

## Chapter 9

# Cumulative Effects of Rapid Land-Cover and Land-Use Changes on the Yamal Peninsula, Russia

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**Abstract** The Yamal Peninsula in northwest Siberia is undergoing some of the most rapid land-cover and land-use changes in the Arctic due to a combination of gas development, reindeer herding, and climate change. Unusual geological conditions (nutrient-poor sands, massive ground ice and extensive landslides) exacerbate the impacts. These changes will likely increase markedly as transportation corridors are built to transport the gas to market. Understanding the nature, extent, causes and consequences (i.e., the cumulative effects) of the past and ongoing rapid changes on the Yamal is important for effective, long-term decision-making and planning. The cumulative effects to vegetation are the focus of this chapter because the plants are a critical component of the Yamal landscape that support the indigenous Nenets people and their reindeer and also protect the underlying ice-rich permafrost from melting. We are using a combination of ground-based studies (a transect of five locations across the Yamal), remote-sensing studies, and analyses of Nenets land-use activities to develop vegetation-change models that can be used to help anticipate future states of the tundra and how those changes might affect traditional reindeer herding practices and the thermal state of the permafrost. This chapter provides an overview of the approach, some early results, and recommendations for expanding the concept of cumulative-effects analysis to include examining the simultaneous and interactive effects of multiple drivers of change.

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## 9.1 Introduction

### 9.1.1 *Impending Changes to the Yamal Peninsula*

Although the Yamal Peninsula is currently one of the most remote regions on the planet with few roads, no major cities, largely intact natural ecosystems, and indigenous people who still live a nomadic lifestyle, it is poised for some of the most dramatic changes in any area of the Arctic (Fig. 9.1). Four major forces are combining to make this a “hot spot” of rapid change: an impending gas-development boom, rapid climate change, an unusually sensitive permafrost environment, and the rapid growth of the populations of gas workers, the indigenous Nenets and their reindeer herds. We address each of these separately in this report, but we are most interested in the combined effect of all four. This chapter focuses on the Yamal, but the approach should be of wide value in many other areas of the Arctic where similar forces of change are occurring (for example see [Chapter 8](#), this volume). The goal is to develop predictive models and tools that can be used to help the indigenous people and other stakeholders in the Arctic to plan for and adapt to future change.

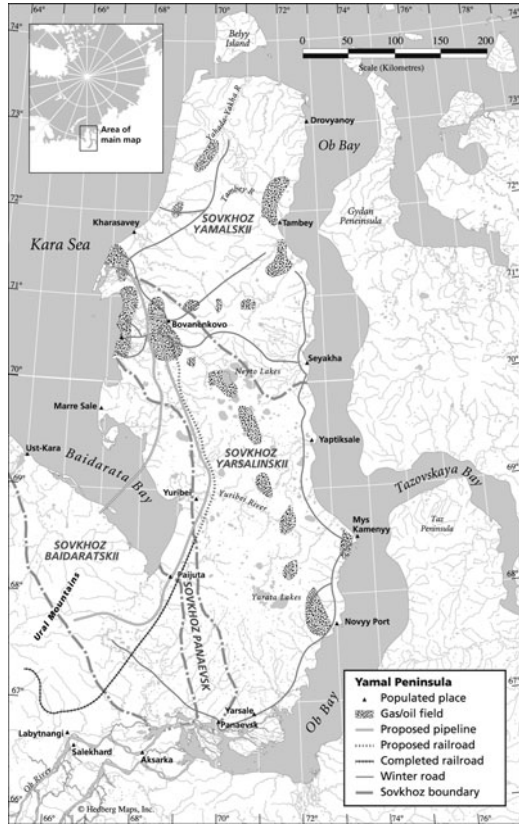
**Fig. 9.1** Nenets reindeer herder passing a gas derrick in the Bovanenkovo gas field, Yamal Peninsula, Russia. The presence of the gas field provides both economic opportunities for the Nentsy and a source of conflict because of competition for land and barriers created by roads and pipelines during the annual migrations. Climate change could enhance the growth of shrubs, also shown in the figure, and change the character of the reindeer pasture lands (Copyright and reproduced by permission of Bryan and Cherry Alexander)



### 9.1.2 *Description of the Yamal*

Yamal is a Nenets term for the “end of the land”, which is fitting for this long tundra-covered finger of land that juts into the Arctic Ocean (Fig. 9.2); the peninsula stretches roughly 700 km from the Arctic Circle (66° 33.5' N) in the south to Ostrov

**Fig. 9.2** Yamal Peninsula and associated gas and oil fields, with existing planned transportation corridors. The main existing gas field is at Bovanenkovo (From Forbes 1999a with permission of the editors of *Polar Research*)



Belyy (White Island, 73° 20' N) at the tip of the peninsula. It is bounded on the west and north by the Kara Sea and on the east by the embayment of the Ob River. The peninsula is about 150 km wide with an area of 122,000 km<sup>2</sup> (somewhat larger than Pennsylvania or North Korea). This flat to gently rolling plain consists of a series of mainly marine, lacustrine, and alluvial deposits; the oldest deposits are in the interior parts of the peninsula at elevations between 45 and 90 m and were deposited more than 130,000 years ago; most of the peninsula consists of younger sediments deposited during and following the last glacial maximum (ca. 30,000–12,000 years ago). The deposits are sandy to clayey, most are saline within the permafrost, and some are saline in the active layer (the layer of soil above the permafrost that melts annually). Hilltops in sandy areas are often windblown with sand hollows, some covering large areas. Low areas between the hills are often occupied by polygonal peatlands. The peninsula was unglaciated during the last glaciation and supported Pleistocene (from 2.588 million to 12,000 years BP covering the world's recent period of repeated glaciations) plants mammals and humans throughout the glaciation and into the Holocene (ca. 12,000 years ago to the present) (Forman et al. 1999).

Politically, the peninsula is the northern part of the Yamal-Nenets Autonomous Okrug (YNAO), a high-level administrative district within Russia. The YNAO is situated east of the Ural Mountains and the northern part of the geographic border between Europe and Asia. The YNAO is 730,300 km<sup>2</sup> or about 1.5 times the size of France, and has a population of only about half a million people most of which are concentrated in cities in the southern part of the okrug that have grown rapidly in response to the discovery of oil and gas in the region, starting in the 1960s. The Yamal Peninsula itself is entirely within the Yamal'skii Raion (district), one of seven administrative districts within the YNAO, and is very sparsely populated; most of the population consists of nomadic Nentsy (see Section 9.4), who use the peninsula as pasturelands for their large reindeer herds (Stammler 2005).

## 9.2 Study Goals and Approach

This study is intended to contribute to the large questions regarding the future of the Nentsy and their reindeer. How will the indigenous people and their herds be affected by the simultaneous major changes associated with climate warming, industrialization, and the growth of their own herds (Forbes 1999a, 2008)? The major foci of our study are the linkages between the vegetation, natural and anthropogenic disturbance factors, climate, sea-ice concentrations, land-surface temperatures, and other landscape variables. A principal goal is to develop better, more far-looking tools to project the cumulative effects of resource development, climate-change, and traditional land use by combining scientific and traditional knowledge of the landscapes, socio-economic analyses, remote sensing, climate change analyses, and vegetation-change models.

### 9.2.1 Information from Previous Studies

The project is a collaboration of investigators from three primary groups: (1) the Earth Cryosphere Institute (ECI), Moscow, (2) members of the Environmental and Social Impacts of Industrialization in Northern Russia (ENSINOR) project at the Arctic Centre in Rovaniemi, Finland, and (3) US investigators who are part of this NASA-funded Land-Cover Land-Use Change project.

The Russian and Finnish investigators have worked in the Yamal region for many years; they are providing key background information and are collaborating in all aspects of this ongoing research. Our aim is the co-production of knowledge, in concert with the Yamal-Nentsy to assess the overall cumulative effects – both positive and negative – from past resource exploration, reindeer herding, and climate change.

