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Land use and land cover change in Arctic Russia: Ecological and social implications of industrial development

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ABSTRACT

Sizable areas in northwestern arctic Russia have undergone fundamental change in recent decades as the exploration of vast hydrocarbon deposits has intensified. We undertook two case studies on the influence of oil and gas activities within neighbouring federal districts in the tundra zone. Employing a strongly interdisciplinary approach, we studied the ecological, spatial and social dimensions of the visible and perceived changes in land use and land cover. Our data are derived from field sampling, remote sensing and intensive participant observation with indigenous Nenets reindeer herders and non-indigenous workers. Important trends include the rapid expansion of infrastructure, a large influx of workers who compete for freshwater fish, and extensive transformation from shrub- to grass- and sedge-dominated tundra. The latter represents an alternative ecosystem state that is likely to persist indefinitely. On terrain disturbed by off-road vehicle traffic, reindeer pastures' vegetation regenerates with fewer species among which grasses and sedges dominate, thus reducing biodiversity. To have maximum forage value such pastures must be accessible and free of trash, petro-chemicals and feral dogs. We found that a wide range of direct and indirect impacts, both ecological and social, accumulate in space and time such that the combined influence is effectively regional rather than local, depending in part on the placement of facilities. While incoming workers commonly commit poaching, they also serve as exchange partners, making barter for goods possible in remote locations. In general, the same positive and negative impacts of the presence of industry were mentioned in each study region. Even using very high-resolution remote sensing data (Quickbird-2) it is not possible to determine fully the amount of degraded territory in modern oil and gas fields. With regard to policy, both biophysical and social impacts could be substantially reduced if information flow between herders and workers were to be optimized.

1. Introduction

Certain Arctic areas in Russia have been undergoing a fundamental change in recent decades as the exploration of vast oil and gas deposits has intensified north of the latitudinal treeline. This has created competition over land-use with indigenous peoples since virtually all of the areas either under or slated for hydrocarbon development serve as grazing pastures, hunting and fishing lands used for centuries by nomadic reindeer herders, fishermen and hunters (Forbes, 2008; Stammler and Wilson, 2006). In West Siberia, where some of Russia's largest untapped gas deposits lie beneath the permafrost, several thousand square kilometres of pasture have already been affected by industrial activities in the Yamal-Nenets Autonomous Okrug or YNAO (Khitun and Rebristaya, 2002). In the neighbouring Nenets Autonomous Okrug (NAO), similarly large-scale oil deposits of the Timan-Pechora region are under intensive development (Tuisku, 2003; Stammler and Forbes, 2006; Stammler and Peskov, 2008). The influence on vegetation and soils is already extensive and growing rapidly. In both regions extraction remains in its early stages and full production is still several years in the future. As such, a major increase in land use and land cover change over the next couple of decades is anticipated (Lavrinenko et al., 2003; Stammler and Forbes, 2006; Forbes, 2008).

Climate-related transformation of tundra vegetation has been suggested for the rapidly warming North Slope of Alaska and Canadian Arctic (Chapin et al., 1995; Sturm et al., 2001; Jia et al., 2003; Verbyla, 2008; Hudson and Henry, 2009). Comparable findings from northern Russia have recently been confirmed (Forbes et al., 2010). In the near future Arctic areas with

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hydrocarbon and mineral deposits are likely to be more affected by industrial impacts rather than climatic effects, or the combination of both (Nellemann et al., 2001a). Disturbances associated with industrialization include a wide range of direct and indirect impacts, such as off-road vehicle use, petro-chemical contamination, permanent infrastructure, blowing sand/dust, and changes in topography and hydrology (Forbes, 1995; Forbes et al., 2001; Khitun and Rebristaya, 2002; Lavrinenko et al., 2003).

Even small-scale, low-intensity anthropogenic surface disturbances can result in long-term changes in tundra vegetation and permafrost soils (Rebristaya et al., 1993; Andreyashkina and Peshkova, 1997; Forbes et al., 2001). For example, the effects of a single passage of an off-road vehicle may be visible for decades (Forbes et al., 2001). Moreover, the recovery of disturbed tundra vegetation is typically slow because of altered thermal and hydrological conditions (Chapin and Shaver, 1981; Forbes, 1998) and low reproductive rates of many arctic species (Bell and Bliss, 1980). However, regeneration is likely to depend on the life-strategy of species (Oksanen and Virtanen, 1997). Earlier studies show that plant groups particularly vulnerable to disturbance include shrubs, certain groups of bryophytes (e.g. *Sphagnum* spp.) and fruticose lichens, whereas many graminoids (*Carex* spp., *Eriophorum* spp., certain *Poaceae* spp.), especially rhizomatous forms, readily regenerate (Oksanen and Virtanen, 1997; Forbes et al., 2001). Moreover, the diversity of vegetation tends to be lower in industrial areas compared to the original vegetation (Forbes et al., 2001; Khitun and Rebristaya, 2002).

Since the 1980s remote sensing images have been used in the detection of industrial impacts in terrestrial arctic and subarctic environments (Walker et al., 1987; Walker, 1996; Mikkola, 1996; Toutoubalina and Rees, 1999; Virtanen et al., 2002; Tømmervik et al., 2003). The resolution of successive platforms has improved steadily over a period of time that overlaps nicely with the progressively intensive industrial development in northern Russia. With more recent very high-resolution (VHR), commercial imagery like IKONOS-2 and Quickbird-2 has sharpened nearly to the level of aerial photography. The large scale effects of hydrocarbon-related infrastructure and habitat disturbance on domestic reindeer herding in northern Russia remain poorly understood. Only Rees et al. (2003) have attempted to incorporate indigenous knowledge of Nenets reindeer herders into a remote sensing analysis of land cover change, although this formed a rather limited part of their analysis and the imagery used (Landsat) was relatively low-resolution. Previous social anthropological studies that have addressed various industrial impacts were based primarily on anecdotal comments by Nenets reindeer herders and did not incorporate quantitative analyses of ecological and geographical aspects of change (Tuisku, 2002, 2003; Zenko, 2004).

Ecological studies from the North American Arctic that treat wild caribou certainly have important lessons to offer, but are not fully comparable because of the fundamentally different manner in which domestic animals and Nenets interact with oil and gas developments (Wolfe et al., 2000; National Research Council, 2003). There is evidence that both wild (Cameron et al., 2005) and domestic reindeer (Vistnes and Nellemann, 2001) *Rangifer* spp., especially females pregnant or with calves, avoid infrastructure such as roads, railways, powerlines and settlements, although animals may become habituated within years under certain circumstances (Haskell et al., 2006). On the other hand, certain anthropogenic habitats are exploited for forage, such as graminoid-dominated sites responding to mechanical disturbance and/or nutrient addition (Truett et al., 1994; Forbes and McKendrick, 2002). Road dust has also been identified as an important ecological factor in YNAO (Forbes, 1995) and animals in northern Alaska have been observed seasonally feeding on dust-affected roadside vegetation (Haskell et al., 2006).

We aimed to gain understanding of the coupled social-ecological systems of NAO and YNAO by employing a strongly integrated interdisciplinary approach. In particular we addressed the following questions: (1) What is the areal extent of land cover change in the vicinities of two modern hydrocarbon developments as detected using remote sensing technologies and detailed ground surveys?; (2) how does vegetation of pastures differ between disturbed and undisturbed areas? In particular, we observed revegetation of 15–20 year old off-road vehicle tracks and compared them with the original vegetation; (3) what are the important ecological and social impacts, both positive and negative, of these two industrial sites from the perspective of contemporary Nenets herders and reindeer herding?; (4) what are the policy implications of these findings? The purpose of this research is therefore not only to detect potentially permanent changes in territories shared by hydrocarbon development and Nenets reindeer herding, but also to forge a new approach to combining ecological, geographical, and social anthropological data in the study of land-use and land cover changes.

