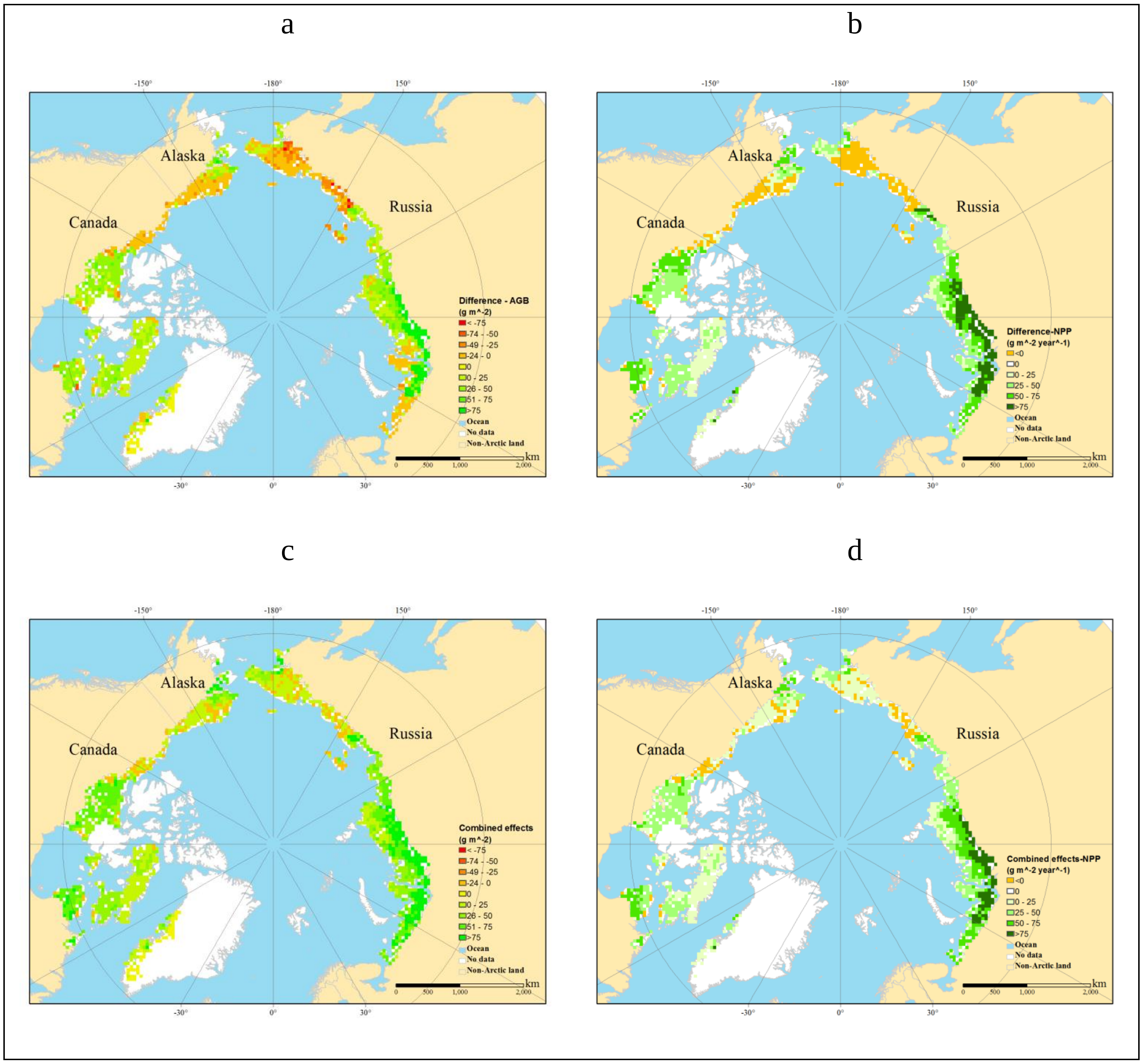
Figure 4.5 Left column shows absolute biomass change and right column the relative biomass change. (a) and (b) show the comparison of grazing and warming effects on absolute and relative aboveground biomass change in each subzone **in areas with grazing**. (c-f) show the comparison of grazing and warming effects on aboveground biomass in each subzone (c, d) and each country (e, f) **across all study areas**.



The differences in aboveground biomass and NPP were compared to the simulation scenario with combined effects (Figure 4.6). The mean difference in aboveground biomass and NPP change between grazing and warming (Figure 4.6a) was

19 gm^{-2}and 27 gm^{-2} year^{-1}, and the mean biomass change due to combined warming and grazing (Figure 4.6c) was 42 gm^{-2} and 32 gm^{-2} year^{-1}.

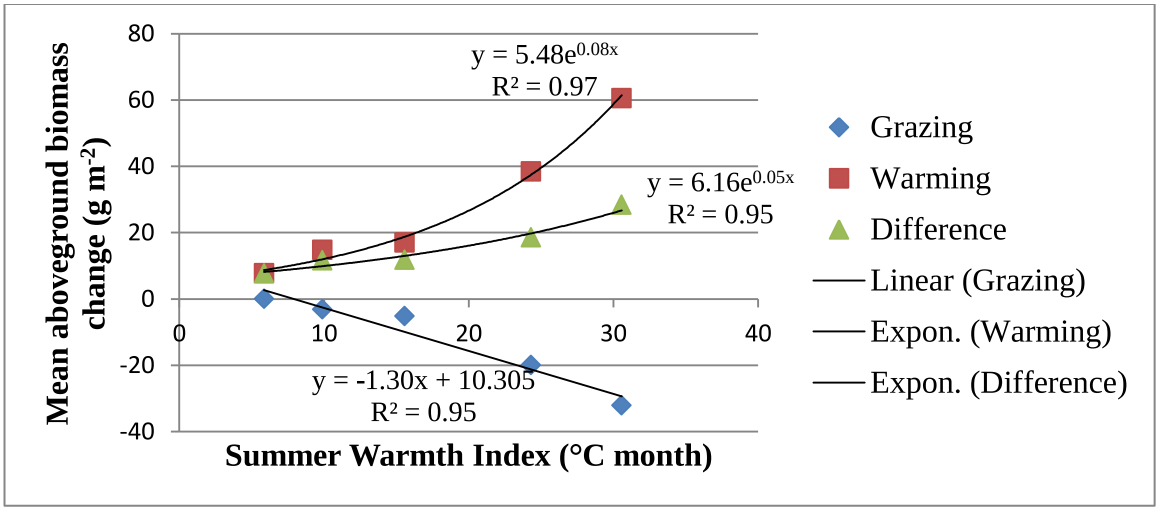
Figure 4.6 Difference between grazing and climate change effects on aboveground biomass (a) and NPP (b) changes across the tundra in grazed areas. Aboveground biomass (c) and NPP (d) change due to combined warming and grazing.