#### 9.2.1.1 ECI Baseline Studies

Researchers from the Earth Cryosphere Institute have been studying permafrost, vegetation and land processes on the Yamal Peninsula since the early hydrocarbon

exploration in the region in the 1970s. In the process, they have developed extensive climate and geocryological spatial data bases for much of West Siberia and northern Russia (Melnikov 1998; Minikin et al. 2001; Drozdov et al. 2005), and considerable field knowledge about the key sites along the Yamal transect. The ECI studies are coordinated with numerous international IPY programs and other Russian integrative and regional programs that are aimed at assessing changing permafrost conditions in Russia. The ECI colleagues are the principal collaborators for the field research in this project involving analysis of climate, vegetation, permafrost, and environmental variation along the Yamal climate transect (see Section 9.5). This knowledge foundation is essential to these cumulative effects studies.

### 9.2.1.2 ENSINOR Project

The ENSINOR project was funded by the Academy of Finland in 2004–2007 to make comparative case studies of oil and gas activities in two key federal districts – the Nenets Autonomous Okrug (NAO) and the Yamalo-Nenets Autonomous Okrug (YNAO) (Stammler et al. 2009). The ENSINOR project is providing key background information on the Nentsy, their reindeer and historical vegetation and landscape changes that have occurred in the Bovanenkovo gas field and elsewhere on the Yamal (Forbes 1999b, 2008; Forbes and Stammler 2009). These districts contain Russia’s most productive proven energy sources for the present and the foreseeable future and so are particularly important to the energy security of Europe. As major clients and/or partners of Russian oil and gas companies, Finland, Norway and other Western European countries have responsibilities to see that the developments proceed in a manner that minimizes negative impacts to the landscapes and indigenous people in the affected areas. The ENSINOR project, conducted mainly by the Arctic Centre at the University of Lapland in Rovaniemi, Finland, undertook a thorough multidisciplinary analysis of the social and environmental consequences of energy development in the study region. This study incorporates knowledge that stems from different traditions among both scientists and herders and their respective ways of knowing about contemporary social-ecological systems.

## 9.2.2 Field Research

One objective of the project is to quantify variations in the natural zonal vegetation and associated biophysical properties across the bioclimate gradient on the Yamal Peninsula, which has vegetation representative of four of the five circumpolar tundra bioclimate subzones<sup>1</sup> contained on the Circumpolar Arctic Vegetation Map

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<sup>1</sup>The Arctic bioclimate subzones are defined by key plant growth forms, species limits and mean July temperatures (MJT): Subzone A: cushion-forb, *Saxifraga oppositifolia*, MJT <3°C. Subzone B: prostrate-dwarf-shrub, *Dryas integrifolia*, 3°C < MJT <5°C. Subzone C: hemiprostrate-dwarf-shrub, *Cassiope tetragona*, 5°C < MJT <7°C. Subzone D: erect-dwarf-shrub, *Betula nana/exilis*, 7°C < MJT <9°C. Subzone E: low-shrub, *Alnus viridis*, 9°C < MJT <12°C (Walker et al. 2005).

(Walker et al. 2005, 2008b) plus the northern boreal forest. Ground observations are being conducted at five locations representative of the subzones during field campaigns in 2007–2009. The locations were chosen to be representative of the zonal soils and vegetation, but also include variation regarding substrate (clayey vs. sandy soils) at each location. Usually this means sampling sites of different geologic age at each location. From north to south, the locations for the ground observations are Ostrov Belyy (subzone B, Kharasavey (subzone C), Vaskiny Dachi (near Bovanenkovo, subzone D), Laborovaya (subzone E), and Nadym (northern boreal forest)) (Fig. 9.2).

A data report summarizing the 2007 field information includes general descriptions of each locality and sample sites with photographs, maps of the study plots, and transects, summaries of sampling methods used, vegetation data (species lists, species cover), leaf-area index (LAI), Normalized Difference Vegetation Index (NDVI), soil data (profile descriptions and chemical and physical soil properties), and active-layer depth (Walker et al. 2008a).

### 9.2.3 Modeling Studies

The modeling approaches are highlighted in another chapter in this book (Chapter 2, this volume) and are only described briefly here. At the global scale, we use the BIOME4 iteration of the BIOME series of models to examine projected shifts of tundra types in the tundra biome as a result of climate change (Prentice et al. 1992; Kaplan et al. 2003). The BIOME models incorporate biogeography and biogeochemistry into a mechanistically-based equilibrium approach that essentially redistributes vegetation types geographically based on a new environment. BIOME4 adds three arctic plant functional types to the nine plant functional types simulated in BIOME3. Driven by General Circulation Model (GCM) output, the BIOME4 model projects a northward migration of the boreal evergreen forest at the expense of arctic tundra, as well as the expansion of erect shrubs to displace prostrate shrubs. A more comprehensive analysis using BIOME4 predicts that the boreal forest extent will increase by 55% and that the arctic tundra extent will decrease by 42%, with a 60% loss of prostrate dwarf-shrub tundra (Kaplan and New 2006).

Another model, ArcVeg (Epstein et al. 2000), uses the results from the Yamal field studies and a comparable transect in North America to predict the long-term dynamic changes in biomass for plant functional types growing within five bioclimate subzones of the Arctic. A modified version of ArcVeg (Epstein et al. 2007) is being used to model the effects of changes in summer temperature, different reindeer foraging regimes, rate of succession following denuding of the land, and responses on different soil types. The model uses a set of twelve plant functional types for five arctic subzones that range from the coldest areas at high latitudes to the relatively warm Low Arctic near tree line. We also assume that for the Yamal region, the managed reindeer graze and trample the range more intensely and more frequently than do caribou of North America. Frequent grazing also increases the interannual



variability in tundra primary productivity. In the final year of the project, we will incorporate the soil data from the Yamal into the model, improve the reality of the grazing subroutine, add a component that will examine succession on barren mineral soils, and conduct a rigorous sensitivity analysis of the effect of grazing on tundra productivity and functional type composition.

## 9.3 Gas Development

### 9.3.1 Overview

Oil and gas development is having large positive and negative economic, social, and environmental consequences in localized areas of Arctic North America, Russia, and Scandinavia, and these consequences will grow in the near future as resource extraction in these regions accelerates (Vilchek 1997; Walker 1997; NRC 2003; Forbes 2004). A 2050 scenario developed by the United Nations Environment Program (UNEP) Global Methodology for Mapping Human Impacts on the Biosphere (GLOBIO) project estimated that with the same growth rates of industrial development that occurred between 1940 and 1990, 50–80% of the Arctic will be accessible by expanding road networks and infrastructure by 2050 (UNEP 2001).

The Yamal Peninsula contains the largest known untapped gas reserves in Russia; several major hydrocarbon deposits were discovered on the Yamal Peninsula in the 1980s, and there are now 200 known gas fields (Gubarkov 2008) – the largest ones are shown in Fig. 9.2. Yamal gas deposits contain 13.5 trillion m<sup>3</sup> of proven gas reserves on land, and an estimated 50 trillion m<sup>3</sup> with additional deposits on the Kara Sea shelf. The deposits near Bovanenkovo, Kharasavey and Novy Port are estimated to contain 5.8 trillion m<sup>3</sup> of gas, 100.2 million metric tons of gas condensate, and 227 million metric tons of oil. The gas deposits of Yamal will contribute considerably to the World production. Proven Yamal reserves are close to the combined reserves of North America (7.5 trillion m<sup>3</sup>) and South America (7.1 trillion m<sup>3</sup>) (Gubarkov 2008).