2. Materials and methods

2.1. Study areas

Research was conducted in two hydrocarbon fields in the Russian Arctic. The gas field at Bovanenkovo, located on central Yamal Peninsula in northwest Siberia (YNAO) (70°20′N, 68°00E), is one of the largest in all of Russia (Fig. 1). This area belongs to bioclimate Subzone D of the Circumpolar Arctic Vegetation Map (CAVM) (Walker et al., 2005), with a mean July temperature of 6 °C (Shiyatov and Mazepa, 1995). The total number of vascular plant species is relatively low due to the combination of nutrient-poor permafrost soils and phytogeographic location (Yurtsev, 1994). The tallest plants in the area are willow (*Salix* spp.), which are up to 2 m in riparian habitats and along lake shores. Bovanenkovo Gas Field is not yet under production, but infrastructure is rapidly expanding, coupled with a massive influx of shift workers. Geological surveys of the gas field began to accelerate in 1980s and the first construction phase started in 1987.

The second research area, Toravei oil field, is located on the Varandei peninsula (68°66′N, 58°33E) in NAO (Fig. 1). Toravei also lies within CAVM Subzone D, although the permafrost soils are richer and the number of plant species greater than at Bovanenkovo. The tallest willows (*Salix* spp.) reach up to 2.5 m in height. Exploration of the oil field began in the late 1970s. In 2001 an offshore oil terminal was opened in Varandei and soon after oil pumping started from Toravei field. The coastal infrastructure, including a state-of-the-art harbor for shipping oil, was still being expanded in late 2007 with several new storage facilities each holding 100,000 tons of oil. Supplementary historical information and future plans for drilling sites, roads/railways and pipelines in each region were obtained from local administrations and workers of the oil and gas industry.

These two cases were chosen, because they represent: (1) the two key Federal districts in modern Russia containing proven onshore oil and gas deposits under development (Stammler and Forbes, 2006); (2) the two most productive regions for reindeer herding in terms of total numbers of animals (Forbes and Kumpula, 2009); and (3) neighbouring regions where both reindeer management and the extent of engagement with the hydrocarbon extraction industry differ substantially (Stammler and Wilson, 2006; Stammler and Peskov, 2008).

In both YNAO and NAO, land is divided between the successor reindeer herding enterprises of Soviet State and Collective Farms, *sovkhozy* and *kolkhozy* which in turn consist of individual work-teams, called brigades. Especially on Yamal Peninsula herders

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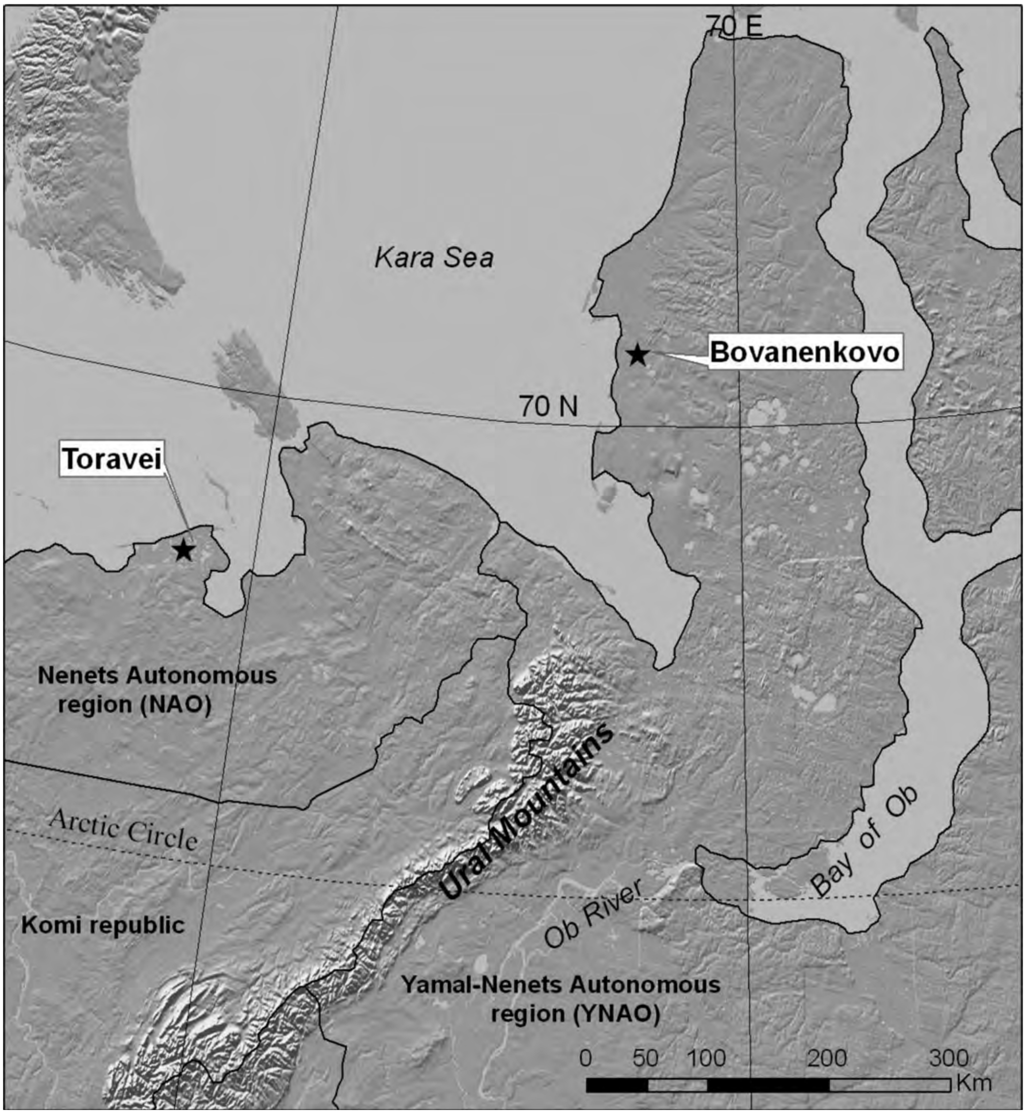

Fig. 1. Locations of the research areas in Arctic Russia. Toravei oil field (NAO) and Bovanenkovo gas field (YNAO).

migration routes are long, some up to 600 km and typically in 5–30 km wide migration corridors. We studied three brigades that are directly or indirectly affected by Bovanenkovo Gas Field. For the analyses in the present manuscript we chose two brigades that are directly affected by Bovanenkovo Gas Field. These two Yarsalinskii sovkhoz (total number of brigades is 21) reindeer herding brigades (with 6000–8000 animals) migrate through the gas field twice a year. First in early July they migrate northwest towards the Kara Sea coast and return back towards the southeast in late August.

In NAO within the Yerv reindeer herding enterprise there are 7 brigades. Here we chose to focus on two out of those because their migration routes went directly through the main oil field under active development at the time of the fieldwork (2006). Yerv's brigades migration regime is more complex than on Yamal and many brigades encounter oil infrastructure and settlements several times annually. Instead of moving along corridors they follow a complicated pattern shaped of multiple figure-8's formed after the demise of the Soviet Union. Crucial variables determining these migration routes are vegetation, local topography, industrial sites and fishing lakes.

Among industrial impacts we focused on off-road vehicle tracks and used them within our study sites to characterize the vegetation change around hydrocarbon industrial sites. Tracks well serve this purpose, since they constitute discrete disturbed patches with sharp boundaries, which enable comparisons with original undisturbed vegetation. In both areas there is an extensive network of off-road tracks resulting from the use of all terrain vehicles during the growing season. Individual tracks vary in width from 4 to 8 m, whereas patches resulting from multiple tracks can vary up to 100 m. Until the early 1990s the tracks were used so intensively that the original vegetation cover was destroyed, but by the time of our field sampling they were naturally revegetated.

2.2. Remote sensing and GIS

Different scales of remote sensing data were used to detect the impacts of industrial sites (Table 1). At the finest resolution we used Quickbird-2 imagery with multispectral 2.4 m resolution and panchromatic 0.63 m resolution. Images were acquired to cover the core areas of ≈120 km^2 at both research sites. Terra ASTER VNIR (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images (15 m resolution) were used for the surroundings not covered by the Quickbird-2 images. At the larger Toravei site SPOT (Satellite Pour l'Observation de la Terre) and Landsat TM images were also used for detection of impacts.

