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Remote Sensing and Local Knowledge of Hydrocarbon Exploitation: The Case of Bovanenkovo, Yamal Peninsula, West Siberia, Russia

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ABSTRACT. The capacity of satellite imagery to detect anthropogenic impacts on land cover was assessed for the Bovanenkovo gas field on the Yamal Peninsula in northwest Siberia, which contains some of the world's largest untapped gas deposits. The region is also the homeland of nomadic Nenets reindeer herders, whose annual migration between the tree line and the northern tundra exposes them to impacts associated with exploration and production activities. These range from physical obstructions, such as roads, railways, and pipelines, to direct and indirect ecological impacts, such as changes in vegetation and hydrology. Nenets' perceptions of their territories encompass changes in the quantity and quality of terrestrial and freshwater habitats and campsites that have been used seasonally for centuries. Industrial impacts on land cover were examined at spatial scales from very detailed to coarse. Very-high-resolution Quickbird-2 imagery revealed the most impacts, but could not detect items like trash that reduce the quality of reindeer pastures. ASTER, SPOT, and Landsat imagery were useful at the broader landscape level. A proper assessment of the overall ecological impacts of hydrocarbon exploitation requires a combination of remote sensing and detailed ground-truthing. Ideally, these efforts should combine scientific and local knowledge from both indigenous herders and non-indigenous industrial workers.

Key words: Nenets, reindeer migration, Quickbird-2, SPOT, Aster VNIR, Landsat, Arctic tundra, oil and gas activities, human impact

RÉSUMÉ. L'aptitude de l'imagerie satellitaire à détecter les incidences anthropogènes sur la couverture végétale a été évaluée dans le cas du champ de gaz naturel de Bovanenkovo, dans la péninsule de Yamal située dans le nord-ouest de la Sibérie où se trouve un des plus grands gisements de gaz inexploités du monde. Les Nénètses, ou éleveurs de rennes nomades, évoluent dans cette région et leur migration annuelle entre la limite forestière et la toundra du nord les met en contact avec les travaux d'exploration et de production du gaz. Il peut s'agir d'obstructions physiques prenant la forme de routes, de chemins de fer et de pipelines ou encore, d'incidences écologiques directes et indirectes touchant notamment la végétation et l'hydrologie. Les perceptions relatives aux territoires des Nénètses concernent des changements en matière de quantité et de qualité des habitats terrestres et d'eau douce ainsi que les lieux de campement qui sont utilisés d'une saison à l'autre depuis des siècles. Les incidences industrielles sur la couverture végétale ont été examinées à diverses échelles spatiales, allant de très détaillée à grossière. Les images de très haute résolution obtenues au moyen de Quickbird-2 ont permis de révéler le plus grand nombre d'incidences, mais n'ont pas permis de détecter des éléments tels que les ordures qui avaient pour effet d'amenuiser la qualité des pâturages destinés aux rennes. Les images obtenues à partir d'ASTER, de SPOT et de Landsat ont été utiles au niveau plus vaste du paysage. L'évaluation adéquate des incidences écologiques générales découlant de l'exploitation des hydrocarbures nécessite à la fois des outils de télédétection et le recours à des sites témoins. Idéalement, ces efforts devraient faire appel tant aux connaissances scientifiques que locales, connaissances provenant des éleveurs indigènes et des travailleurs industriels non-indigènes.