The YNAO is Russia's top gas producing region – as of 2003 it accounted for about 25% of the total world gas production and one-fifth of the total revenue of the Russian government; however, the gas deposits of the Yamal Peninsula itself have remained untapped because infrastructure development was blocked due to unsolved ecologic problems in the 1980s and proceeded slowly during the time of political upheaval in Russia in the 1990s. During this time, the Russian government developed oil resources in more southerly parts of West Siberia, such as the Khanty-Mansiysky Okrug of Tyumen Oblast (Stammler 1998, 2005; Starobin 2008). To date, most of the major infrastructure on the Yamal Peninsula is in the giant Bovanenkovo gas field, where there is an extensive network of drilling sites, construction pads, and roads that began in 1987 (Vilchek 1997; Forbes 1999a, 2004). Russia is currently on the verge of approving development schemes on the Yamal Peninsula costing

billions of dollars. The Gazprom gas consortium has accepted the Yamal hydrocarbons transportation scheme of a main pipeline across the Baidarata Bay of the Kara Sea (Fig. 9.2). Four pipelines will transport 50–60 billion m<sup>3</sup> of gas each. A new road to the south and the Obskaya-Bovanenkovo Railway are under construction now. A cargo train operation is planned for in 2009 and passenger train service by 2011. There are plans to build an airport and river port in Bovanenkovo settlement. The seaport and fleet of vehicles are expanding in Kharasavey settlement as well. A network of winter roads between the various gas fields is estimated to be finished by 2020 (Gubarkov 2008).

Industrial activities and infrastructure on the Yamal Peninsula are currently concentrated in relatively small areas around the major gas deposits and along the railway/road corridor being constructed from Obskaya, near Labytnangi, to the Bovanenkovo Gas Field (70°17' N, 68°54' E). Outside these areas of relatively focused activity, there are many off-road vehicle trails and scattered signs of the exploration activities (Vilchek 1997; Forbes et al. 2001).

### ***9.3.2 Land-Cover and Land-Cover Changes Within the Bovanenkovo Gas Field***

Remote sensing and geographic-information-system (GIS) technology are being used to characterize the present-day distribution of vegetation and plant biomass and to catalog the changes to the landscape within the Bovanenkovo gas field and elsewhere on the peninsula. A combination of Advanced Very High Resolution Radiometer (AVHRR), Landsat Multi-Spectral Sensor (MSS), Landsat Thematic Mapper (TM), Satellite Pour l'Observation de la Terre (SPOT), Advanced Spaceborne Thermal Emission and Reflection (ASTER) TERRA, Quickbird-2, Corona and aerial-photo imagery are being used. A digital elevation model of the gas field was prepared from 1:100,000-scale topographic maps of the region. Details of the infrastructure (road network, pipeline network, off-road vehicle trails, construction pads, and quarries) were delineated on the remotely sensed images (Fig. 9.3). Comparison of the information that could be identified on each type of imagery showed that Quickbird multispectral imagery with 63-cm resolution gave results that were comparable and sometimes better than ground surveys (Table 9.1) (Kumpula et al. 2010; Kumpula 2008). For example, off-road tracks were easier to detect on the Quickbird imagery. All infrastructure pads, roads, pipelines, quarries and detectable off-road-vehicle trails were digitized and entered into a GIS of the region.

The total area covered by direct impacts including the footprint of the roads, pipelines and construction pads totals 9.3 km<sup>2</sup> (Table 9.2). The total perimeter of the gas field where there is restricted access to traditional pasturelands of the Nentsy is 448 km<sup>2</sup>, or about 48 times the area of the planned impacts.

The extent direct impacts of the Bovanenkovo field can be compared to similar data from the North Slope of Alaska, where the giant Prudhoe Bay and Kuparuk oil fields are situated (NRC 2003) (Table 9.2). The total direct impacts of the North



**Fig. 9.3** (top) Landscape and main developed area in the Bovanenkovo gas field. Reproduced by permission of D.A. Walker. (bottom) Quickbird image of the main developed area. Colored lines were digitized for GIS analysis and show construction pads for buildings and storage and roads (black), pipelines (blue), and off-road vehicle trails (red). Reproduced by permission of Timo Kumpula



Slope cover about 6.7 times as much area as the Bovanenkovo impacts. The total extent of the areas affected by the North Slope development (defined by the perimeter of the field) is about 2,600 km<sup>2</sup>, or about 5.8 times the extent of the Bovanenkovo field. There are about twelve times as many roads, ten times as much area covered by gravel pads, and six times as much area affected by quarries on the North Slope compared to the Bovanenkovo field.

Some indirect terrestrial ecological impacts associated with seismic surveys, off-road vehicle trails, pollution of pastures by trash and petrochemicals, road dust and disturbance from the roads and quarries can be assessed from the aerial images (Forbes 1995, 2004; Vilchek 1997). Additional related social impacts that are not visible on the images include exposure of herders to alcohol, feral dogs which can harass and kill reindeer, plus the spiritual and energetic toll from altered migration routes, driving herds across roads/railways, and the degradation of sacred sites, key fishing lakes and streams, and traditional camp sites (Forbes 2008; Forbes et al. 2009).

The available data indicate that the indirect impacts that are detectable on the available images at Bovanenkovo cover 8.8 times the area of the direct impacts

**Table 9.1** Analysis of relative detectibility of disturbance features using different sensor methods. Reproduced with permission of Timo Kumpula

Impact type	Field survey	Quickbird-2 panchromatic	Quickbird-2 multi-spectral	ASTER		
				TERRA VNIR	Landsat TM	Landsat MSS
Soil contamination, oil & chemicals	x	–	–	–	–	–
Removal of topsoil and vegetation	xxx	xxx	xxx	xx	x	x
Quarries	xxx	xxx	xxx	xxx	xx	x
Garbage						
– Metal	xx	–	–	–	–	–
– Glass	x	–	–	–	–	–
– Concrete	xxx	x	x	–	–	–
– Wood	xxx	x	–	–	–	–
Pipelines	xxx	xx	x	–	–	–
Powerlines	xxx	xx	x	–	–	–
Roads	xxx	xxx	xxx	xxx	x	x
Offroad tracks	xx	xxx	xx	xx	x	x
Winter roads	xx	xx	xx	xx	x	–
Drill towers	xxx	xxx	xx	x	–	–
Barracks	xxx	xxx	xx	x	–	–
Trucks/vehicles	xx	xx	x	–	–	–
Changes in hydrology	xxx	xxx	xx	xx	x	x

(direct: indirect = 7.1: 62.4 km<sup>2</sup>; Table 9.2). On Alaska’s North Slope, the documented indirect impacts cover about a third of the area of the direct impacts (24: 9.3 km<sup>2</sup>; Table 9.2). However, the data sets are not totally comparable because different methods were used to determine indirect impacts – high-resolution Quickbird satellite images were used in the Bovanenkovo field, whereas historical

**Table 9.2** Extent of Bovanenkovo gas field impacts (modified from Kumpula 2010) compared to extent of the North Slope, Alaska oil development (NRC 2003)

Impact type	Area (Length) km <sup>2</sup> (km)	
	Bovanenkovo	North Slope
Direct impacts:		
Roads	2.9 (79)	12.0 (954)
Airstrips	0	1.1
Gravel pads	2.1	23.5
Quarries	4.3	25.8
Off-shore gravel placement	–	0.6
Total direct impacts	9.3	62.4
Other affected area (includes peat roads, disturbed areas around pads, tractor trails, major off-road vehicle trails)	24	7.1
Total extent of field (perimeter, including currently enclosed unimpacted areas)	448	2,600

high-altitude aerial photographs were used on the North Slope (see also Forbes et al. 2009, Table S1). Also, the nature of the off-road-vehicle trails are different in both areas – in northern Alaska, specially designed vehicles with low-pressure tires have created extensive networks of off-road trails that are difficult to detect on the available images and were not quantified in the US National Research Council data (NRC 2003). Despite these differences, ground observations in both areas indicate that there is a relatively relaxed regulatory environment on the Yamal compared to that in northern Alaska. Transport on the Yamal tundra has legally not been allowed in summer since 1989, but this restriction is routinely ignored, resulting in extensive surface disturbance. More recent construction methods have reduced but not eliminated the extent of these types of disturbance.

The extent of developed areas on the Yamal Peninsula will rapidly increase as the Bovankenovo field is brought into production and additional gas fields are developed. Big questions remain regarding how to minimize disturbance and remediate impacts when they do occur.