Table 1
Satellite imagery used in research.

Satellite imagery	Acquired	Resolution	Investigated area
Quickbird-2	15.7.2004	0.63 m	Bovanenkovo
Quickbird-2	15.7.2004	2.4 m	Bovanenkovo
Quickbird-2	5.8.2005	0.63 m	Toravei
Quickbird-2	5.8.2005	2.4 m	Toravei
ASTER VNIR	21.7.2001	15 m	Bovanenkovo
ASTER VNIR	4.7.2001	15 m	Toravei
SPOT	19.7.1998	20 m	Bovanenkovo
SPOT	24.7.1993	20 m	Toravei
LANDSAT TM	7.8.1988	30 m	Bovanenkovo
LANDSAT TM	3.8.1988	30 m	Toravei
LANDSAT +ETM/7	7.7.2000	30 m	Bovanenkovo

ERDAS 9.1 and ArcGIS 9.2 software were used in image processing and interpretation. Kumpula et al. (2010) presents how different scales of hydrocarbon impacts on land cover can be detected. For distinguishing narrow off-road vehicle tracks from different satellite imagery (Quickbird-2, Terra ASTER VNIR, and Landsat TM/ETM7) unsupervised and supervised classification did not prove to be suitable even at the highest resolution. Attempts to classify off-road tracks and other anthropogenic classes as own class were not successful due to their mixture into several other tundra vegetation classes. We also tested change detection with Landsat TM/+ETM7 imagery from 1988 to 2000 with Normalized Vegetation Index (NDVI). NDVI based change detection revealed change in general but to identify the nature of change and especially in this case vehicle tracks, the results were not satisfactory. Landsat's resolution was too coarse and older VHR imagery from late 1980s or early 1990s were not available. Visual interpretation proved to be most accurate, especially from Quickbird-2 (2004, 2005) and Terra ASTER VNIR (2001) images. We used the multispectral and panchromatic channels separately and pan-sharpened NIR channels of Quickbird-2 imagery to identify vehicle tracks, typically 4–8 m wide (Fig. 2). From these images all visible vehicle tracks, infrastructure, pipelines, roads and quarries were digitized into separate layers. In areas where Quickbird-2 data were not available we used Terra ASTER VNIR and Landsat TM/+ETM7 (1988 and 2000) images were used. After digitizing, buffers were created around roads (18 m) and individual vehicle tracks (6 m). After that the affected area around each object was calculated. Widths of the respective buffers used were measured in the field (Bovanenkovo summer 2005, Toravei summer 2006). The road buffer is based on 15 field measurements and 15 corresponding measurements from Quickbird-2 pan-sharpened and panchromatic images. In the field different types of imagery were used to interpret off-road vehicle tracks and other industrial impacts correctly. An average track width of 6 m (based on field measurements and image interpretations) was used to calculate coverage of tracks interpreted from Quickbird-2 images. When calculating the area of off-road tracks interpreted from Terra ASTER VNIR image an average track width of 8 m was used.

2.3. Vegetation

Vegetation sampling was conducted at Bovanenkovo in July 2005 and at Toravei in July 2006. Three multi-pass 15–20 year old vehicle tracks were randomly chosen with the aid of satellite imagery within each of the three major vegetation types in both study areas. These vegetation types were willow thicket, dwarf shrub tundra and mire (cf. Andreyashkina and Peshkova, 1997; Pajunen et al., 2010). Within each track six treatment plots (50 × 50 cm) were set up in the middle of the track and six control plots were situated along a parallel transect in adjoining undisturbed vegetation 12 m away.

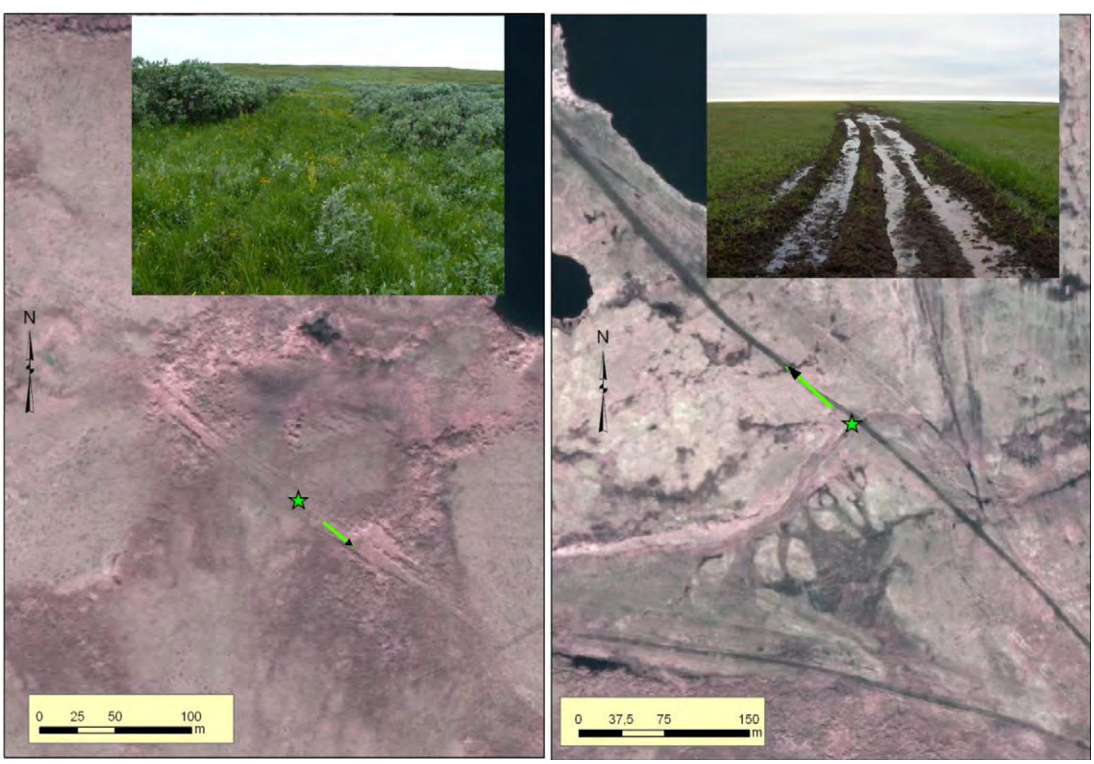

Fig. 2. Two zooms from a single Quickbird-2 image (dated 05.08.2005) from Toravei research area. They are based on a combination of multispectral (2.4 m resolution) and panchromatic (0.64 m resolution) images. On the left ≈20 year old off-road track going through dense erect willow shrubs. The track has naturally revegetated with graminoids as willows (mainly Salix lanata) have not regenerated after the initial disturbance. On the right a recent track crossing a wet mire. Green stars within the images show the locations and black-green arrows shows the direction of general aspect photographs. Copyright: Digital Globe & Eurimage. Digital photographs taken in the field (12.7.2006) by E. Kaarlejärvi (left), T. Kumpula (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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The starting point was chosen randomly and the distance between all the plots was 12 m. Within the plots the cover of each species, including bryophytes and lichens, was estimated visually using the following scale: +, , 1, 2, 3, . . ., 10, 15, 20, 25, . . ., 100.