4. Discussion

This study conducts a novel analysis of the potential climate change and biotic disturbance controls on arctic tundra vegetation dynamics. The main finding is that grazing can abate tundra plant response to climate change in terms of aboveground biomass and NPP (Figure 4.6a, 4.6b). This is consistent with results from field studies in northern Fennoscandia where reindeer grazing was found to reduce shrub response to warming (Olofsson, Lauri Oksanen et al. 2009). Olofsson et al (2009) argued that the recent shrub expansion would have been more dramatic if increased reindeer density in northern Fennoscandia had not inhibited it. Individual effects of climate change, grazing and their difference were further quantified and compared (Figure 4.7). Across the bioclimate subzones, changes in aboveground biomass increased with summer warmth exponentially due to warming (r^2 = 0.97) but decreased due to grazing, resulting in an abated exponential increase (r^2 = 0.95). When comparing scenarios with the simple difference between grazing and climate change effects on biomass to the scenario with combined effects, the plant responses were different (Figure 4.7). Previous studies suggested that grazing interacts with climate change (Post and Pedersen 2008; Yu, Epstein et al. 2009; Yu, Epstein et al. 2011), resulting in different tundra plant community responses to climate change.

Figure 4.7 Grazing and warming effects across subzones are shown across all regions.



For areas with grazers, the effects of grazing dominated the relative changes of aboveground biomass in subzones A, B and D (Figure 4.5b), while across all study areas, warming dominated the relative changes in aboveground biomass in subzones A and B (Figure 4.5d). Such contrast indicates that grazing is important both locally and regionally.

Southern subzones (D and E) responded to climate change (warming) with greater biomass increases than northern subzones (A, B and C) (Figure 4.7). This is consistent with remote sensing studies that found greater NDVI increase in vascular-dominated tundra regions (e.g. Olthof et al 2008). Multi-decadal time-series of the NDVI shows a “greening” trend across the arctic tundra biome, with spatial differences in magnitude that likely reflect regional trends in climate and summer sea-ice extent (Olthof, Pouliot et al. 2008; Bhatt, Walker et al. 2010). However, these coarse-resolution satellite-derived measurements provide minimal information with regard to whether these changes are the result of forcings other than just climate.

Grazing may complicate our interpretation of the “greening” of the arctic tundra. Comparing tundra plant community responses to warming with and without grazing presence, the aboveground biomass change was quite different. Additionally, how vegetation response to warming can be reduced by intensive grazing remains unknown. There can also be greater potential heterogeneity in tundra plant responses to climate change due to differences in grazing, soils, warming magnitudes and other disturbance history across the Arctic (Yu, Epstein et al. 2009; Walker, Forbes et al. 2010; Yu, Epstein et al. 2011). Different grazing patterns and pressures may also produce vegetation communities with different dominant species (van der Wal 2006).

The history of reindeer/caribou grazing, as one contributing disturbance in the Arctic, is an important factor that needs to be considered, when we try to understand the variations in "greening" magnitudes (Olofsson, Lauri Oksanen et al. 2009; Epstein, Raynolds et al. 2012). Our results demonstrate that differences in grazing pressure across the Arctic can result in very different levels of observed "greening" of the Arctic. Additionally, reindeer overabundance in some arctic regions might have implications that permeate throughout trophic systems (Ims, Yoccoz et al. 2007).

There are several factors that need to be considered before we can decide which direction heavy grazing is taking tundra plant communities. First, altered nutrient cycling by reindeer includes processes such as expedited decomposition through reindeer digestion. Soil compaction and reduced soil moisture can be caused by trampling. Additionally, dwarf shrubs are more susceptible to trampling comparing to graminoids. Declines in shrubs may increase light availability to understory plants and promote their growth. Shrub growth and how it responds to climate warming are critical for both the local ecosystems and also for the climate system due to the ability of shrubs to alter albedo. A change in shrub cover could also alter the hydrology of the tundra through increasing summer transpiration and radiation absorption (Hallinger, Manthey et al. 2010).

In addition to modeled environmental factors, including the latitudinal climate gradient, soil organic nitrogen, grazing, and temperature change, factors such as permafrost, snow and others are not yet incorporated in the ArcVeg model, and this can contribute substantially to the uncertainty of tundra plant response to climate change and the interpretation of the "greening" signal detected by satellite remote sensing.

Acknowledges

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Appendix

Grazing and warming caused absolute and relative biomass change across different floral provinces were shown in Figure 4.A.1 and 4.A.2 respectively.

Figure 4.A.1: Comparison of grazing and warming effects on aboveground biomass in each floral province across all study areas.