Mots clés : Nénètses, migration des rennes, Quickbird-2, SPOT, Aster VNIR, Landsat, toundra de l'Arctique, activités pétrolières et gazières, incidences de l'être humain

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Абстракт. Возможность и степень адекватности с помощью спутниковых снимков определять антропогенное воздействие на поверхность земли оценивалась для Бованенковского месторождения, находящегося на территории Ямало-Ненецкого округа (Западная Сибирь), в этом районе имеются самые большие в мире неразработанные газовые месторождения. Этот регион также является родиной кочевых оленеводов – ненцев. Во время ежегодных сезонных миграций между лесной зоной и северной тундрой они испытывают воздействия, связанные с деятельностью по разработке и добыче гидрокарбонатов. Данные влияния варьируют от создания физических помех (таких как – дорог, железных дорог, трубопроводов, пересекающих пути миграций), до прямых и косвенных воздействий на экологию (например, изменение вегетационного покрова, гидросистемы). Ненцы, оценивая качество территорий кочевий, придают значение количественным и качественным изменениям состояния наземных и водных ресурсов, стоянок и мест вокруг них (места для стойбищ использовались сезонно в течение многих столетий). Промышленное воздействие на покров земли было исследовано нами в пространственном масштабировании: от предельно детализированного до самого грубого (обобщенного). Очень высокое разрешение снимков Quickbird-2 позволило увидеть большинство деталей последствий промышленного воздействия, однако с их помощью нельзя было определить такие детали как, например мусор (склянки-железки), который существенно ухудшает качество оленьих пастбищ. Снимки ASTER, SPOT и Landsat были очень полезны при более общей оценке состояния ландшафта. Наиболее адекватный подход для комплексной оценки экологических изменений вследствие добычи и разработки гидрокарбонатов требует совмещения дистанционного зондирования и детальной верификации данных на местности. В идеале такое исследование позволяет сочетать научные данные со знанием и опытом как коренного оленеводческого, так и приезжего индустриального населения.

Ключевые слова: ненцы, миграция оленей, Quickbird-2, SPOT, Aster VNIR, Landsat, арктическая тундра, нефте- и газо разработка, антропогенное воздействие

INTRODUCTION

Russia is rapidly becoming more important as a producer and supplier of oil and gas to European and eventually North American markets (Andreeva and Kryukov, 2008). The Iraq war and post-war chaos contributed to instability in the world markets, pushing the price of oil to record levels for much of 2007–08. Meanwhile, Russia has invested in pipelines across eastern and central Europe, and tanker traffic via the Northern Sea Route is increasing (Meschtyb et al., 2005). Among the main sources are the giant oil fields of the European Nenets Autonomous Okrug (NAO), Khanti-Mansisk Autonomous Okrug (KMAO), and the super giant gas fields of the Yamal-Nenets Autonomous Okrug (YNAO) (Forbes, 2004).

Russian production has an image of being more stable and safe from political crisis than some of the big Middle East producers, although recent disruptions in supplies to Belarus and Ukraine have challenged this perception (Kramer, 2007). Regardless, Russia has once again become a powerful trading partner, in particular as a major source of energy for the global market. At present, Russia supplies 25% of the world's natural gas, which makes it the number one producer (Mahalingam, 2004). Some 90% of this production comes from West Siberia. As for oil, Russia shares the leading position in world production with Saudi Arabia, at times being the number one (Osborn, 2006) or number two producer. About 60% of Russia's oil is from West Siberia. Overall European Union (EU) dependency on both oil and gas from Russia is high and increasing in relation to European sources like Norway and as the export capacity of the United Kingdom is declining. In 2005 the EU received 25% of its oil (30% of all imports) and 25% of its gas (50% of all imports) from Russia. Dependency on Russia among individual EU countries, however, varies greatly. For example, Finland relies on Russian sources for 100% of its natural gas, whereas France, with its traditional ties to Algeria, imported only 24% of its gas from Russia as of 2004 (Stammler and Forbes, 2006).

As oil and gas industrial infrastructure expands rapidly throughout Russia's North, it has profound implications for the environment and the region's economies and local people, in particular indigenous groups such as the Nenets, who practice a traditional livelihood of herding domestic reindeer (*Rangifer tarandus*), hunting, and fishing. The expansion of the Russian empire has affected these groups to varying degrees over the last 500 years. Up until the 19th century, the main resource produced from these northern regions was fur, whereas from the mid-20th century onward, oil and gas products became the central focus (Stammler, 2005).