The cover estimates of plant species were pooled on the basis of their functional group following Chapin et al. (1996) with few exceptions. First, we separated low (<50 cm) (dwarf) deciduous shrubs from tall shrubs and combined them with evergreen dwarf shrubs. Secondly, we pooled sedges (*Cyperaceae* spp.) and grasses (*Poaceae* spp.) as one group of 'graminoids'. Chapin et al. (1996) divided bryophytes into *Sphagnum* and non-*Sphagnum* species, whereas we treated them as a single group. The covers of dwarf shrubs and lichens were not analysed, because they were infrequent overall and almost absent in mires. They were, however, included in the group of reindeer forage plants together with upright deciduous shrubs, forbs and graminoids. This group therefore contained both summer and winter pastures' forage species. The impact of disturbance, area, vegetation type and their mutual interactions on the cover of functional groups of species and species richness of vegetation (total number of species, number of vascular plant species, number of cryptogram species) was tested with mixed linear models (LME) (Pinheiro and Bates, 2000). In order to obtain satisfactory residual plots of the models, square root transformation was applied to the data of deciduous shrub and forb cover prior to modeling. We used track as a random factor in the analyses, whereas disturbance, area, vegetation type and their interactions were set as fixed factors in the initial models. According to principles of the minimum adequate model (Crawley, 2002), non-significant terms were removed, and the final models contained only significant explanatory variables. Statistical analyses were run using R version 2.6.2 statistical environment (R Development Core Team, 2008).

2.4. Participant observation

In YNAO anthropological fieldwork consisted mainly of participant observation with herders, which took place in summer 2005, building on preliminary interviews in spring 2005 and earlier fieldwork between 1998 and 2001 (Stammler, 2005). Work involved migrating with the herders of camps 4 and 8 from the sovkhoz Yarsalinskii. The camps were accompanied while approaching the industrial impact zone starting at N70′15.385, E68′44.785, then crossing the Se Yakha River and moving through the area of the gas deposit along roads, quarries, pipelines and industrial production bases, until leaving further north towards the shore of the Kara Sea ending at N70′27.870, E68′03.969.

Comparative fieldwork was done in 2006 and 2007 in camps 2 and 7 of the Yerv herding cooperative in NAO. Herders and their animals were likewise accompanied on their way through active and abandoned industrial installations, in an area centered at approximately N68°66′, E58°33. Due to the NAO brigades' more complex migration route, herders drew their own migration maps, first on satellite imagery, then on a blank paper, commenting to the anthropologist on the choice of the route. This map-making process was documented on video for further analysis. To ensure comparability, fieldwork was carried out by the same researcher (Stammler, in cooperation with Forbes in summer 2005). Both groups, herders and industry workers were also invited to comment on each other's activity and on opportunities and problems of coexistence.

During migration in both study regions, structured and unstructured interviews were conducted with herders about their everyday decision making concerning the exact migration route, advantages and disadvantages of the proximity of industry, the impact of industrial development on herders and reindeer grazing, and views of the future impact of industrial development on their livelihoods. In addition to moving with the camp, herders were accompanied during their work with the herd, particularly during the night shifts in industrially impacted areas during mosquito harassment – where both humans and animals are exposed to multiple natural and anthropogenic pressures. They provided detailed information on landscape changes over the last three decades, using topographic maps and high- and very high-resolution satellite image printouts. Social impacts of industrial development were assessed while accompanying herders to the settlements of Bovanenkovo (YNAO), and Varandei (NAO), where they re-supply their households with staple food, and accompanying gas workers to the herders' camps, thus experiencing how relations develop between these two contrasting groups of land users.

3. Results

3.1. Magnitude of land cover change in Bovanenkovo and Toravei

Estimates of the spatial extent of industrial impacts are presented in Table 2. With regard to their industrial geography, the two study regions differ considerably in so far as the Toravei field in NAO consists of several smaller oil deposits located in close proximity to each other, while the Bovanenkovo field in YNAO is a giant gas deposit situated in one area.

Terrain that can be visually interpreted from satellite imagery and from field observations to be affected in the vicinity of Bovanenkovo covers an area nearly 7 times greater than that around Toravei (Table 2 and Figs. 3, 4). For brigades on Yamal, the industrial development for the time being is concentrated within their pastures used during July and August. 225 km^2 out of the 1019 km^2 summer pasture territory of brigade 4 lies inside the affected area of Bovanenkovo gas field. For brigade 8 the total is 200 km^2 of affected terrain out of 762 km^2. These figures reveal that, as of 2005, the brigades migrating through Bovanenkovo have direct impacts on more than 20% of their late summer pastures (Fig. 4). The reindeer herding camps 2 and 7 in the Toravei area are less mobile than their Yamal counterparts. They have most of their pastures in close proximity to industrial installations throughout the year. Since brigades migrate through narrow corridors only a few km wide, even a relatively small-scale industrial site covering 10–30 km^2 may partially or completely block a given brigade route. The result is that brigades/camps and also the whole *sovkhozy* can be quite sensitive to minor changes in land use when the survival of units is dependent upon access to limited pastures and subtle shifts in meat markets (Zenko, 2004; Stammler, 2005). The Nenets have had to change their route as the construction of the stations has spread, but also as a result of changing weather conditions year to year (Zenko, 2004; Stammler, 2005). In each region all territories are already allocated, and for brigades that lose pastures relocating onto neighbouring areas is not an option.

3.2. Changes in the reindeer pastures' vegetation in the vicinity of industrial sites

The cover of most plant groups was lower on mechanically disturbed terrain than on undisturbed vegetation, indicating slow

Table 2
Impacts of industrialization in Bovanenkovo (YNAO) and Toravei (NAO).

	Bovanenkovo	Toravei
Permanently changed area	9.3 km^2	4.7 km^2
Buildings and yards	2.1 km^2	1.9 km^2
Roads	2.9 km^2	0.9 km^2
Sand quarries	4.3 km^2	1.9 km^2
Pipeline, length	16 km	230 km
Off-road tracks, length	2400 km	800 km
Off-road tracks, area	24 km^2	6.4 km^2
Total affected area	448 km^2	67 km^2

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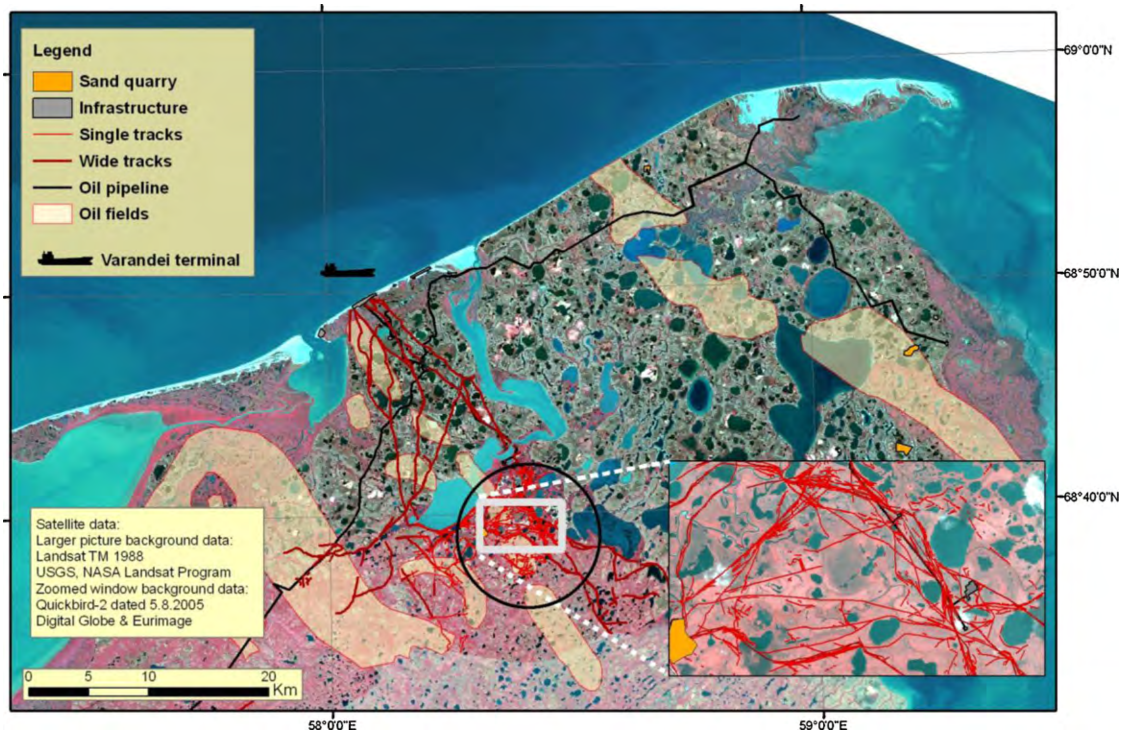

Fig. 3. Map of oil deposits, infrastructure and disturbed areas in the Varandei region, including the study area in the vicinity of Toravei oil field. Quickbird-2 image zoom of the intensively studied Toravei area. A sand quarry in the lower left corner increased above the licensed extent and the brigade's camp site became unusable. The migration routes of camps 2 and 7 of the Yerv herding cooperative overlap directly with the development in and around Toravei, indicated by the black circle.