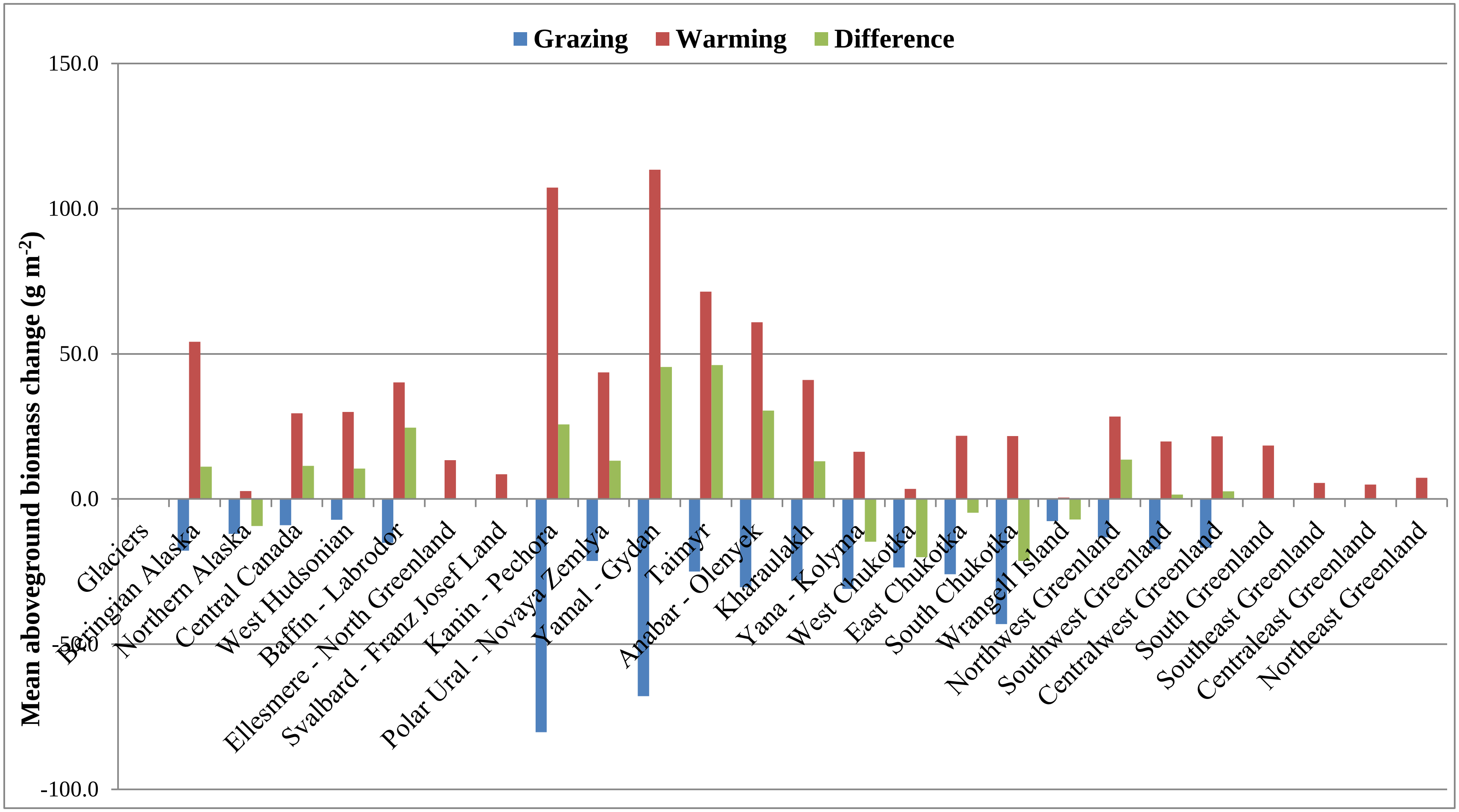
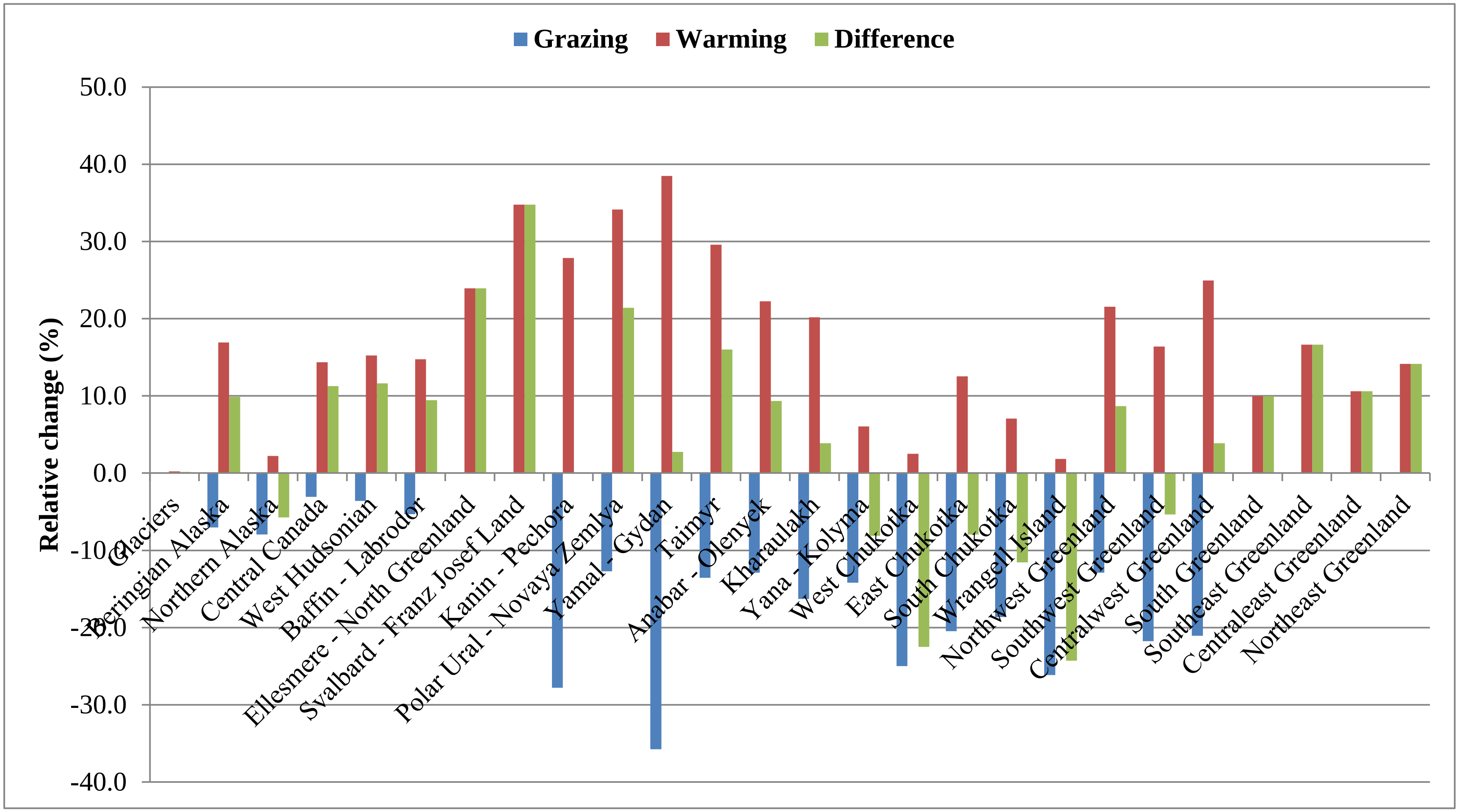


Figure 4.A.2: Comparison of grazing and warming effects on relative aboveground biomass change in each floral province across all study areas.



Chapter 5: Land cover and land use change in the vicinity of an oil/gas facility in northwestern Siberia, Russia

Abstract

Northwestern Siberia has been undergoing various land cover and land use changes from both animal husbandry and oil/gas development. Oil and gas development can obviously cause conspicuous changes in the land cover due to extensive road and pipeline networks which denude vegetation from the surface. In this study, multi-temporal and multi-spatial remotely sensed images were assessed and used to quantitatively examine the impacts of changed areas on surface vegetation, radiation, and hydrological properties. The results indicate that the impacts of extensive development were significant in terms of Normalized Difference Vegetation Index (NDVI), albedo and Normalized Difference Water Index (NDWI) near the developed area with logarithmic relationships between these physical indices (derived from remotely sensed images) and distance from the developed areas. Additionally, these remotely sensed indices suggest that the development impacts can persist for decades.

Keywords: arctic ecosystems; Corona; land use change; Landsat TM; QuickBird; permafrost; remote sensing indices; Siberia

1. Introduction

The linkages among climate, sea ice, vegetation, and human activities can have profound impacts on arctic ecosystems (Bhatt, Walker et al. 2010; Walker, Forbes et al. 2010). The vulnerability to climate change in the Arctic has been assessed (Richter-

Menge et al. 2011) and compared with many other parts of the world (Turner, Matson et al. 2003; ACIA 2004; Ford, Smit et al. 2006). However, interaction effects of other anthropogenic factors with climate warming on arctic ecosystems, such as those in northwestern Siberia, have not received enough attention until recently (see Kumpula et al.2011). Demands for energy from oil and gas have caused population growth and industrial development in the Arctic. Nomadic people in northern European countries and Russia rely heavily on reindeer husbandry and therefore on arctic vegetation. Human activities have caused land cover and land use changes that can interact with climate warming, altering surface energy budgets and having a potentially great impact on the arctic system, including both marine and terrestrial components (Pielke 2002; Hinzman, Bettez et al. 2005; Huntington, Boyle et al. 2007).