### ***9.3.3 Geological Factors Contributing to Landscape Sensitivity***

#### **9.3.3.1 Sand Deposits**

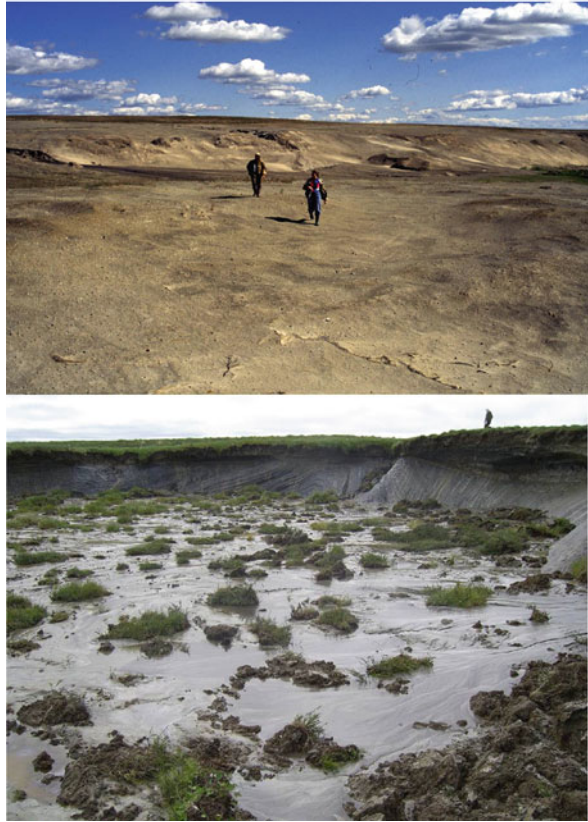
Two major geological factors add to the sensitivity of the Yamal landscapes to disturbance. First, much of the region is covered by eolian and alluvial sand deposits that have been dated to 30,000–12,000 years  $^{14}\text{C}$  B.P. in the vicinity of Marresale (Forman et al. 2002). Although peat accumulation has occurred throughout most of the Holocene, there has been considerable recent reactivation of these sands starting about 1,000 years  $^{14}\text{C}$  B.P., that is thought to reflect abundant sand from denuded hilltops associated with heavy reindeer grazing starting at about that time (Forman et al. 2002). Generally areas of active eolian activity are concentrated in the windier environments near the coast and where reindeer are most frequent. The animals focus on hilltop areas where lichen cover is the greatest and snow cover is at minimum.

Once exposed by disturbance, the nutrient-poor sands are difficult to re-vegetate (Forbes and McKendrick 2002). This has implications for both infrastructure construction and reindeer-herding activities. Large sand quarries are mined for construction and these are difficult to stabilize and re-vegetate (Fig. 9.4, top). The sands are also exceedingly poor material for constructing roads, which require constant maintenance, especially each spring after many sections of the roads wash away when the snow melts. As reindeer populations increase and the area available for forage is reduced by expanding infrastructure networks, this type of disturbance is likely to increase.

#### **9.3.3.2 Massive Ground Ice and Landslides**

Another important geological factor is the massive tabular ground ice that is common throughout the region. Ice deposits from <1 to >20 m thick are found in

**Fig. 9.4** Landscape factors that add to the sensitivity of the Yamal to disturbance. (*top*) Barren sand quarry, near Obskaya. The sandy nutrient-poor soils are common in the region and are difficult to revegetate, especially in the more northern bioclimate subzones. Photo by Bruce Forbes. (*bottom*) Thawing permafrost and earth flow in Central Yamal within the designated corridor of the pipeline. Note tabular ice beneath organic soils along the headwall of the slide area. Reproduced by permission of Marina Leibman.



thousands of boreholes at various depths from a few to dozens of meters (Dubikov 2002). This ice occurs at the interface between salty marine clay and overlying sandy sediments (Streletskay and Leibman, 2003). The origin of this ice is not entirely clear (Leibman 1996). If the overlying deposits are removed or thermal and hydro-logic conditions are changed sufficiently, the ice-rich sediments are liquefied and landslides occur, exposing underlying clay-rich and salty marine sediments that are within and beneath the ice (Leibman and Kizyakov 2007). Slope failures resulting from thawing of ice-rich permafrost often occur, forming earth flows consisting of meltwater mixed with mineral and organic material (Fig. 9.4, bottom). The landslides resulting from thawing of tabular ground ice is hazardous for infrastructure construction.

Landslide disturbances are so common on the Yamal Peninsula that they dominate the landscape in many areas. In August 1989, 400 new landslides occurred within an area of 10 km<sup>2</sup>, where previously there were only three modern landslides (but hundreds of ancient landslides). This was in response to an abnormally wet year. During the last two warm summers (2006–2007) several new areas of tabular

ground ice were exposed by landslide activity. So both abnormally wet and abnormally warm years can trigger major landslide events. Five of the older landslides near Bovanenkovo were dated to be 300–2,000 years old (Leibman and Kizyakov 2007).

The landslides totally change the substrates available for plants. A striking aspect of the vegetation of the central Yamal region is the abundance of willow thickets (*Salix lanata* and *S. glauca*) that cover many hill slopes and valley bottoms (Ukrainitseva 1998) (Fig. 9.5). Climatically, Bovanenkovo is in bioclimate subzone D where the typical zonal vegetation is low-growing sedges, dwarf shrubs, and mosses (including *Carex bigelowii*, *Vaccinium vitis-idaea*, *Salix polaris*, *S. phyllifolia*, *Betula nana*, *Hylocomium splendens*, *Aulacomnium turgidum*). Normally in subzone D dense shrublands are found mostly along streams and in association with anthropogenically disturbed sites, places where there are abundant nutrients and warmer soils.

Studies of the willow communities in relationship to landslides have included: (a) vegetation succession, (b) ash chemistry of each vegetation group, (c) ground water chemistry, and (d) plant and soil chemistry using water extraction and X-ray-fluorescent analyses of air-dry and homogenized plants (Ukrainitseva 1997, 1998; Ukrainitseva and Leibman 2000, 2007; Ukrainitseva et al. 2000, 2002, 2003). There is a strong correlation between disturbance age, soil fertility, and willow growth. The soil of stable hilltops is characterized by low acidity (pH 5.5–5.8), very low base saturation (4.5%), low nitrogen content (0.08–0.18%), and rather high organic carbon (1.5–2.3%); whereas, recent landslide surfaces have high soil pH (7.5–8.0), much higher base saturation (50–100%), and low organic carbon content (0.2–0.7%). Desalination of old marine sediments after the landslide events leads to soil enrichment with water-soluble salts, which supply plants with nutrition, provide



**Fig. 9.5** Shrubby vegetation (*Salix lanata* and *S. glauca*) occurs on an old landslide surface that flowed from the foreground into the right middle background. A more recent 1989 landslide occurred behind the standing figure and is being naturally revegetated mainly by grasses and forbs (e.g., *Deschampsia* sp., *Poa alpigena*, *Puccinellia sibirica*, *Phippisia concinna*, *Tripleurospermum hookeri*). Reproduced by permission of D.A. Walker



active re-vegetation of herbs, and re-formation of soils, followed by willow-shrub expansion.

Tall willow thickets occupy old landslide surfaces due to additional nutrients and especially where there is enhanced (but not the deepest) winter snow cover. On 1,000–2,000-year old landslides, soils showed gradual reduction in pH (down to 6.5) and base saturation (down to 24.5%) that indicate continuing desalination of the active layer deposits towards the background conditions. Organic carbon and nitrogen concentrations in the older soils were double those of recent landslide surfaces. The chemical composition of the plants is also related to the age of the landslide surface. The plants growing on the landslide surfaces had higher nutrient content. Concentrations of carbon (C) and nitrogen (N) increase with age of the landslides, and trace elements in willow branches essentially follow an age sequence with the highest values in the modern slides, followed by old and then ancient landslides and finally willows growing on stable surfaces (Ukrainitseva and Leibman 2000). The nutrient content of plants growing on landslides is also an important consideration for forage quality for reindeer.