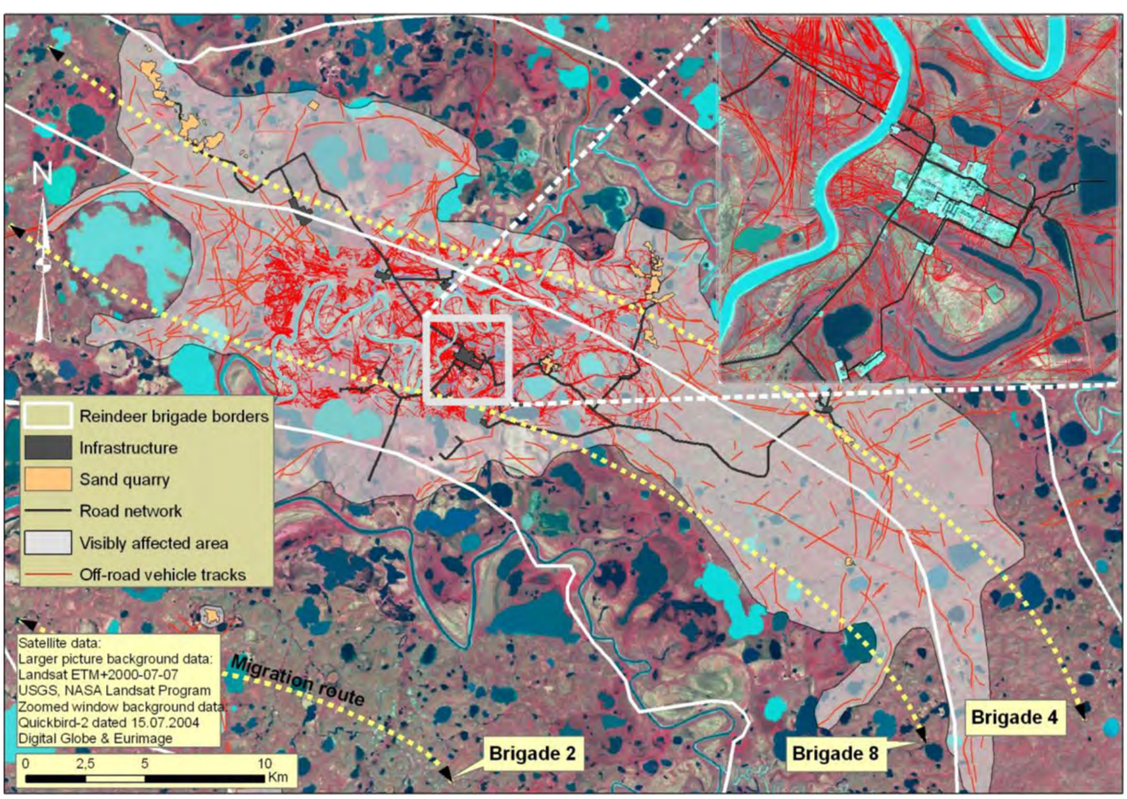

Fig. 4. Analysis of visibly affected terrain in the vicinity of Bovanenkovo gas field. The migration routes of brigades 4 and 8 of the Yarsalinski sovkhoz overlap directly with the gas field, whereas brigade 2 moves well to the south. Quickbird-2 image zoom of the Bovanenkovo gas field center. Result of unregulated off-road traffic during the construction phase in late 1980s–1990s. If tracks are revegetated they are more difficult to detect visually in the field, this demonstrates the utility of the VHR satellite imagery to track small scale industrial impacts.

regeneration within most species groups (Fig. 5 and Appendix 1). Most clearly this held for erect deciduous shrubs, the effect being strongest in willow thickets (Fig. 4 for the LME test results, see Appendix 1). In contrast with the other plant groups, the cover of graminoids was significantly greater on disturbed ground (Figs. 2 and 5, Appendix 1). The effect of disturbance on bryophytes depended on the study area, being stronger in Bovanenkovo than in Varandei (Fig. 5 and Appendix 1). In Bovanenkovo *Carex aquatilis*, *Eriophorum angustifolium* and *Calamagrostis stricta* were the most common graminoid species and in Toravei *Carex aquatilis*, *Eriophorum vaginatum* and *Carex rariflora*. The cover of reindeer forage plants in Bovanenkovo was approximately the same in disturbed and undisturbed vegetation, whereas in Varandei the cover of palatable plants was significantly lower in disturbed vegetation (Fig. 6 and Appendix 1). The total species richness and the species richness of vascular plants and cryptograms were all lower in disturbed vegetation than in undisturbed vegetation (Fig. 6 and Appendix 1).

3.3. Changes in pasture quality and herders' perceptions of impacts in YNAO and NAO

Old and disused off-road vehicle track networks have the largest areal impact in both areas. The decrease in willows resulting from off-road vehicle traffic was about 15–20% estimated from digitized tracks and land cover classification. This was seen as negative by herders as willow is important food spring summer and autumn. The revegetated graminoid-dominated vegetation types were seen as potentially good reindeer pastures by reindeer herders. Especially in early summer when young shoots and leaves have high forage value for reindeer. However, industrial waste limited the utilization of these revegetated tracks.

The physical impact of industry on pasture quality and herders is greatest during the initial construction phase, when the pressure on terrestrial and freshwater systems is intense. According to herders some of the negatively affected tundra, streams and lake are able to recover once construction ends and production is under way. If there are no oil spills and it is possible to traverse pipelines and maintenance roads, the impact of such extraction facilities is manageable for herders. Less extensive, but socially significant, are settlements/installations with constant human presence (compressor stations, workers' settlements, repairing stations for transport, air- or sea-ports).

Industrial garbage occurs in conjunction with all of the aforementioned impacts. Industrial garbage in both study regions severely disrupted grazing and migration practices by humans and animals. Herders avoided garbage-strewn sites in order to minimize the negative impact. Precise knowledge of the location and the type of trash is required. Barrels containing petrol or other toxic liquids potentially contaminate pastures and water. However, everything made of wood is welcomed by herders and used for either construction or as heating and cooking fuel. Small scattered garbage is worse than large concentrated garbage. Nails, screws and other sharp metal items can injure animals, which then get infectious diseases and have to be slaughtered. Half covered garbage, hidden among foliage, is more dangerous for animals, and humans without protective footwear, than open trash. Scattered and spatially small garbage was mostly impossible to identify even from Quickbird-2 images. Only intensive field inventory, if even that, can detect scattered trash deposits (Kumpula et al., 2010).

For any construction sand and/or gravel are needed. Sand quarries in Bovanenkovo covered 4.3 km^2 and in Toravei 1.9 km^2. Direct impacts for herders include the loss of pasture area as sand quarries, which are located on hills elevated above boggy ground. Herders in both areas have lost several campsites to such quarries. Near Bovanenkovo, one brigade has lost six campsites. The situation is similar in the Toravei area, where the 'semi-legal' expansion of one quarry has led to the loss of one of the last campsites in the vicinity. In cases where the quarry is on higher terrain, free of human presence and waste, it can also serve as a relatively exposed, windy place to obtain insect relief for the herd.