Since the discovery of oil/gas deposits in the Russia Arctic during the 1950s, related industrial development, including facilities, roads, and pipelines, has had local and regional impacts on tundra vegetation, and surface radiation and hydrological properties, which could influence permafrost stability. A set of many complex and interacting factors control permafrost dynamics (climate, soil, vegetation, and hydrology) associated with terrain evolution across the broad geomorphic environments of arctic ecosystems (Jorgenson and Osterkamp 2005; Jorgenson, Romanovsky et al. 2010). Observations in Siberia have shown that permafrost has warmed about 0.5 to 2 °C from 1984 to 2009, and disturbed sites have higher ground temperatures at 10m depth than undisturbed sites of similar conditions (Romanovsky, Drozdov et al. 2010). Land use effects on arctic ecosystems have been studied for decades through field observations and aerial surveys (Walker, Webber et al. 1987; Walker and Walker 1991). Small-scale, high-intensity human activities, such as road construction and off-road vehicle tracks can eliminate tundra vegetation, cause soil compaction, and alter soil nutrients, soil moisture, and pH, and in some cases, initiate permafrost degradation (Auerbach, Walker et al. 1997). These above-mentioned plot-scale studies shed light on how road construction and associated dust has affected tundra vegetation and soils. However, the impact of human activities on land cover properties in the Arctic needs further investigation.

Satellite imagery has been widely used to detect land cover and land use dynamics (Turner, Skole et al. 1995). Satellite imagery can complement field studies that are limited in space and time, since remote sensing can be used to observe systems at various spatial scales and potentially over long time periods. Using the Normalized Difference Vegetation Index (NDVI) derived from Advanced Very High Resolution Radiometer (AVHRR) data, a “greening” trend in arctic tundra vegetation, consistent with increasing temperatures, has been reported in several studies (Jia, Epstein et al. 2003; Goetz, Bunn et al. 2005; Bhatt, Walker et al. 2010). Shrub expansion in the Arctic, presumably also caused by warming, has been captured by studies using repeat aerial photographs (Sturm, Racine et al. 2001; Tape, Sturm et al. 2006). Many other physical and environmental parameters related to land surface dynamics can also be retrieved from remotely sensed data, such as surface temperatures (Qin, Karnieli et al. 2001; Jones, Kimball et al. 2007), snow cover (Chang et al. 1987, Brown et al. 2010), soil freeze-thaw state (Smith, Saatchi et al. 2004), and growing season timing and length (Kimball, McDonald et al. 2004; Stow, Hope et al. 2004).

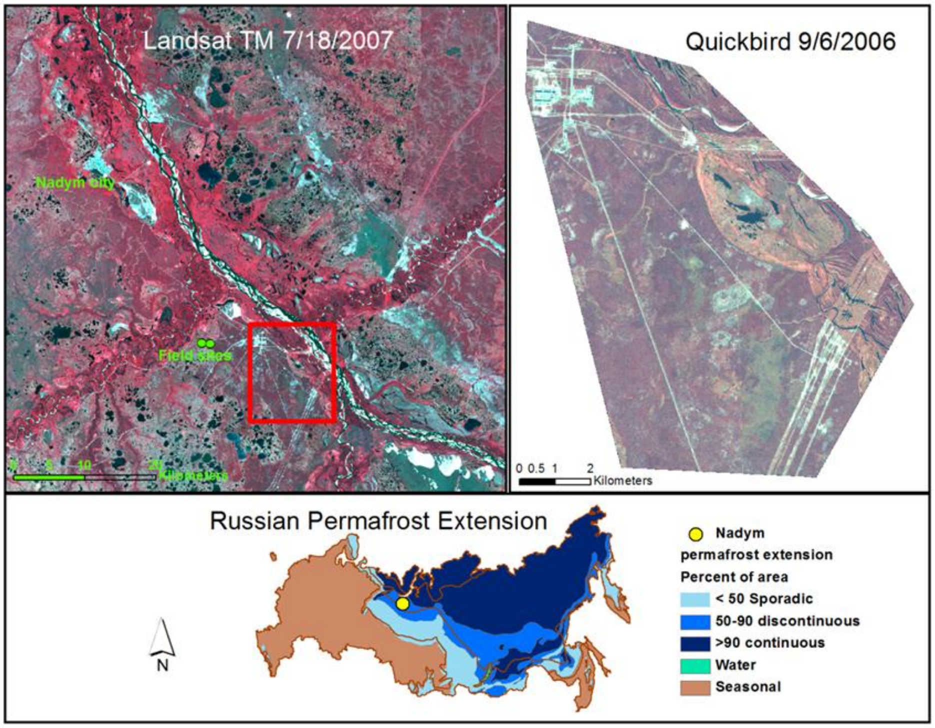
Northwestern Siberia has become a “hot spot” of land cover and land use change. It is undergoing climate change and has been impacted by various other anthropogenic forcings (e.g. city expansion, oil/gas development and animal husbandry). Oil and gas development can cause extraordinary changes in the land surface due to extensive road and pipeline networks. Walker et al. (2010) used a relatively long (25 year) time series of coarse-resolution (AVHRR) satellite imagery for the Yamal Peninsula, Russia to show that much of the land surface of this region has been influenced by land use and development. However, identifying the detailed relationships between the tundra and these disturbances requires some satellite imagery of a high resolution (tens of meters or finer). The research objectives of this study are to use multi-temporal and multi-spatial remotely sensed images to understand the impacts of land use change on vegetation, surface reflectance and hydrological properties.

2. Methods and materials

2.1 Study region and data

The study region encompasses the city of Nadym at 65°19' N and 72°53'E (Figure 5.1), which is located to the south of the Yamal Peninsula, in northwestern Siberia. This area is of tremendous strategic importance to Russia and has become the main source of Europe's current and future energy resources, consequent to the discovery of the gas deposit "Medvezhye" in 1967. This region lies within the discontinuous permafrost zone, with permafrost mostly confined to peatlands and frost-heaved mounds. Two field sites at Nadym were set up for zonal vegetation studies in 2007, close to a site of the Circumpolar Active Layer Monitoring (CALM) project (Walker et al. 2008). The mean annual air temperature is -5.9 °C, and the mean summer air temperature is 10.8 °C. The growing season normally extends from late June to late September. Tundra vegetation is present, and well-drained locations along the river valleys are covered by boreal forest. The trees are mainly Scots pine (*Pinus sylvestris*) and mountain birch (*Betula tortuosa*) mixed with Siberian larch (*Larix sibirica*). The understory consists of dwarf shrubs (*Ledum palustre*, *Betula nana*, *Empetrum nigrum*, *Vaccinium uliginosum*, *V. vitis-idaea*), lichens (mainly *Cladonia stellaris*) and mosses (mainly *Pleurozium schreberi*). In areas affected by frost heave, sparse cedar (*Pinus sibirica*) forests with wild rosemary-lichen communities and wild rosemary-sphagnum-lichen communities predominate (Walker, et al. 2008).