The exploration and exploitation phases of northern areas like the YNAO and NAO were launched in the 1960s with extensive resource prospecting. Geological surveys searched through the tundra zone with heavy drilling equipment and left clear and lasting imprints on the permafrost landscapes while mapping the oil and gas deposits (Forbes et al., 2001). Drilling was first initiated in the boreal and subarctic areas with easiest access from the south, such as existing railways and roads. Surveys and drilling farther north in truly Arctic areas required enormous amounts of new infrastructure, including pipelines, expanded road and rail networks, and residential facilities. Supply of the most remote Arctic exploration sites (via winter road networks, helicopters and other aircraft, and ships through the Northern Sea Route) has been difficult. In the post-Soviet period, oil and gas have become a vital source of profits to the overall Russian economy. The exploration and exploitation phases of oil and gas development result in benefits and wealth; but at the same time, they produce many direct and cumulative impacts on ecosystems and cultures all along the route from source to market (Forbes, 2004; Fondahl and Sirina, 2006; Stammler and Wilson, 2006). New drilling sites and oil and gas fields have been connected to transport networks to export oil and gas to world markets. This infrastructure has, of course, increased impacts on the environment and the local indigenous communities.

In the YNAO, indigenous lifeways of the Nenets, Khanty, Komi-izhemtsy and Sel'kup fishermen, reindeer herders, and hunters—many of whom are still nomadic or seminomadic—are comparatively well preserved. While the use of reindeer reaches back at least 1000 years, the large-scale herding of domestic reindeer has developed since the 1600s (Krupnik, 1993; Forbes and Kumpula, 2009). In the YNAO on the Yamal Peninsula, reindeer herding survived from the Soviet period with the least amount of damage compared to the lifestyles of other indigenous cultures elsewhere in Russia (Golovnev and Osherenko, 1999; Stammler, 2005).

To date, environmental assessments of petroleum activities have used satellite images mainly in marine and coastal applications. Radar satellite images are especially suitable for detection of marine oil spills (Fingas and Brown, 1997; Benelli and Garzelli, 1999; Espedal and Johannessen, 2000; Jones, 2001; Solberg et al., 2003; Brekke and Solberg, 2005). Detecting oil spills from terrestrial drilling sites is more difficult, however. Surrounding vegetation hinders effective reflection compared to aquatic conditions; the coarse resolution of most imagery reduces its capacity to detect small-scale spills; and the spreading of oil on terrestrial surroundings is limited by topography and soil factors. In many cases the spatial extent of impacts is small: for example, 5 m wide off-road vehicle tracks or 30 × 30 m wide drilling sites. An exception in terrestrial Arctic conditions was the Kolva River oil spill, a large-scale oil disaster that occurred near Usinsk, northwest Russia, in 1994. Using Landsat TM images from 1988 and 2000, Walker et al. (2006) were able to see the effects of this oil spill through changes in the normalized difference vegetation index (NDVI). Spectral and spatial resolution limitations of standard optical remote sensing platforms such as the Système pour l'Observation de la Terre (SPOT), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), or Landsat limit their application to terrestrial oil spill detection. Hyperspectral imagery like Airborne Imaging Spectro-Radiometer for Applications (AISA) and high-resolution synthetic aperture radar (SAR) imagery may be the solution for terrestrial spill detection. In AISA, the data width of a single channel can be 10 nanometers (nm) or less whereas, for example, in Quickbird-2 data it varies from 60 to 140 nm, depending on the channel used (Salem et al., 2005). Laser LIDAR (Light detection and ranging) technology might have some applications because its sensors are capable of identifying oil on backgrounds that include water, soil, ice, and snow (Fingas and Brown, 1997; Samberg, 2007). One of the most important factors is the availability of data. When a spill occurs, even very high-resolution (VHR) images should be acquired before evaporation, mixture with the vegetation, or cleanup takes place. Acquiring these images may be impossible in remote areas, especially where information of such events may be withheld.