Roads serve the dual function of structuring territory for herders and herds. Whereas for industry they serve exclusively as

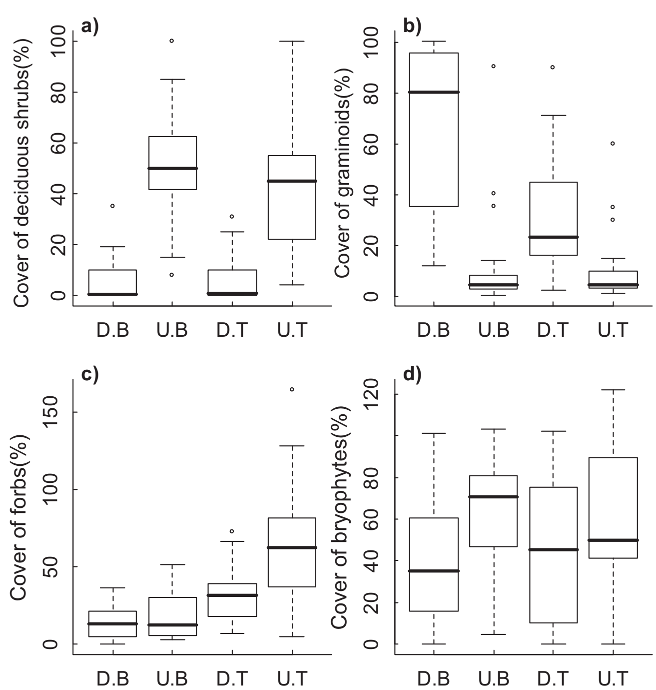

Fig. 5. The cover of functional groups of species in willow thicket in Bovanenkovo (B) and Toravei (T) (for the other vegetation types, see Appendix 1). The abbreviation D indicates disturbed plots and U undisturbed plots. The differences between disturbed and undisturbed plots were all significant in the LME models (for test results, see Appendix 1). The horizontal line inside the box represents the median, and the bottom and top of the box show lower and upper quartiles, respectively. The vertical dashed lines represent either maximum or minimum values of the data or 1.5 times the interquartile range of the data, whichever is smaller. Extreme values are marked as separate dots if they go beyond 1.5 times the interquartile range added to the lower and upper quartiles.

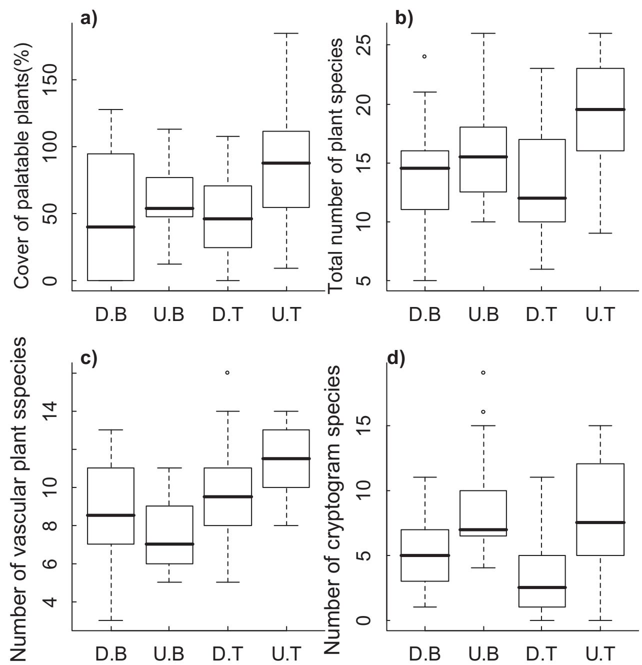

Fig. 6. The cover of palatable plants for reindeer (a), the total number of plant species, number of vascular plants (c) and number of cryptograms (d) in willow thicket in Bovanenkovo (B) and Toravei (T) (for the other vegetation types, see Appendix 1). The abbreviation D indicates disturbed plots and U undisturbed plots. The differences between disturbed and undisturbed plots were all significant in the LME models (for test results, see Appendix 1). For the boxplot interpretation, see Fig. 5.

'live arteries', linking them to the rest of the world, for the former they are also borders/barriers compartmentalising territory. As most roads and railroads are built upon elevated foundations, herds and migrating camps consisting of numerous caravans have to climb and then cross them. As well, herders benefit from roads and use them for summer supply transport for bread and other staples. Herders have direct contact with workers during the time they are actually crossing the gas field, including business relations pertaining to velvet antlers (Stammler, 2007). On Yamal, meat is processed far away from the industrial facilities at a municipal slaughterhouse in the village of Yar-Sale. It is traded on the open market regionally and since 2007 internationally.

Pipelines that are not elevated pose insurmountable barriers to herders and animals, unless there are passageways constructed at sites and in intervals determined by reindeer herders. In some cases passageways have been constructed according to herders' preferences, in other cases the reply by the company was that the particular spots could not be included in to the 'project of construction' in time. Therefore, pipelines constructed the wrong way can render whole areas inaccessible for reindeer grazing and nomadic migration, which means the functional loss of territory is notably larger than the number of hectares occupied by the pipeline. Besides the pipeline itself, maintenance roads running parallel are usually built with all the direct and indirect impacts described above for roads. This accumulation of multiple components increased the overall negative impact with which tundra residents are confronted, rather than the separate assessments of individual installations that are typically performed by companies.

In general, the analysis of perception of changes brought about by industry and the relations of herders with oil/gas workers revealed a high degree of similarity in both cases. More or less the same positive and negative impacts of the presence of industry were mentioned. This is remarkable as there are clear differences between the cases in terms of detail.

The presence of workers in such settlements has both positive and negative impacts on herders: workers commit poaching, they have released dogs to the tundra that subsequently become feral and 'turn into wolves hunting calves', as herders say. They also serve, however, as exchange partners. Meat, fish and fur exchanged for bread, tea, sugar, petrol and ammunition are the most common items.

The Bovanenkovo gas field is in a strategic location for brigades 4 and 8 and their herds, as their only way of reaching the coastal summer pasture areas goes directly through the Bovanenkovo Gas Field. Potential encroachment of infrastructure will have the effect of blocking other herds from accessing the coastal pastures. In summer 2005, the gas company started telling them that they should prepare for a future regime without crossing the gas field anymore. However, herders opposed that option of being completely cut off from the coast, and as of 2008 they began having their camps transported on trucks through the deposit.

Since the area around Toravei oil field has industrial installations scattered across a larger territory, connected via pipelines, in practice most of the migration territory of camps 2 and 7 is affected in some way. From almost any point along the migration routes industrial facilities are visible and within reach by reindeer. In winter additional impact derives from the winter road connecting Varandei to the regional capital Naryan Mar, with numerous trucks bringing desired and undesired goods and people to the tundra.

4. Discussion

In both regions industrial development is still at an early stage. In NAO, oil production from Toravei has just recently started and in YNAO gas production from Bovanenkovo is expected to begin within a few years. The near future will bring massive infrastructure development. New roads, pipelines, and at least one railway line are in the works or already completed and a large number of new pumping stations are about to be opened. The cumulative ecological impacts of transportation networks have been reported from previous studies in Arctic Alaska and Eurasia (Nellemann et al., 2001a,b; National Research Council, 2003). The growing transport network is likely to create more difficulties for herders along their migration routes via increasingly degraded or inaccessible pastures and freshwater systems (Forbes et al., 2009).

In both areas the directly affected area remains rather small at present. However, the spatial figures are not enough to explain the overall situation in detail. Development in both regions is rapidly accelerating as this article is written, so by the time of publication much more area will be already affected. Secondly, not only the extent of the affected area is important, it matters more if good quality pastures and camps sites are disturbed or destroyed. We acknowledge that estimating the affected area is always a compromise and depends on the chosen method of assessment. The Russian impact assessment in Yamal, for example, distinguished three gradients of ‘impact zones’. However, even untouched areas can be made inaccessible for use by herders, if passageways for herds and camps above or beneath pipelines, roads and railroads are not built (see above).