Figure 5. 1 Study region shown in a Landsat TM scene (2007) of approximately 5625 km2 and a QuickBird scene (2006). The red square on the Landsat image shows the QuickBird image range. Both images are shown with the band combinations: red-NIR band, green-Red band, blue-Green band. The study region is situated in the discontinuous permafrost zone.



Multi-temporal and multi-sensor remotely sensed imagery, including high resolution Corona photos (available from 1959 to1972), QuickBird-2 imagery (since 2001) and Landsat Thematic Mapper (TM) images (since 1982) were collected in order to detect changes in land surface properties. My objective was to conduct spatial analyses within the gas development areas. The selected images were acquired during the growing season, preferably during the peak of growing season, which ranges from mid-July to early-September in high latitude regions (Jia et al. 2009). Table 5.1 lists the basic spectra, spatial, and temporal information of the images.

2.2 Imagery processing and indices derivation

Landsat images from 1984-2011 were collected from the USGS (glovis.usgs.gov). To minimize the impact from cloud cover, we selected images with less than 10% cloud cover across the study region. All images were pre-processed using a high-end processing tool called the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS version 10.07.11) provided by the NASA LEDAPS team (Masek et al. 2006). All images were geo-referenced and sub-sampled to an area covering the Nadym city and the old oil/gas facility. Bio-physical indices, including NDVI (Rouse et al. 1974), albedo (Liang 2001), and NDWI (Normalized Difference Water Index) (Gao 1996) were derived from surface reflectance for each year.

NDVI was calculated with the following equation.

$$\mathrm{NDVI} = ((\rho\_{NIR} - \rho\_{RED}))/((\rho\_{NIR} + \rho\_{RED}))$$

Or $$\mathrm{NDVI} = ((\rho\_{4} - \rho\_{3}))/((\rho\_{4} + \rho\_{3}))$$

Where ρ_{RED} and ρ_{NIR} stand for the spectral reflectivity acquired in the red and near-infrared wavelength intervals, i.e. band 3 (0.63-0.69um) and band 4 (0.76-0.90um) of Landsat images.

Albedo was estimated using the equation derived by Liang (2001) for Landsat ETM+ using the following formula. I assumed the surface was Lambertian to use reflectance of each band as narrow-band albedo.

$$\text{albedo} = 0.356*\rho_1+0.130*\rho_3+0.373*\rho_4+0.085*\rho_5+0.072*\rho_7-0.0018$$

where $\rho_{1,3,4,5,7}$ are the narrow-band reflectances.

NDWI, a more recently developed index calculated from the near infrared (NIR) and shortwave infrared (SWIR) channels, captures changes in both surface water content and water in vegetation canopies (Gao 1996). Negative values in NDWI are generally associated with dry bare soils.

$$\text{NDWI} = ((\rho\_\text{NIR}-\rho\_\text{SWIR}))/((\rho\_\text{NIR}+\rho\_\text{SWIR}))$$

$$\text{or NDWI} = ((\rho\_4-\rho\_5))/((\rho\_4+\rho\_5))$$

Where ρ_NIR and ρ_SWIRstand for the spectral reflectivity acquired in the near-infrared and short-wave infrared wavelength intervals, i.e. band 4 (0.76-0.90um) and band 5 (1.55-1.75um) of Landsat images.

QuickBird imagery was acquired for September 10th, 2006. The image was radiometrically and atmospherically corrected. Corona images were acquired from 1968, and the images were geo-referenced and co-registered with the QuickBird imagery. The images were mosaicked for further change detection analysis with the QuickBird imagery.

Table 5.1 Imagery collected for use in this study included a pair of Landsat images of 30m spatial resolution and a pair of VHR imagery of less than 2.4 meter of spatial resolution.

Mission and Sensor	Date	Spectral bands	Pixel resolution
Corona	8/21/1968	Pan	2m
Quickbird	9/10/2006	Multi, Pan	2.4m, 0.8m
Landsat-5, TM	6/6/1986, 9/13/1987, 7/15/2006, 7/18/2007, 7/23/2009, 8/24/2009, 6/27/2011	Multi	30m
Landsat-4, TM	6/19/1988	Multi	30m

2.3 Temporal and spatial analyses

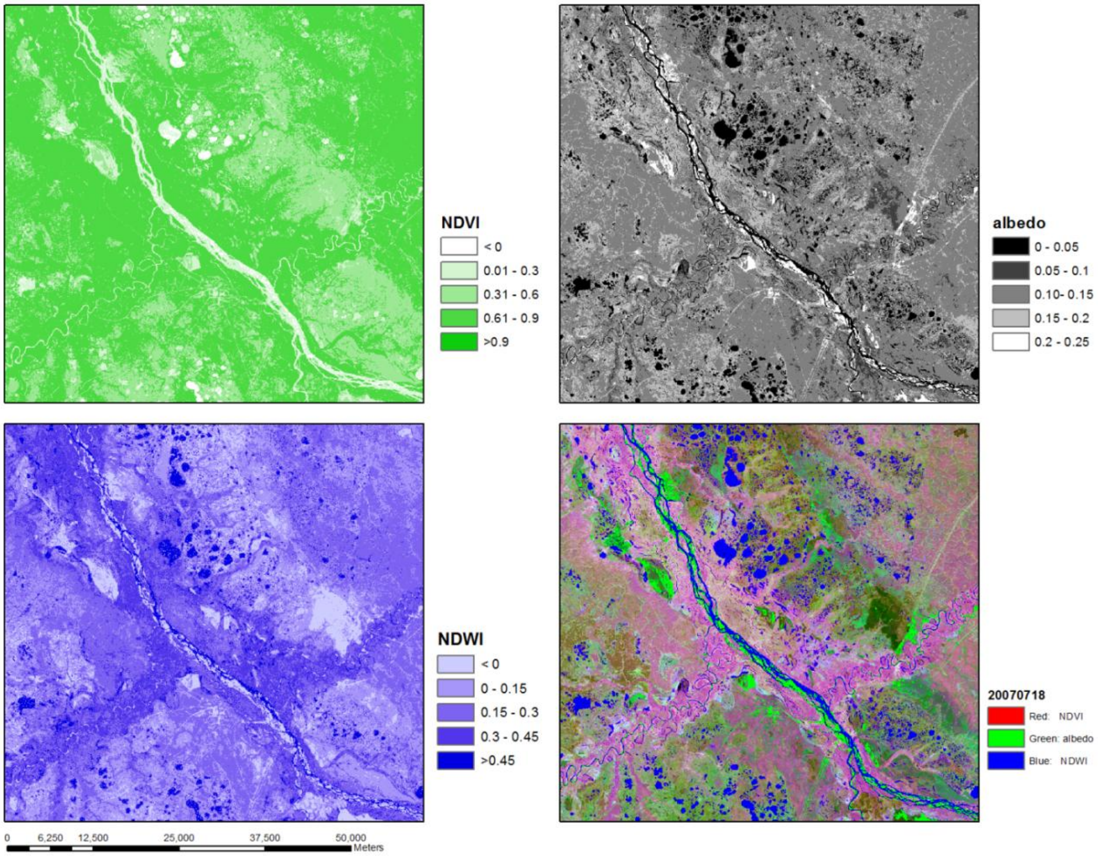
To analyze land use impacts on vegetation, surface reflectance properties and hydrological regimes, roads, facilities and vehicle tracks (feature data) were digitized, based on the QuickBird imagery. Then I used the buffer tool in ArcGIS to create a series of buffer zone data along the digitized roads and facilities at 30 meter intervals up to 600 meters away from the oil/gas industrial infrastructure. To reduce the seasonal impact due to vegetation phenology, we acquired and analyzed four images in 2007 (May 15th, July 18th, September 4th and September 20th), in order to understand how these indices may vary across a growing season. Then spatial statistical analyses within each buffer zone based on extraction of Landsat-derived NDVI for scenes from each year, were conducted in ArcGIS using the zonal spatial analysis tool. Heavily disturbed regions were determined by visual interpretation centered on the gas facility. The analyses were conducted in ENVI 4.9 (Exelis Visual Information Systems Inc.) and ArcGIS 10.0 (ESRI Inc.).