In assessing the environmental impacts from petroleum exploration and extraction, remote sensing research tends to focus on the long-term effects that are detectable both on the ground and within available imagery. However, such studies are rare in the Russian Arctic. Impacts of industrialization in the northern Russian mining towns of Noril'sk and Vorkuta have been studied with Landsat TM data (Toutoubalina and Rees, 1999; Virtanen et al., 2002). Tømmervik et al. (2003) investigated the effects of air pollution on vegetation along the Norwegian-Russian border by using multitemporal Landsat MSS/TM data. Rees et al. (2003) studied land cover change in the NAO with Landsat TM and ETM+ images. Walker et al. (2009) used Landsat TM imagery to determine human impacts on the environment in Russia's third important oil region, the Pechora basin. Stow et al. (2004) reviewed the possibilities for change detection studies in Canadian and Alaskan Arctic areas with available remote sensing data.

For Arctic Alaska, there are a few detailed remote sensing analyses of oil and gas impacts. For example, Walker et al. (1987) employed aerial photographs to detect the cumulative impacts of oil fields. The limiting factor for such analyses in the Russian Arctic is access to aerial photo archives. In the Russian Federation, aerial photos are forbidden for scientific use because of their detailed resolution. Walker and Walker (1991) presented a hierarchical approach to analyzing both natural and petroleum industry–related landscape changes in Arctic Alaska. In their study, the capacity to detect disturbances was estimated from point sampling combined with analysis of SPOT, Landsat TM/MSS and Advanced Very High Resolution Radiometer (AVHRR) imagery.

New very high-resolution satellites like IKONOS-2, Quickbird-2, and ALOS have spatial resolution of less than 4 m and so have the potential for extremely detailed impact assessments. It is now possible to acquire such detailed imagery for anywhere in the world. Stow et al. (2004) demonstrated the potential of IKONOS-2 imagery for change detection and off-road vehicle disturbance mapping in the Barrow Environmental Observatory test site. IKONOS-2 images have also been employed in evaluation of the quality and condition of lichen tundra pasture studies in Fennoscandia (Allard, 2003; Kumpula, 2006). When checking from the Google Earth or Quickbird-2 archive server, for example, it can be noticed that large areas of Russian Arctic oil and gas fields have already been acquired.

Rees et al. (2003) attempted to incorporate indigenous knowledge of Nenets reindeer herders into land cover change interpretation, although this topic formed a rather limited part of their analysis. One problem associated with such attempts is that indigenous knowledge is highly situational, very detailed, learned and enacted by people moving through the land. Some scientists have therefore questioned its compatibility with natural science knowledge. Scientific knowledge can be put into databases and treated as a body of information independent from its context, whereas indigenous ways of knowing are culturally embedded sets of practices (Ingold, 2005; Stammler, 2005; Forbes and Stammler, 2009).

In the project entitled *Environmental and Social Impacts of Industrialization in Northern Russia* (ENSINOR), we conducted a multidisciplinary analysis combining state-of-the-art scientific technologies with the indigenous or local perceptions of processes of change by Nenets reindeer herders. This method of co-producing knowledge can be expected to yield results that are both highly relevant to local and regional needs and practical for policy implementation. The immediate objectives were to characterize the effects of two to three decades of industrial development of oil and gas on traditional livelihoods and the supporting society in the YNAO and NAO. In this paper, we report on impacts that can be detected from satellite images of different resolutions. We also discuss the significance of field surveys and local and indigenous knowledge in enhancing the interpretation of the various satellite images.