There are different measures for assessing the loss of territory due to industrial activities. For example, although unpaved roads are just 15–20 m wide, the zones of impact reach up to 1 km on either side of the road, via windblown dust. In general, with a good road network there is less off-road vehicle traffic, although dust fall from roads can also affect tundra vegetation and permafrost soils over large areas for instance by increasing the pH-value of soils (Forbes, 1995; Auerbach et al., 1997). Off-road tracks serve as a good example of mechanical effects overall, and therefore the results of our study may be used for prediction of revegetation after any mechanical disturbance.

What is new here is the level of detail in which we have quantified land cover changes within active hydrocarbon fields in modern Russia, the comparison between oil (NAO) and gas (YNAO) production facilities and the extent to which we have brought in local and indigenous knowledge. Only a few attempts in this field in the Arctic have been made before (Rees et al., 2003; Walker et al., 2006). Most importantly, the satellite data used were VHR Quickbird-2 images, which allowed detailed spatial evaluation of most industrial disturbances in both regions. Quickbird-2 imagery demonstrated a remarkably high capacity to distinguish 15–20 year old off-road vehicle tracks from the network that sprawls around the oil and gas fields. In cases where the tracks were revegetated it was sometimes difficult or impossible to detect them visually in the field, illustrating the utility of the VHR satellite imagery for tracking overall regeneration of the vegetation cover. Kumpula et al. (2010) shows that even reindeer herds and herders' activities can be visible in Quickbird-2 imagery.

Revegetation in disturbed sites occurred but the composition of the secondary community fundamentally differed from the original. This supports the notion of Oksanen and Virtanen (1997) according to which recovery of arctic-alpine vegetation after disturbance is slow, but essentially depends on the life-strategy of species. In the 15–20 years since the cessation of widespread off-road vehicle traffic, there had been a widespread transformation from shrub willow vegetation, tundra heaths and mires to graminoid-dominated vegetation. This is mainly due to the ability of rhizomatous graminoids to reproduce effectively primarily by vegetative means (Oksanen and Virtanen, 1997; Forbes et al., 2001). The regrowth of vegetation was generally greater in mires than in other vegetation types supporting earlier studies that have shown that the more moisture there is in the soil, the faster the vegetation regenerates (Rebristaya et al., 1993; Andreyashkina and Peshkova, 1997; Forbes et al., 2001). The spreading of graminoid-dominated vegetation at the expense of other plant groups – sometimes referred to as ‘grassification’ (Shchelkunova, 1993) – and the persistence of the effects have been well known for some time from studies of industrial disturbance in Russian and North American tundra regions (Forbes, 1992; Khitun, 1997; Sumina, 1998; Forbes et al., 2001; Khitun and Rebristaya, 2002; Lavrinenko et al., 2003). Like most other plant groups, except for graminoids, bryophytes had regenerated poorly after the disturbance. A common response to the removal or thinning of the bryophyte layer is an increase in the depth of the active layer (Kevan et al., 1995; Pavlov and Moskalenko, 2002). An increase in thaw depth may have profound impacts on the thermal regime of the soils (Forbes, 1998; Pavlov and Moskalenko, 2002) including the potential to induce thermokarst in ice-rich permafrost areas (National Research Council, 2003).

In the revegetated secondary communities, the cover of reindeer forage species was relatively high, in mires of Bovanenkovo even much higher than in the original vegetation. This suggests that if only considering forage species, these swards could be relatively high-value pastures. This is the case despite the radical change in vegetation structure resulting from the almost complete displacement of erect shrubs and the dense understory of forbs – which was especially evident at the more productive Toravei study site – in undisturbed willow thickets. However, as our combined interdisciplinary findings here reveal, supporting our previous findings (see also, Kitti et al., 2006; Forbes et al., 2009), the suitability of reindeer summer pastures' depends not only on the nutrient values of forage plants, but also on factors such as degree of insect harassment, accessibility of herders to good fishing places, and amount of anthropogenic disturbance, which can diminish so called “grazing peace”.

Anthropogenic disturbance reduces the species richness of vegetation. Earlier studies have reported similar results, according to which a decrease in species richness has been related to different forms of industrialization, off-road traffic, roads, railroads, quarries, and chemical disturbance (Sumina, 1998; Forbes et al., 2001; Khitun and Rebristaya, 2002; Lavrinenko et al., 2003). By incorporating the herders' perspective, our study supports the holistic landscape approach, where lowering of biological diversity is seen as linked to reduced indigenous access and so-called ecodiversity (Naveh, 1995).

The herders' perception of changes in land use/land cover is of double value for scientific analysis, since they not only detect changes over time as ‘facts’, they also evaluate them in terms of their significance for reindeer herding practice. Although perceptions alone may be enough to affect human behaviour, particularly in a time of rapid environmental change that is well documented (ACIA, 2005; IPCC, 2007), it remains necessary to distinguish between scientifically verifiable facts and those perceived by Arctic indigenous peoples (Huntington et al., 2004). Alongside the facts perceived over time, interviews directed our analysis by classifying changes. This classification allowed us to see the importance of the physical changes analysed in this paper in relation to other factors. These changes encompass the omnipresent off-road vehicle tracks as well as infrastructure (sand quarries, pipelines, and roads). Other aspects include natural environmental dynamics independent of industrial development (landslides, climate change impacts, coastal erosion), and herders' perceptions of fish, and cumulative social impacts that go beyond the scope of this paper and are the subject of separate analysis (e.g. Stammler and Peskov, 2008; Stammler, 2008).

The tundra brigades of YNAO and NAO that experience the greatest pressures overall are those which come into direct contact with industrial sites in the tundra. In Bovanenkovo, the migration of two brigades is already strongly affected by the gas field so the question remains: what will happen when the gas field will be in full production in years to come. In YNAO there is significant pressure on private herders, whose interests are poorly represented in development decisions since most of them do not belong to a registered land-using entity (e.g. sovkhoz, private reindeer enterprise). Perceived pressures can also differ among brigades depending on how many animals they manage. As a rule, the less reindeer a family has, the more it relies on fish as a staple food and commodity. In both regions there are fishermen-nomads and partially sedentary fishermen. For them, the effects of industrial development on grazing land are less severe since it is easier to navigate a small herd around a garbage field than a herd of 5000 animals. On the other hand, impacts on fish migration/waterway blockages affect those people more seriously. Thus individual groups of actors may develop different hierarchies of criteria that influence their practices of interacting with the tundra. At the same time, herders have to balance their own needs with the needs of the animals (Kitti et al., 2006).

The result is an ongoing practice of ranking potential impacts in the minds of nomads whose situations differ according to the number of animals one has and the importance of various subsistence practices in the broader pool of economic activities. In terms of territory, it is likely that surrounding brigades, or even the whole sovkhoz may be affected if certain regions become less accessible or unusable. On the other hand, our data reveal that there are elements in which the two contrasting land uses are also partially complementary. For example, industry provides a local market for herders' production (meat), and herders obtain some benefits from the presence of industry (compensation, barter for goods, health care). We emphasize that the rankings discussed here stand only for the particular groups of people we worked with, and even their views cannot be quantified in a table given their complexity. What the rankings show, however, is that functional loss of territory is not necessarily the principle concern of reindeer herders. We further demonstrate that the past 30 years has been a period of mutual coexistence on the land, although it is uncertain how much longer this can last.

5. Conclusions

Our study shows with help of two cases how industrial activities affect complex social-ecological systems. The results we found may be helpful in predicting future changes also in other Arctic areas, where the level of industrialization is predicted to multiply in the coming decades (Nellemann et al., 2001a). In the same area the effects of climatic warming are predicted to be most pronounced (ACIA, 2005; IPCC, 2007), which is likely to complicate the predictions.

Our material shows that even using VHR remote sensing data (e.g. Quickbird-2) alone it is not possible to determine fully the amount of degraded territory in modern oil and gas fields, even if we can reliably detect shifts in vegetation composition/cover on strips and patches less than a few meters across. The value of pastures to herders is partly dependent on various factors not visible in satellite imagery, e.g. small-scale garbage, accessibility, good fishing lakes etc. Territories disturbed by industrial development are quite local, but have greater impacts on reindeer herding and migration via the sprawling transport networks. Large portions of reindeer pastures can be easily rendered inaccessible due to imprecise planning or purposefully neglecting herders' recommendations, e.g. with regard to citing pipeline construction.