3. Results

3.1 Indices derived based on Landsat images.

NDVI, albedo and NDWI were calculated for all Landsat images. Figure 2 shows an example of derived indices for July 18th, 2007. The average NDVI, albedo and NDWI across the study region during the growing season for a typical cloud-free scene are 0.61, 0.13, and 0.18 respectively.

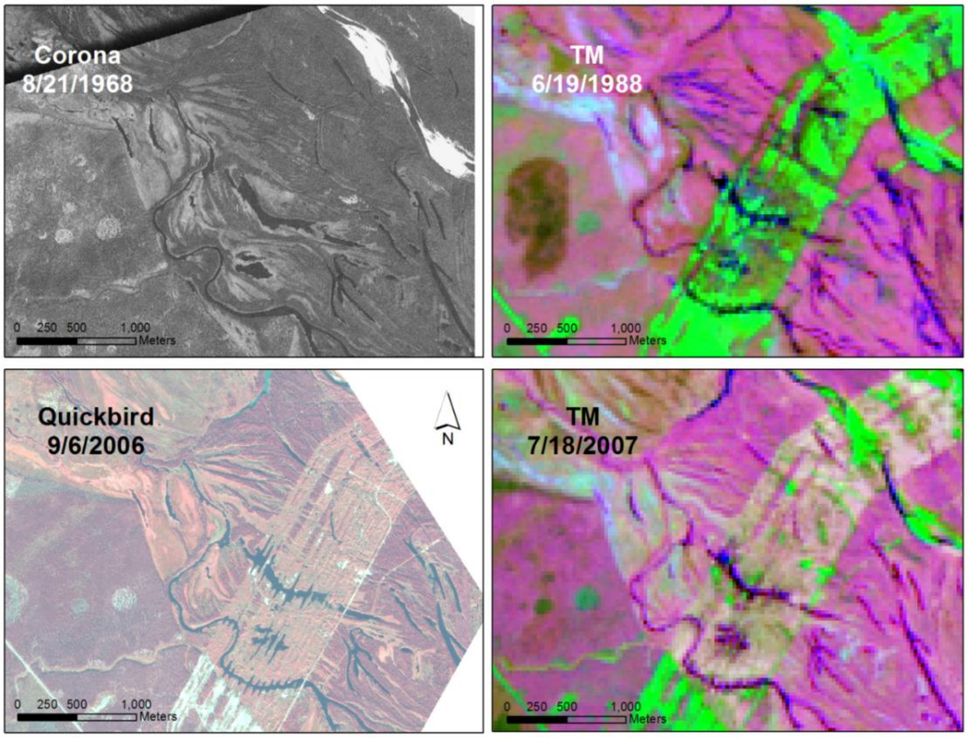
Figure 5.2 NDVI, albedo and NDWI calculated for an image acquired on July 18th 2007. A three band composited image (red-NDVI, green-albedo, blue-NDWI) shows the contrast between vegetated areas (high NDVI) and city and industrial development (high albedo).



3.2 Multi-temporal change detection and thermo-erosion caused by disturbances

Various significant changes were detected over time (Figure 5.3). On the mosaicked Corona images from 1968, there were no disturbances, such as gas facilities, roads, and tracks in the study region. However, extensive developments are shown on both Landsat TM scenes from 1988 to 2007 and the QuickBird scene in 2006. Such development had destructive impacts on vegetation at the local scale. There were bidirectional changes in the selected study region since 1988. Based on the comparison between TM scenes, vegetation decreased in developed areas due to new roads and tracks with declining NDVI and increasing albedo, but there were also disturbed regions with increased NDVI and decreased albedo, indicating a recovery of vegetation along abandoned roads and tracks. Surface reflectivity increased in areas with new facilities, new roads and buildings with a conspicuous increase in albedo. In 2007, only small scale buildings and short roads remained. Some areas showed abandoned vehicle tracks, with vegetation recovery that increased NDVI, when comparing the 2007 TM scene to an earlier TM scene (e.g. 1988). There were fragments of water bodies caused by road/track disturbances in comparisons of the Corona images and the Quickbird scene (Figure 5.3), indicated by water impounded along the tracks. Such changes require higher spatial resolution data (such as the Quickbird image) than Landsat TM to detect.

Figure 5.3 Multi-temporal images show the changes along roads/tracks. Corona images are panchromatic and shown as grey-scale. The Quickbird image is shown with false-color band combinations (Red-NIR, Green-R, Blue- G). Landsat TM images are shown with derived-index combinations (Red-NDVI, Green-albedo, Blue-NDWI).



3.3 Zonal spatial analyses

The zonal statistics showed that TM-derived indices were related to the distance away from the roads/tracks with a logarithmic relationship, consistently across years but with variations due to growing season differences (Figure 5.4). Similar patterns in the acute slopes in Figure 5.5 indicate that these impacts persist over decades.

NDVI varies with growing season (Figure 5.4). On May 5th 2007, NDVI was lower than 0.1 and surface albedo was above 0.25, indicating no vegetation growth and a surface covered with snow and ice. As the growing season progressed, NDVI reached a peak between July 18th and September 4th and then started to decline by September 20th. Surface albedo is stable during the growing season but varied greatly between seasons. NDWI has similar pattern as surface albedo, as it reflects mixed soil moisture and vegetation signals, but mainly soil moisture.