## 9.4 Reindeer Herding

Amidst the ongoing rapid industrial expansion at the dawn of the twenty-first century, the Yamal Nenets continue to migrate with their reindeer much as they have for countless generations, cued by – among other things – the cyclic greening and senescing of tundra vegetation, the melting and re-freezing of ancient rivers, and the appearance and disappearance of biting insects. There is archaeological evidence that these migrations have been taking place for at least 1,000 years, perhaps significantly longer (Stammler 2005). Some of the Nentsy travel over linear migration routes from the forests south of peninsula to the summer pastures on Kara Sea coast and back – up to 1,200 km (Fig. 9.6). These remarkable migrations occur annually between the beginning of April and the end of December and are described by Florian Stammler, who in 2000–2001 lived and traveled with a group of herders and their families (Stammler 2005). Other groups of Yamal Nentsy, mainly in the northern part of the Yamal, have shorter more circular migration routes and stay year round on the tundra (Fig. 9.6).

The Yamal region is currently the top reindeer herding area in Russia. Approximately 5,000 nomadic indigenous Yamal Nentsy live on the Yamal migrating with about 290,000 reindeer. The proposed massive new development schemes would significantly affect the social-ecological systems of the Nentsy (Forbes et al. 2004, 2009; Stammler and Wilson 2006; Forbes 2008; Forbes and Stammler 2009). The steady increase of reindeer as well as humans living on the tundra, mainly gas workers but also Nenets, is exceptional. This has resulted in increased use of natural resources, such as heavy spring to autumn grazing over most of the reindeer pastures and unsustainable fishing practices in lakes and rivers accessible to gas workers.





**Fig. 9.6** (left) Current land-use patterns for Nentsy who use corridor (linear) migration routes in the southern and western part of the Yamal region (two headed arrows) and local (circular) migration patterns in the northern part of the Yamal Peninsula (circular arrows). (right) Red lines delineate corridors for brigades. Brigade numbers in each corridor are shown by Roman numerals. Brigade corridors IV and VIII pass through the Bovanenkovo gas field. Reproduced by permission of Florian Stammer

Many regions across Russia experienced a near total collapse of reindeer herding after the demise of the Soviet Union. Yet, within the North and Far East, there is a general sense that Yamal has fared quite well compared to other regions (Stammer 2005; Forbes 2008). There are many positive social and economic effects of development, including access to health care, extensive support for urban-based populations, jobs, and the possibility to barter or pay cash for goods on the tundra during migrations. Helicopter transport and relations between oil and gas workers and reindeer herders are central aspects of life on the tundra. Overall, reindeer herders continue to be mostly in favor of the ongoing gas development, although as the development accelerates they wish to be more carefully consulted about plans for

new infrastructure and to receive appropriate compensation for lost pastures and access for migrations (Stammler et al. 2009; Forbes et al. 2009). For example, two brigades that traditionally used the Bovanenkovo region for their summer pasturelands now avoid these areas and have lost 22 and 25% of their total summer pasturelands due to the presence of the gas development (Kumpula et al. 2010). It is predicted that 165 families of nomadic Nenets people will move to live in the settlements as a result of reduction of the pastures, and 286 families will have to change the pasture routes for the same reason. Experts estimate that expenses exceeding several billion dollars are needed to minimize negative impact of development on the human life and disturbed environments by 2011. Both herders and scientists have cited the ongoing gas field infrastructure development and destruction of vast areas of pastures as extremely important issues for the future of reindeer herding in the region.

Nenets reindeer herders whose migration routes intersect the most intensive areas of infrastructure development participated in a study pertaining to land-cover changes that have occurred over the past 30+ years. Their participation in the earlier ENSINOR project was through group and individual interviews with members of three herding brigades to document local knowledge of plant-animal-climate interactions in the vicinity of Bovanenkovo, where both hydrocarbon-related activities and reindeer grazing/trampling exert important controls over vegetation (Fig. 9.7). Herders participated in interviews along the course of the Yamal migration. The interviews included presentation of a set of “what if” scenarios of projected changes, leading to discussions of the implications of these changes to land-cover and land-use changes, reindeer herding and traditional ways of life for the Nentsy.



**Fig. 9.7** Florian Stammler interviewing a Nenets family. In addition to taking part in the daily life and experiencing how the reindeer and fishing resources were managed, the combined anthropology and ecology research teams conducted semi-structured interviews that were recorded on digital media or film. Very high-resolution satellite imagery of the areas helped to focus the discussions on specific places and features that the herders recognized easily. Photo by Bruce C. Forbes



**Fig. 9.8** Reindeer herding and effects: (a) Nenets brigadier and children playing volleyball in front of herded reindeer. Animals are often concentrated in small areas for selection of animals for sled teams and other purposes. (b) Barren area due to trampling caused by concentrated reindeer activity. (c) Grassification – replacement of typical shrub tundra vegetation with grassland (foreground) following heavy grazing and trampling. The Nenets camp in the background is that of a brigade. Four to 12 herders with their families travel together in a brigade, usually moving camp every 2–3 days. Each tepee-like structure (chum) houses 1–2 families. (d) Wind erosion in sandy areas aggravated by heavy trampling by reindeer. Photos by Bruce C. Forbes

The reindeer exert important controls over the structure and function of the Yamal tundra. When the animals are concentrated in small circumscribed areas on organic substrates, dense graminoid swards can develop (grassification) (Fig. 9.8a–c). These can be seen in and around campsites and along migration routes. On well-drained, sandy substrates with minimal organic content, concentrated trampling can thin and eventually break through the otherwise closed vegetation mat, leading to erosion via deflation (Fig. 9.8d). Perhaps most significant to the vegetation is the projected simultaneous reduction in available pasturelands due to infrastructure expansion and the increases in the Nenets and reindeer populations that will make heavy demands on the pasturelands in the future. Between 1981 and 2004, the number of nomadic households on the Yamal Peninsula increased from 693 to 964, and the number of private reindeer (excludes state-owned collectives) has increased about three fold from about 54,000–158,000 (Stammler 2005 77–78).

## 9.5 Climate-Vegetation Relationships

Climate change is another factor affecting ecosystems across the Arctic (ACIA 2004). The very extensive retreat of the summer sea-ice in 2007 alerted scientists to the possibility of a summer-ice free Arctic within this century (Stroeve et al. 2007; Nghiem et al. 2007; Comiso et al. 2008). More open water during the summer in the Arctic will very likely lead to increased flow of heat to the land (Lawrence et al. 2008). The expected changes include changes in vegetation, thawing permafrost, changes in soil characteristics, and changes in the habitat and migration characteristics of the fauna. It is hypothesized that an earlier ice-melt forces atmospheric and land-surface temperatures changes, leading to increased summer warmth and enhanced greenness of vegetation. Increased vegetation greenness has been noted in some areas of the Arctic such as northern Alaska and is attributed to warmer summer temperatures and the expansion of shrub vegetation (Jia et al. 2003; Chapter 2, this volume; Tape et al. 2006; Walker et al. 2009; Forbes et al. 2010). The warming temperatures are also affecting permafrost temperatures leading to local thaw, subsidence, and altered hydrological regimes (Romanovsky and Osterkamp 2001; Hinzman et al. 2005).

Some of the critical questions related to climate change involve how are the changing sea-ice regimes related to changes in vegetation and permafrost regimes. For example, if winds become stronger or precipitation decreases or temperatures increase, wind erosion of sandy surface deposits would become more common. On the other hand if summer precipitation increases, landslides may become more frequent, and shrubby tundra would probably cover larger areas of the peninsula. Shrubs also would likely generally increase if the climate warms. The increased cover and height of shrubs would likely trap more snow in the landscape. Perhaps most critical to the Nentsy is the possibility of increased frequency and severity of winter thaws when melt water in the snowpack refreezes at the soil surface to form a hard “ice shield” that acts as a barrier to reindeer seeking the underlying vegetation (Stammler 2005; Bartsch et al. 2010).