With regard to policy, biophysical and social impacts could be substantially reduced if information flow were to be optimized both horizontally (between herders and workers on the tundra) and vertically (between herders and their bosses on the one side and workers and their bosses on the other). Concrete examples include: (1) the presence of garbage that might have been removed long ago if headquarters would formally approve cleaning efforts that workers on the ground have already partially done out of their own initiative; and (2) passageways across pipelines/roads/railways could always be in the right location if communications between herders, workers and their headquarters would be efficient. A serious issue is the ongoing withdrawal of territories through semi-coercive and borderline-legal means (Stammler, 2008, p. 88; Stammler et al., 2009).

Our findings demonstrate highly significant differences between the two case study regions, although both comprise traditional homelands of the same indigenous group (Nenets) and are characterized by the same livelihood (nomadic tundra pastoralism). On the other hand our data clearly reveal that the perceptions of changes and impacts resulting from industrial development are strikingly similar among comparable user groups. In other words, the perception of a road is more similar among herders of both regions (Bovanenkovo, YNAO and Toravei, NAO), than between a herder, a sedentary fisherman, and an indigenous villager within the same region. We argue that this greater similarity among the same users across regions, versus the variation among slightly different users within the same region, shows the potential of such research to yield highly relevant results that can be generalized for a broader range of industrial impact studies. Our material also shows that the combined biophysical, social and cultural impacts on northern reindeer nomadism are much greater than the sum of assessed impacts of individual impacts or infrastructural components (e.g. one pipeline, road, quarry, or oil/gas deposit). The broader regional effects become apparent only after a holistic *strategic impact assessment* (Spiridonov, 2006), for which so far neither the companies nor the relevant administrations have made concrete efforts.

In the wake of our study we have become more confident that future assessments of environmental and social impacts in the Arctic will benefit by deploying interdisciplinary teams and exercising tighter integration across traditional disciplinary borders beginning already at the planning stages. Involving local practitioners early in the planning process is necessary to ensure conservation of scarce research funding by focusing on the most relevant locations and issues (cf. Forbes et al., 2006). It is essential to link the latest remote sensing and GIS methods to ecological investigations at scales relevant to local actors, in this case reindeer herders. The end result is a suite of interpretations, extremely rich in detail and context from both scientists and local stakeholders, which would not have been achievable without each other.

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Appendix A. Effects of mechanical disturbance on shrub tundra vegetation in Bovanenkovo (B) and Toravei (T). The abbreviation D indicates disturbed plots and U undisturbed plots. Mi = stands for mire, tu for tundra and wi for willow thicket. Values present the averages ± standard deviation.

	B mi D	B mi U	B tu D	B tu U	B wi D	B wi U	T mi D	T mi U	T tu D	T tu U	T wi D	T wi U	Source of variation	*F* value	*p*-Value	Transformation
Cover of erect deciduous shrubs	0.4 ± 1.4	16.6 ± 15.4	2.1 ± 4.8	12.6 ± 11.6	5.8 ± 9.5	51.1 ± 23.1	2.5 ± 2.7	4.4 ± 2.9	2.5 ± 4.2	4.9 ± 4.8	6.3 ± 9.4	43.5 ± 27.9	Disturbance × area	$F_{1,24} = 7.3$	0.01***	No
													Disturbance × type	$F_{2,24} = 16.9$	<0.0001***	Sqrt
Cover of dwarf shrubs	0 ± 0	0 ± 0	1.1 ± 2.6	13.2 ± 18.8	0 ± 0	0.7 ± 2.3	0 ± 0	0 ± 0	3.9 ± 3.9	47.3 ± 28	0 ± 0.1	5.1 ± 14.6				
Cover of graminoids	79.2 ± 22.6	27.2 ± 17.7	51.5 ± 32.2	36.3 ± 27.5	66.7 ± 32.6	12.1 ± 21.3	10 ± 3.4	10.7 ± 6.6	39.9 ± 19.6	21.8 ± 16.4	33.2 ± 24.2	11.1 ± 15.5	Disturbance	$F_{1,27} = 19.0$	0.0001***	No
													Area	$F_{1,27} = 12.5$	0.001***	No
													Type	$F_{2,27} = 0.6$	0.5	No
Cover of forbs	2.7 ± 3.4	3.1 ± 2.5	5.2 ± 6.4	7.3 ± 12.8	13.9 ± 10.3	18.1 ± 15.4	6.5 ± 4.7	4.4 ± 5.6	3.7 ± 6.1	20.2 ± 16.7	32.3 ± 18.9	66.2 ± 41.2	Disturbance	$F_{1,27} = 5.0$	0.03***	No
													Area	$F_{1,27} = 10.7$	0.003***	No
													Type	$F_{2,27} = 22.6$	<0.0001***	Sqrt
Cover of bryophytes	25.3 ± 33.4	99.8 ± 2.7	68.8 ± 30.6	92.1 ± 12.3	43.6 ± 35.6	65.7 ± 26.3	100.1 ± 2.7	101.5 ± 4.5	93.7 ± 19.1	83.3 ± 23.9	45.9 ± 38.2	58.3 ± 31	Disturbance × area	$F_{1,24} = 9.0$	0.006***	No
													Area × type	$F_{2,24} = 3.7$	0.04***	No
Cover of lichens	0 ± 0	0 ± 0.1	2.3 ± 6	9.9 ± 12.6	2.7 ± 6.6	5.9 ± 7.9	0 ± 0.1	0 ± 0.1	0.1 ± 0.5	7.3 ± 9.3	0.1 ± 0.2	0.6 ± 1.8				
Cover of reindeer forage species	69.4 ± 37.3	35.6 ± 29.3	34.6 ± 36.4	53.9 ± 32.8	45.2 ± 45.2	59 ± 25.7	14.8 ± 5.3	11 ± 9.2	42.7 ± 24.5	88.7 ± 37	46.9 ± 32.2	90.1 ± 47	Disturbance × area	$F_{1,22} = 8.8$	0.007***	No
													Disturbance × type	$F_{2,22} = 9.8$	0.0009***	No
													Area × type	$F_{2,22} = 13.8$	0.0001***	No
Total number of species	6.2 ± 3.8	12 ± 3.1	15.5 ± 5.3	18.8 ± 7.3	13.9 ± 4.7	16.1 ± 4.4	12.3 ± 3.8	15.3 ± 3.8	10.4 ± 3.2	13.6 ± 3.9	13 ± 5.1	19.2 ± 4.6	Disturbance	$F_{1,25} = 17.3$	0.0003***	No
													Area x type	$F_{2,25} = 9.2$	0.001***	No
Number of vascular plant species	4.5 ± 2.4	6.1 ± 1.1	6.7 ± 2.4	5.8 ± 1.8	8.5 ± 3	7.5 ± 1.9	5.5 ± 1	6.6 ± 1.8	5 ± 1.5	6.1 ± 1.2	9.5 ± 3	11.3 ± 1.9	Disturbance	$F_{1,27} = 0.8$	0.4	No
													Type	$F_{2,27} = 17.9$	<0.0001***	No
													Area	$F_{1,27} = 2.1$	0.2	No
Number of cryptogram species	1.7 ± 1.9	5.9 ± 2.5	8.8 ± 4.7	13.1 ± 6.6	5.4 ± 2.9	8.6 ± 3.9	6.8 ± 3.7	8.7 ± 2.2	5.4 ± 2.8	7.6 ± 3.5	3.5 ± 3.2	7.9 ± 4	Disturbance	$F_{1,25} = 27.1$	<0.0001***	No
													Area × type	$F_{2,25} = 12.7$	0.0002***	No

*** Symbols indicate that *p*-value of a explanatory factor in the LME models is lower than 0.05.

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