Figure 5.4 Zonal seasonal changes in NDVI, albedo and NDWI along roads/tracks in year 2007 at distances from roads/tracks up to 600m.

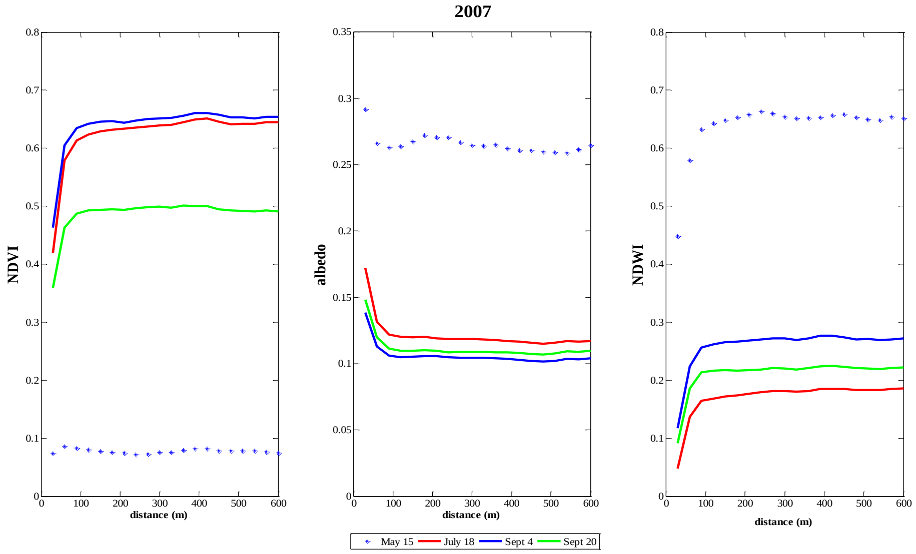
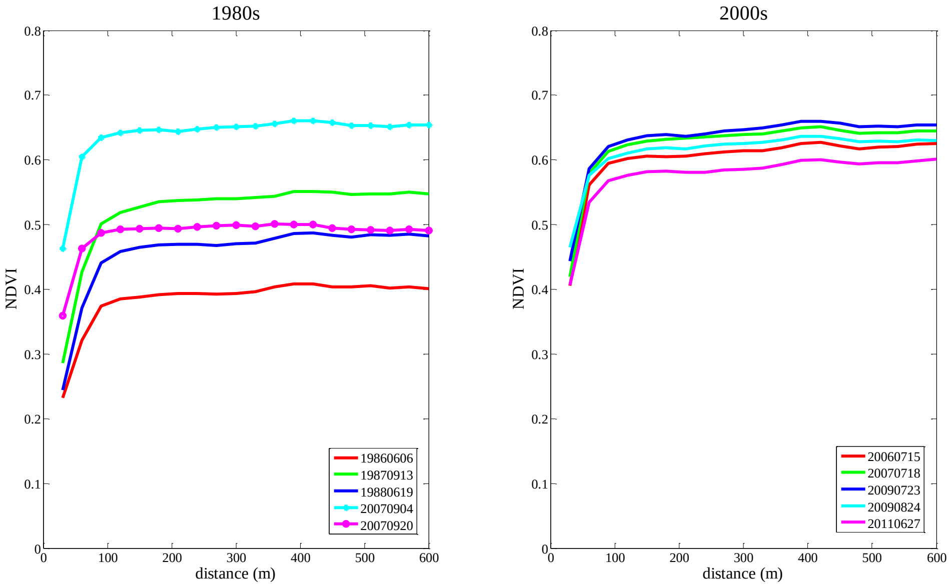


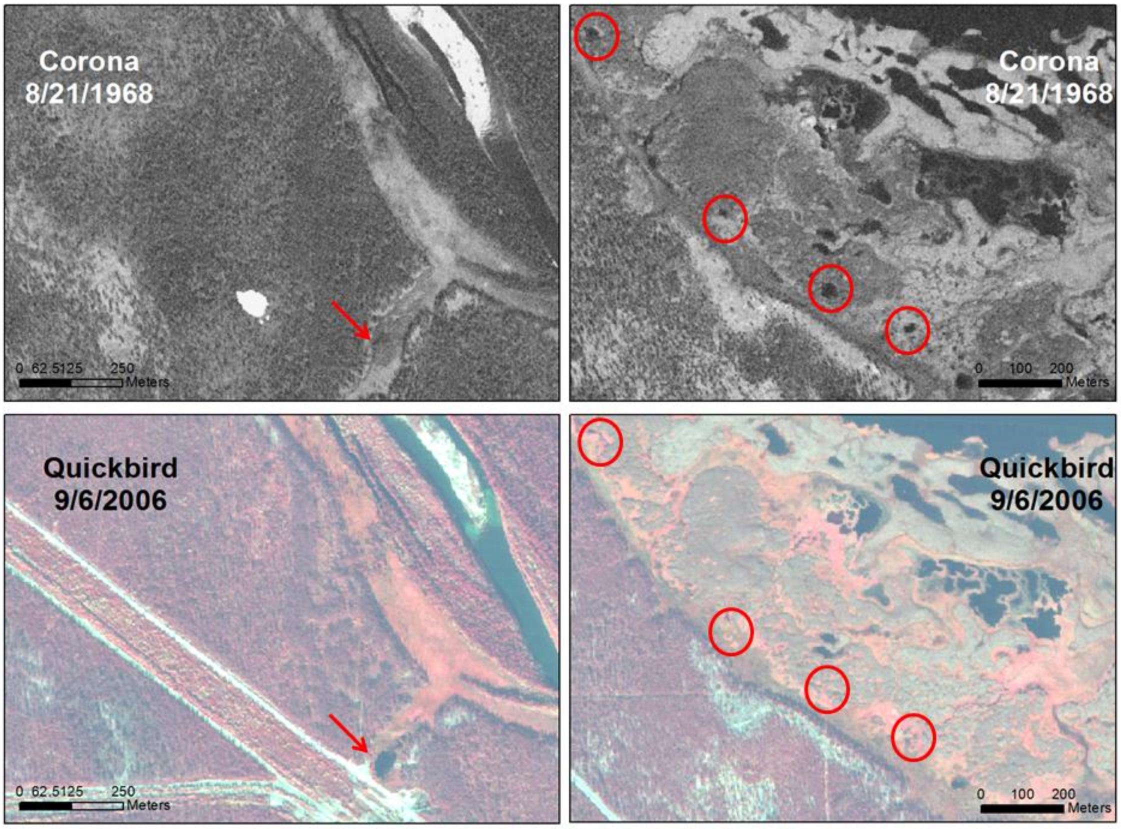
Figure 5.5 Comparison of zonal analysis on image-derived NDVI around roads/tracks at distances up to 600m.