### 9.5.1 *Spatial Distribution of Vegetation Productivity (NDVI)*

A question in the present analysis is how would a warming climate contribute to the expected changes in plant production as manifested by NDVI? In most of the Arctic, NDVI is strongly related to the amount of summer warmth available for plant growth (Raynolds et al., 2006, 2008a). We were interested in how the present distribution of NDVI on the Yamal Peninsula conforms to the general circumpolar pattern of decreasing NDVI with latitude (and decreasing summer warmth). Information for this analysis was extracted from a circumpolar GIS database containing a variety of landscape variables including dominant vegetation, elevation, landscape type, substrate type, land-surface temperatures, and percent lake cover. Much of the information came from the Earth Cryosphere Institute (Drozdov et al. 2005; Melnikov

and Minkin 1998; Minkin et al. 2001), and the Circumpolar Arctic Vegetation Map (Walker et al. 2005). The methods used in constructing the maps of land-surface temperature and maximum NDVI are described in Raynolds et al. (2008a).

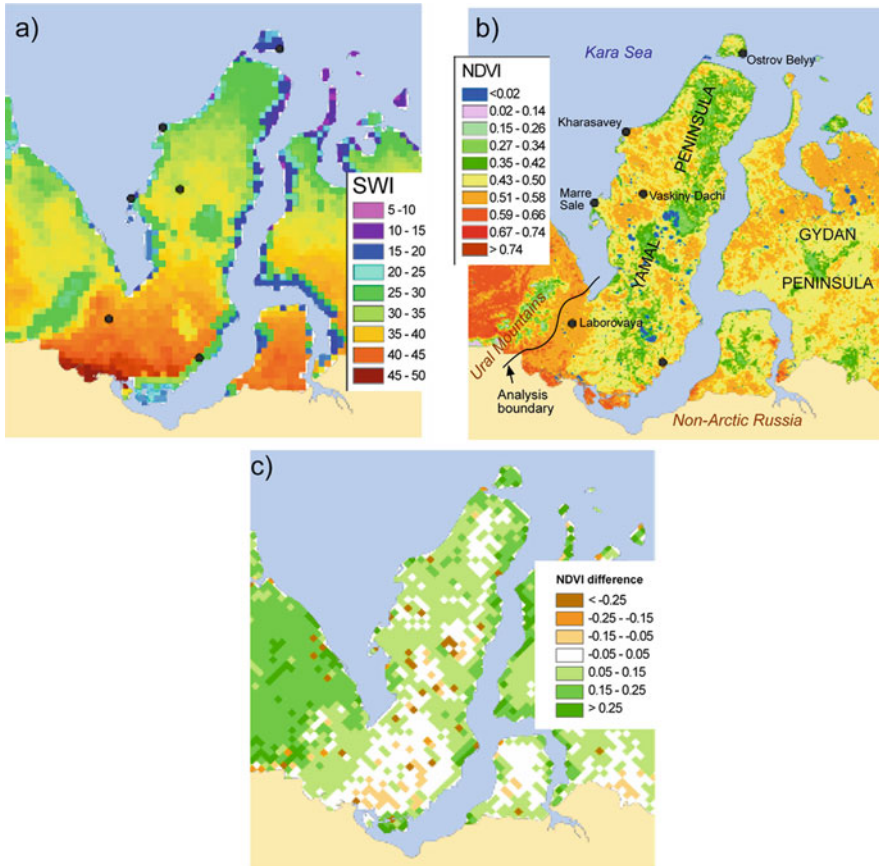
Global tundra land-surface temperatures were calculated from AVHRR thermal data compiled from 1982 to 2003, providing the longest satellite temperature record available (Raynolds et al. 2008a). Daily differencing and moving window techniques were used to eliminate cloud-contaminated pixels (Comiso 2000, 2003). A constant emissivity value of 0.94 was used to calculate temperature from the thermal infrared channels.

As in Chapter 2, we used a Summer Warmth Index (SWI) to characterize the amount of warmth available for plant growth at the ground surface. This index combines the effect of both the length and the warmth of summer temperatures, and is the climate variable found to correlate well with variations in arctic plant diversity and biomass trends within the Arctic (Young 1971; Rannie 1986; Edlund 1990; Walker et al. 2005). This index characterizes the plant growing season by summing monthly mean temperatures that are greater than 0°C. The units of SWI are °C mo, or thawing degree months.

Across most of the Arctic, from north to south, NDVI increases as summer land-surface temperatures increase. A regression of NDVI vs. the summer warmth index explains about 58% of the total variation in circumpolar NDVI values (Raynolds et al. 2008a). Given the rather strong north–south temperature gradient (Fig. 9.9a), the presence of four of the five Arctic bioclimate subzones along the Yamal Peninsula and the strong circumpolar correlation between NDVI with summer temperatures we would expect to see a similar strong trend in NDVI related to temperature on the Yamal (Fig. 9.9b). In fact the correspondence between NDVI and surface temperatures is rather weak on the Yamal (Fig. 9.10). Using the same data set as for the circumpolar analysis, surface temperature explains only about 22% of the spatial variation in NDVI on the Yamal Peninsula (Raynolds et al. 2008b). Most of the peninsula has higher NDVI values than would be expected from the global trends of NDVI-temperature relationships (Fig. 9.9c).

A General Linear Model analysis using data from a regional GIS (Fig. 9.11) revealed that temperature explains less than 2% of the total deviance in a data set containing many more variables than the simple NDVI-SWI regression (Raynolds et al. 2008b) (Table 9.3); 49% of the NDVI deviance is explained by a combination of elevation and landscape type (e.g., low plains with marine deposits, low plains with alluvial and lacustrine deposits, high plains with fluvial and lacustrine deposits, foothills, and mountains); another 9% is explained by substrate type (peat, clay, silt, sand) and broad vegetation categories from the Circumpolar Arctic Vegetation Map. The rather paradoxical positive correlation between NDVI and elevation (normally NDVI decreases with elevation in the mountains) is due to the geography of the Yamal Peninsula, where elevations increase toward the warmer southern part of the peninsula, and the uplands have dense dwarf-birch (*Betula nana*) plant communities with high NDVI values. The pattern of landslides and shrubs is undoubtedly a major control on the high NDVI patterns over much of the peninsula. Although individual landslides cannot be resolved at the scale of the maps, the areas of



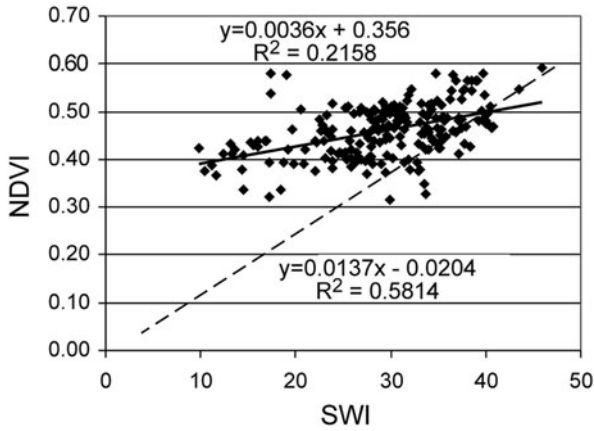


**Fig. 9.9** Land-surface temperatures, NDVI, and NDVI on the Yamal compared to expected values from a global arctic land-surface temperature – NDVI relationship (Raynolds et al. 2008a). (a) Summer Warmth Index (SWI) is the sum of the mean monthly land-surface temperatures above freezing (1982–2003) as measured with the AVHRR thermal infrared bands. (b) Maximum NDVI of the Yamal region. (c) NDVI on Yamal compared with expected values based on global NDVI-surface-temperature relationship. Green areas are warmer than predicted by the regression model (Fig. 9.10) and brown areas are cooler. The southern boundary of the colored maps corresponds to tree line. Reproduced by permission of Martha Raynolds