RESEARCH AREA

The Yamal-Nenets Autonomous Okrug lies in the extreme north of the West Siberian lowland, which encompasses the largest wetland (technically a peatland) in the world. In the Nenets' own language, "Yamal" means "the end of the earth" or "land's end." About 700 km long and 150 km wide, the Yamal Peninsula is the core area of tundra Nenets reindeer herding, with winter pastures occupying the forest-tundra transition zone to the south. Ice-rich permafrost is widespread and susceptible to thermokarst erosion (caused by thawing permafrost) arising from both natural and anthropogenic disturbance. As a result, much of the terrain is considered moderately to extremely unstable for purposes of engineering and infrastructure developments such as roads, bridges, and pipelines (Nelson et al., 2001).

Today the YNAO is numerically the world's most productive reindeer herding region, with 631 000 domestic reindeer herded by approximately 14 500 nomadic Nenets and to a lesser extent by Komi and Khanty families (data as of 2006, A. Nesteruk, pers. comm. 2008). Approximately 276 300 reindeer and 1000 fully nomadic households live on the Yamal Peninsula. While successor enterprises of Soviet state farms (*sovkhoz*) dominate the institutional landscape in reindeer herding, private clan communities are developing rapidly in the North of the okrug and hold three-quarters of the reindeer population (Stammler, 2005). Large-scale industrialization since the 1970s has led to an influx of people from the south, which is why today the indigenous share of the overall population is less than 7% (Stammler and Forbes, 2006).

This paper focuses on the vast Bovanenkovo gas field in the northwestern part of the Yamal Peninsula (Fig. 1). The gas field is located in the area to which the Yarsalinski

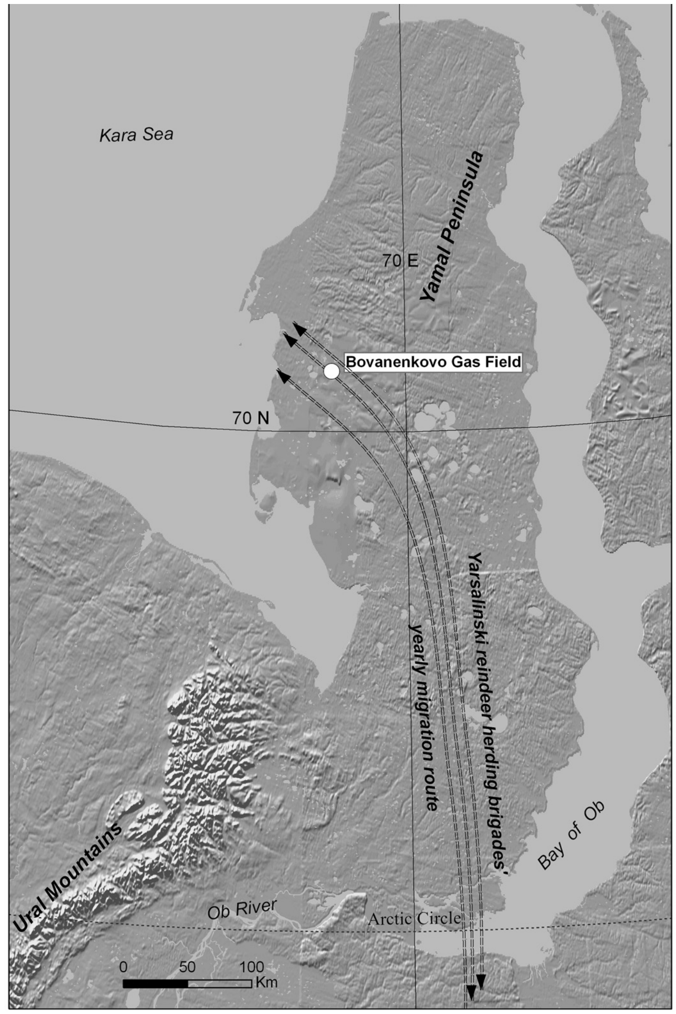

FIG. 1. Map of the Yamal Peninsula, showing the location of the Bovanenkovo Gas Field (white circle) at 70°20′ N, 68°30′ E. Arrows indicate the yearly migration paths of the Yarsalinski sovkhoz brigades. The brigades travel 1200–1400 km with the reindeer herd between the most distant summer pastures by the Kara Sea coast and the winter pastures that lie south of the Bay of Ob (background map data: ESRI).