4. Discussion and conclusion

I found that vegetation, surface reflectance and hydrological properties varied logarithmically with distance from roads and facilities. This is similar to what Auerbach et al. (1997) found in field studies along the Dalton Highway in Alaska (Auerbach, Walker et al. 1997). Image-derived indices also suggest that such effects persist over decades given that the zonal trend along the developed area did not change, even though some increases in NDVI and decreases in albedo suggested recovery of vegetation along vehicle tracks. This finding is consistent with the analyses based on images of high spatial resolution in other regions of northwestern Siberia (Forbes, Ebersole et al. 2001; Kumpula, Pajunen et al. 2011).

Figure 5.6 Comparison of Corona and QuickBird images. The left two figures show that there was a new lake formed along the roads. The right two figures show that some lakes disappeared between 1968 and 2006.



Significant changes in surface water caused by roads and tracks may have altered surface energy budgets for these areas. Water absorbs more energy than reflective surfaces such as roads and vehicle tracks. Changes in lake sizes may therefore have altered surface energy exchanges accordingly. There was a new thaw lake formed along a road, based on the comparison of QuickBird and Corona images (Figure 5.6). This may suggest that human activities accelerated surface warming and thus caused belowground thaw. There are also opposite directional changes such as disappearing lakes, indications of underground thaw which causes existing lakes to drain (Smith, Sheng et al. 2005).

Zonal spatial analyses based on image-derived indices suggest that roads and other development impacts are generally local and constrained within 200 meters. However, data also suggest that these development effects on surface properties do persist over decades. Given the importance of permafrost, further investigations on how these surface impacts extend belowground are warranted.

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Chapter 6: Discussions and future research

Arctic system components are interconnected and feedbacks among these components are pivotal to understanding of how arctic systems can contribute to global change and the changes within arctic systems (Duarte, Lenton et al. 2012). Low temperature and thus low rates of nutrient turnover has been limiting these ecosystems for long period of time (Chapin 1992). Amplified climate warming in the Arctic has initiated a chain of changes which may in turn change nutrient regimes and thus have impacts at the ecosystem and even broader levels. In this dissertation, different approaches were used to estimate how tundra vegetation has changed in response to multiple environmental changes include climate, grazing and land use. An existing tundra vegetation dynamics model was used to explore individual and interaction effects of climate, soils and grazing on tundra plant communities across Russian- and Pan- arctic regions. A set of remotely sensed imagery was used to assess changes around oil/gas development in Northwestern Siberia, where exploration can pose great threat to wildlife, semi-domestic reindeer herding, and tundra vegetation.

The model was first adapted from 20 plant functional types to 12 plant functional types and validated with data from North America Arctic Transect (NAAT) and Eurasia Arctic Transect (EAT). The model was developed with data essentially from North America and correlated to the biomass data collected from NAAT well. However, the model seemed to under-predict the biomass in EAT, indicating differences in controls on plant community properties.

The application of ArcVeg model to the Yamal Peninsula has revealed three major mechanisms:

1. Grazing is the most important regional control on tundra plant community biomass and composition in addition to latitudinal climate gradient. Certain plant functional types such as deciduous shrubs and lichen that are palatable to reindeer can be susceptible to intense grazing, while evergreen shrubs may benefit from increased grazing intensity. 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 in subzones C and D when evergreen shrub growth rates were decreased in the model. At the circumpolar scale, grazing can abate plant responses to climate change and thus complicating our interpretation of remotely sensed vegetation trends.

2. Warming promote tundra plant growth in ways of increasing decomposition rates, which was the main assumption of ArcVeg. Plant biomass and NPP (net primary productivity) were significantly increased with warmer bioclimate subzones, greater soil nutrient levels and temporal climate warming, while they declined with higher grazing frequency. The response of moss, lichen and forbs to warming varied across the different subzones. 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) within tundra plant communities.

3. Our results suggest that high SON can support greater plant biomass and plant responses to climate warming, while low SON and grazing may limit plant response to

climate change. In addition to the first order factors (SON, bioclimate subzones, grazing and temporal climate warming), interactions among these significantly affect plant biomass and productivity in the arctic tundra and should not be ignored in regional scale studies.

Multi-sensor and multi-temporal remotely sensed data has revealed the changes caused by oil/gas development, particularly has denuded surface when these development started. These impacts can last for a few decades according to temporal-spatial analysis of derivatives from remotely sensed data.

Decreased sea ice cover, shrub expansion and thawed permafrost are seemingly multiple lines of the change but rather can be interconnected changes. In addition to temperature, sea ice change can potentially affect regional energy budget and thus affect tundra vegetation at the circumpolar scale (Bhatt et al 2010). Snow distribution in the Arctic has implications for shrub tundra response to warming and grazing. Although shrub-snow interactions can promote shrub growth during the early growing season (Sturm, McFadden et al. 2001; Sturm, Douglas et al. 2005), recent research found declines in snow cover in North America and Eurasia (Shi and et al. 2011). Decreased snow cover can strengthen snow-shrub interactions, allowing more shrubs to be exposed and lower surface albedo and increasing solar radiation absorption. Climate warming in the Arctic can be accelerated by these feedbacks (Chapin, Sturm et al. 2005). But these shrubs can become new food to reindeer especially when freezing event became more often, thus supporting reindeer population during winter and early growing season (Bartsch, Kumpula et al. 2010).

As Arctic sea ice decline and arctic becomes more accessible, land use impact will also be necessary to be considered for better understanding of tundra vegetation dynamics (Forbes 1992; Forbes 1999; Forbes, Ebersole et al. 2001; Forbes, Boelter et al. 2006). Land use change can have significant short term impact on regional tundra vegetation and such impacts were found to persist for decades (Kumpula, Pajunen et al. 2011). With continual extensive oil/gas exploration since 1957 till present in northwest Siberia, impacts on tundra vegetation may have abated “greening” signal in this region. Developments in the Arctic are on the work schedule of tourist companies etc. This is the second important factor next to Arctic climate change affecting tundra ecosystems (Forbes, Ebersole et al. 2001). Tundra fire regimes have changed in recent decades. Multiple factors including record high summer temperature, low summer precipitation and extremely dry soil conditions explained the largest recorded tundra fire in Anaktuvuk River region (Jones, Kolden et al. 2009). Recovery from fire can result in increase in shrub cover comparing to pre-fire condition (Racine, Jandt et al. 2004). Warming has changed vegetation phenolgy and thus animals that rely on it. Insects may start their life cycles earlier in spring. Reindeer, caribou and other mammals need to migrate earlier to the north to minimize the impacts of these changes.

Other disturbance regimes may have changed since warming of the Arctic. For example, fire in tundra has become more frequent and severe. Multiple factors including record high summer temperature, low summer precipitation and extremely dry soil conditions explained the largest recorded tundra fire in Anaktuvuk River region (Jones, Kolden et al. 2009). Recovery from fire can result in increase in shrub cover comparing to pre-fire condition (Racine, Jandt et al. 2004). Nitrogen fixation and deposition are crucial nitrogen input to the tundra ecosystems and ArcVeg currently has not fully included in our modeling process. These effects need to be considered when we try to understand tundra vegetation dynamics.

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