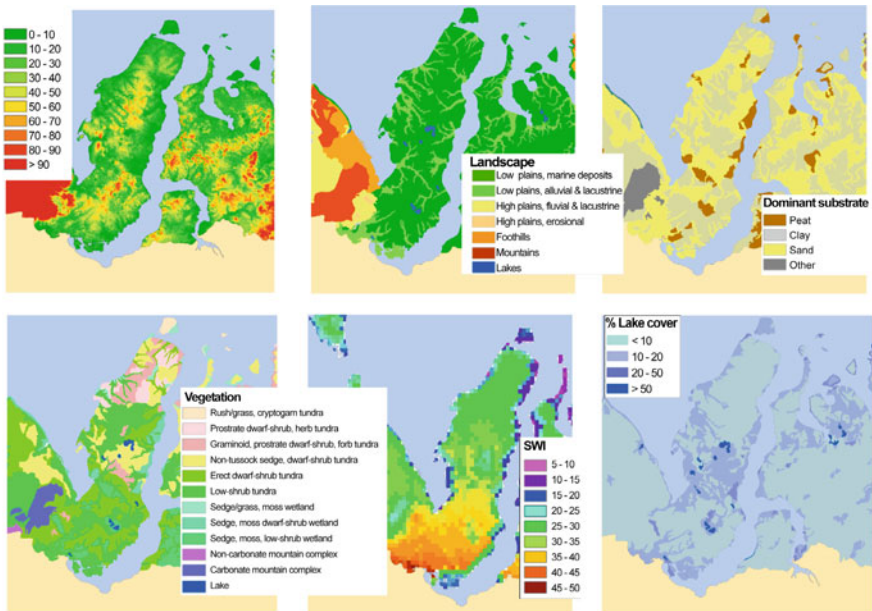
higher-than-expected NDVI values tend to be concentrated on low marine plains and alluvial valleys that have been eroded into the sandy upland deposits. These areas have abundant cover of low-shrub vegetation that has developed on ancient landslides.

In summary, the NDVI on the Yamal Peninsula increases with warmer summer land-surface temperatures, but the relationship is not as strong as in the Arctic as a whole. Broad valleys with concentrations of marine clays have higher NDVI than upland areas dominated by sands. These trends are related to the distribution of ancient landslides and valley floors where willow thickets dominate.





**Fig. 9.10** Regression between NDVI and ground-surface temperatures as measured using the summer warmth index (SWI). *Solid line* and *dots* show the data from the Yamal region. *Dashed line* is the regression for the entire circumpolar region. Data points for the circumpolar regression line are not shown. Reproduced by permission of Martha Raynolds



**Fig. 9.11** Variables used in the general linear model to examine the NDVI relationships. Reproduced by permission of Martha Raynolds

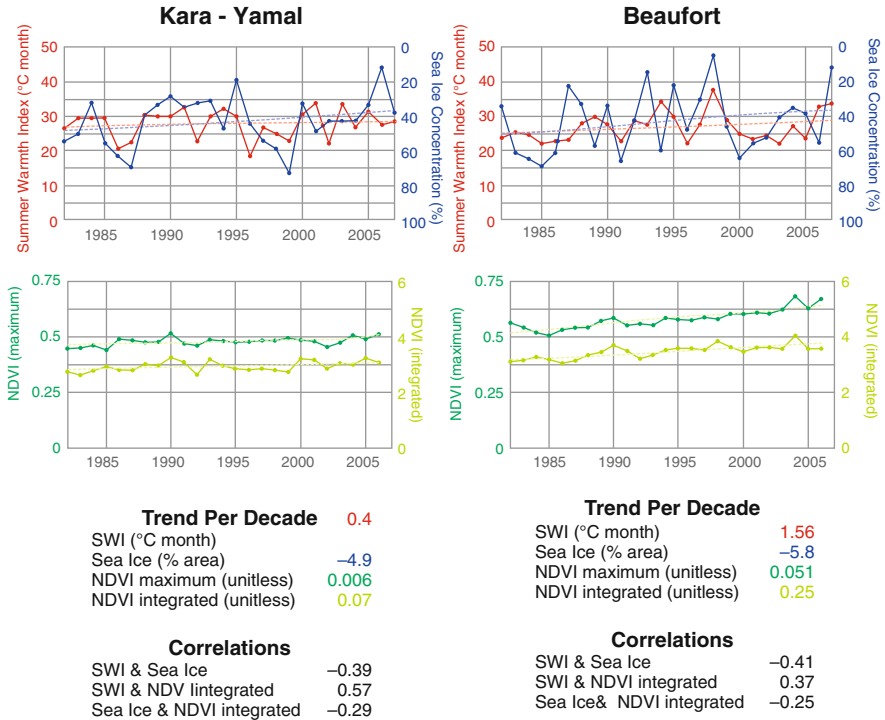
**Table 9.3** Results of general linear model analysis of NDVI compared to other variables in a geographic information system (Raynolds et al. 2008b)

GIS variable	Deviance	Residual deviance	Deviance accounted for (%)	Significance
Null		2.065		
Elevation	0.603	1.462	29.21	< 0.000000
Landscape	0.407	1.055	19.72	< 0.000000
Substrate	0.101	0.954	4.88	< 0.000000
Vegetation	0.088	0.865	4.29	0.000004
Land temp	0.039	0.827	1.87	0.000012
Lake area	0.032	0.794	1.57	0.000934
Total			61.55	

### 9.5.2 Temporal Changes in Sea-Ice Concentration, Land-Surface Temperatures, and NDVI

This portion of the study utilizes satellite-derived data to examine the recent trends in sea-ice distribution, land-surface temperatures (LST), and patterns of vegetation greening as indicated by the NDVI (Bhatt et al. 2007). We use ice-cover data derived from historical 25-km resolution Spectral Sensor Microwave Imager (SSM/I) passive microwave data (Comiso 1999), AVHRR surface temperature data (Comiso 2006, 2003), and 8-km AVHRR-NDVI data (Tucker et al. 2005). The analysis employs data covering the 26-year period from January 1982 to December 2007. The sea-ice, LST, and NDVI trends were examined in a 50-km terrestrial region seaward and landward of the Arctic coastline in the Yamal/Kara Sea region. These relationships are compared and contrasted with other sub-basins within the Arctic Ocean as defined in the Russian *Arctic Atlas* (Treshnikov 1985). Here we compare the trends in the Yamal/Kara Sea area with those in the Beaufort Sea area, where the land warming and NDVI trends have been described previously (Jia et al. 2003). Patterns for the Northern Eurasia region are described in Chapter 2 of this volume (Goetz et al.). Climate analysis techniques were applied to evaluate the direct relationship between the trends of sea-ice, LST and NDVI and various climate indices such as the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), and the Pacific Decadal Oscillation (PDO). The NCEP/NCAR Reanalysis provided climate information for the analysis (<http://dss.ucar.edu/pub/reanalysis/index.html>).

Between 1982 and 2007, sea-ice in the 50-km coastal strip of the Yamal/Kara Sea area during the period 18 June–22 July decreased  $-4.5\%$ /decade (Fig. 9.12). The time period (18 June–22 July) was selected because this is the time of transition to summer-ice conditions across most of the Arctic and is the time when sea-ice concentrations have the most variability. Land-surface temperatures (as indicated by the summer warmth index (SWI), showed a slight increase ( $0.2^\circ\text{C mo}$ ). This was less of a response than for the Eurasian area as a whole, where sea-ice decreased  $-5.8\%$ /decade, and SWI increased  $+1.2^\circ\text{C mo/decade}$ . The greening response of the vegetation (as indicated by the summer maximum NDVI and the total integrated NDVI) increased modestly 0.01 and 0.13 NDVI units per decade, respectively. This



**Fig. 9.12** Trends and correlations of sea-ice concentration, land-surface temperature (SWI) and maximum and integrated NDVI for (left) the Kara/Yamal region and (right) the Beaufort Sea region. Reproduced by permission of Uma Bhatt

was somewhat more than for Eurasia as a whole (0.006 and 0.06/decade, respectively), and much less than in the Beaufort Sea of North America region where SWI increased 1.6°C mo and the integrated-NDVI increased 0.33/decade (Bhatt et al. 2007, 2008, 2010) (Fig. 9.12). In the Kara/Yamal region, sea-ice concentrations and SWI were negatively correlated ( $r = 0.41$ ,  $p > 0.05$ ) and the SWI and integrated NDVI were positively correlated ( $r = 0.65$ ,  $p > 0.05$ ) (see Chapter 2, this volume) for a more full discussion of the analysis of the sea-ice, SWI, and NDVI trends and climate correlations for the seven seas in the Northern Eurasia region). These trends are consistent with all other coastal areas studied in the Arctic – i.e., periods of lower sea-ice concentration are correlated with warmer land-surface temperatures and higher NDVI values. Compared to areas that are contiguous with the North Atlantic and the North Pacific, the Kara/Yamal is more continental and displayed relatively large decreases in sea-ice (–3.7 to –7.3%/decade) and modest increases in SWI (+0.2C mo/decade). The sea-ice and land-surface trends are much stronger in the E. Siberian and Chukchi sectors of the Russian Arctic (< –10%/decade respectively and > 2.2°C/decade).

Sea-ice concentrations trends in the Kara/Yamal region showed a significant negative correlation with the NAO during the December to March period of the preceding winter ( $r = 0.41$ ,  $p > 0.05$ ) and summer warmth index had a weak positive correlation ( $r = 0.28$ ) with the NAO. The NAO is a measure of the north-south surface pressure gradient in the North Atlantic. The positive phase of the NAO is generally characterized by enhanced storminess in the Arctic, increased heat transport from lower latitudes, and warmer winter temperatures. This would be consistent with the negative correlation between the NAO and sea-ice concentrations in the Kara Sea region.

In summary, sea-ice has retreated somewhat earlier over the past 24 years in the Kara/Yamal region but not as strongly as in the E. Siberian and Chukchi Seas. Land surface temperatures on the Yamal have increased slightly, but nowhere near as strong an increase as in the E. Siberia, Chukchi and Bering Sea regions. Greenness has increased, but not as strongly as it has in other areas of Northern Eurasia (e.g., W. Bering and Chukchi seas regions) and in the Beaufort Sea.

## 9.6 Cumulative Effects

Resource development often proceeds in a piecemeal fashion – a process called “nibbling” (Horak et al. 1983; Beanlands et al. 1986; Lee and Gosselink 1988). The US Regulatory definition of cumulative impacts is:

an impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable-future actions regardless of what agency (Federal or non-Federal) or person undertakes such actions. Cumulative impacts can result from individually minor but collectively significant actions taking place over a period of time (CEQ 1978).

The approach used here expands the concept of cumulative impacts to include the simultaneous and interactive effects of developing many gas fields and other ongoing social and ecological factors such as population growth and climate change. The aim is to look further into the future and anticipate the combined effects from several agents of change.

Some of the most critically needed models are ones that will anticipate the structure of future networks of pipelines and roads. Such models are being developed in Canada (Holroyd and Retzer 2005). These models can help predict the length and density of road and pipeline networks based on assumptions about the geological structure of the gas fields and gas-field technology. Best practices scenarios can be developed if the assumptions in the models are accurate and based on the latest and best information from all sides – including petroleum geologists, oil-field engineers, and land-use planners. If reasonable assessments of road and pipeline densities can be made, then the implications for wildlife habitat can be made (Weller et al. 2002), as well as the consequences to resident populations of people.

A comparison with cumulative effects of developments in other Arctic areas could lead to better international understanding of the unique constraints imposed on

the development of arctic gas fields with different environmental, political, social, regulatory, and economic systems. The data presented in Table 9.2 of this analysis compares the available information from the Bovanenkovo field with data in northern Alaska, that was obtained by the National Research Council during a large publicly funded assessment of the cumulative effects of oil and gas activities on Alaska's North Slope (NRC 2003). The 18-member committee responsible for writing the report included experts in geology, permafrost, economics, anthropology, marine and terrestrial mammals, birds, fish, vegetation, contaminants, arctic ecology, and the native people, and included members of government agencies, private consultants, university professors, and non-governmental agencies. The North Slope oil fields began development in 1968 and oil was flowing through the trans-Alaska pipeline by 1977; this 30-year history provides much valuable insight to ecologically sound development of arctic oil and gas resources. The cumulative effects issues being faced on the Yamal are in many ways similar to those being faced in Alaska (Walker et al. 1987), the Mackenzie River delta region of Canada (Holroyd and Retzer 2005) and the Barents Sea region of northern Norway (Mathiessen 2008, also see Chapter 7, this volume), and are a precursor to much more extensive changes that are sure to come in northern Russia, including the Nenets Autonomous Okrug, and elsewhere.

## 9.7 Conclusions

The multiple effects of rapid resource development, climate change, and population growth make the Yamal Peninsula one of the most rapidly changing areas in the Arctic. New tools are needed for the various stakeholders in the region to envision the cumulative effects of these and other influences. Here we have enumerated the effects of industrial activities, climate change, and the expanding populations of gas workers, Nenets and reindeer. We have shown that the direct (planned) impacts of industrial activities are currently relatively local and limited in extent, but this is changing fast as extensive gas fields are developed and land and sea transportation corridors are developed to transport the gas to market. Indirect impacts, such as those from blowing sand and dust, are much more extensive than the direct impacts. Industrial development (mainly roads and pipelines) is creating serious barriers to migration corridors and limiting the areas of summer pasture. As well, fishing is threatened from poaching and as rivers and lakes are damaged during road and pipeline construction (Forbes 2008; Forbes et al. 2009). Herders generally view the threats from industrial development to be much greater than threats from climate change (Forbes and Stammler 2009). Land withdrawals by industry, increasing populations of gas workers and Nenets, and larger reindeer herds are increasing pressure on the rangelands as well as fishing resources. However, despite the negative impacts, the Nentsy have an overall positive view of gas development because of increased economic and social advantages (Stammler 2005; Forbes 2008; Forbes and Stammler 2009).

Satellite data suggest that there has been a modest summer land-surface warming and only slight greening across the Yamal during the past 24 years. The trend is not as strong as in other parts of the Arctic, such as the Beaufort Sea. The trend in land-surface temperatures has co-varied with the trend in sea-ice – low sea-ice in the preceding December–March period is correlated to warmer land temperature the following summer. Climate analysis indicates that the trends of sea-ice and land temperatures in the Kara Sea-Yamal region are tied to variation in the North Atlantic Oscillation index. The small greening response to warming is partially due to a generally lower than normal correspondence between vegetation production and local climate. This is due to the high level of natural disturbance (landslides) that is responsible for abundant willow growth across much of the peninsula, which gives the region higher than expected NDVI values. The actual effects of climate-change on vegetation are currently hard to document at the ground level because of lack of baseline and long-term ground observations and difficulty of excluding reindeer in these studies. Ground-based baseline studies, are important for documenting future changes in plant species composition, biomass, NDVI, active layer depths and soils properties.

There is high potential for extensive landscape effects due to unstable sandy soils, and extremely ice-rich permafrost near the surface on slopes. If exposed by natural or anthropogenic causes the ice-rich permafrost is highly susceptible to catastrophic failures. Over large areas of the Yamal, landslides have transformed the zonal sedge, dwarf-shrub tundra to the low-shrub tundra that is typically found on disturbed sites in this subzone. Present evidence indicates that the landslides are triggered most abundantly in wet years, as in 1989, and in warm years, as in the recent years since 2005.

Vegetation change models such as ArcVeg will help predict the changes that will occur to the vegetation from the combined influence of climate change, industrial development, and changes in reindeer foraging impact (see Goetz et al., [Chapter 2](#)). Additional modeling efforts are needed to predict the effects of new road and pipeline networks. Also needed are more wide-ranging assessments that include air and water quality, and biodiversity of terrestrial and aquatic organisms. Comprehensive assessments and models that can anticipate numerous development scenarios and draw on other international experiences are needed to plan for the cumulative effects of resource development, climate change, and demographic changes that are occurring on the Yamal and other Arctic regions.

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