reindeer sovkhoz holds the principal land title. Officially the gas field covers an area of 2052 km^2 (VNIPIGazdovycha, 2005). Bovanenkovo is on the migration path of two major Yarsalinski reindeer brigades or collective management units. These brigades reach the gas field from the south in early to mid July on their way to the Kara Sea coast, where reindeer are brought for access to insect relief and high-quality forage. The brigades return through Bovanenkovo in mid to late August when they start migration towards their winter pastures on the south side of the Ob River. In addition, at least a dozen private reindeer herding camps use the larger Bovanenkovo area as reindeer grazing grounds. In comparison to the brigades, they have smaller herds and shorter migration routes, and their presence in the vicinity of the gas field is longer, lasting from early summer until October–November. Very little is known about the exact migration patterns of these private herders. However, their number has been increasing since the fall of the Soviet Union, and today their herds, as well

TABLE 1. Satellite sensors and their radiometric and spatial resolution. The division of scales used and number of pixels for thresholds between individual classes.

Sensor	No. of Channels	Pixel Size (m)	Pixel Area (m^2)	Small Scale (No. of Pixels) 0.0025 ha	0.01 ha	0.09 ha	Medium Scale (No. of Pixels) 1 ha	Large Scale (No. of Pixels) 10 ha
Quickbird-2 pan	1	0.6 × 0.6	1.2	20.8	83.3	750.0	8333.3	83333.3
Quickbird-2 multi	4	2.4 × 2.4	5.76	4.3	17.4	156.3	1736.1	17361.1
SPOT pan	1	10 × 10	100	0.3	1.0	9.0	100.0	1000.0
SPOT multi	3	20 × 20	400	0.1	0.3	2.3	25.0	250.0
ASTER VNIR	3	15 × 15	225	0.1	0.4	4.0	44.4	444.4
Landsat TM	7	30 × 30	900	0.03	0.1	1.0	11.1	111.1
Landsat ETM+7	7	30 × 30	900	0.03	0.1	1.0	11.1	111.1
Landsat MSS	4	80 × 80	6400	0.004	0.02	0.1	1.6	15.6

as their families, probably outnumber those of the officially registered herding brigades.

MATERIALS AND METHODS

Field Surveys

Field expeditions to the Bovanenkovo gas field and its surroundings were conducted in July 2004 and July 2005. In total 220 field sites were surveyed for satellite image interpretation. Each site was marked with GPS and the vegetation type characterized as follows. For each site, from 5 to 10 quadrats of 50 × 50 cm were used to identify the main vegetation types and to estimate coverage and height for dwarf shrubs, willows, grasses, sedges, lichens, and bryophytes. Coverage of bare soil and litter were also measured, and special attention was given to visible signs of human impact. A large digital-image database was collected, focusing on different natural and anthropogenic impacts.

Yamal reindeer are intensively managed 24 hours per day, 365 days per year, by whole families through generations. Representatives of two brigades and private herders migrating through the study area were interviewed. In each brigade there were about 10 key informants. Long-term (≥ 18 yrs) gas workers (8 key informants) at Bovanenkovo and administrative staff members in the municipalities were also interviewed to understand the perspectives of Nenets and Russians and how their own relations have developed.

Each group of herders comprised from two to nine nuclear families consisting of 10 to 90 people and managing 3000 to 9000 animals. While two of the largest brigades have experienced the greatest impact in the tundra region, with territory withdrawn for infrastructure and disturbance of terrestrial and aquatic habitats, neighbouring camps migrate near enough to Bovanenkovo to trade but have only minimal infrastructure and disturbance on their territory. Herders from two brigades, who were accompanied (July 2005) during their summer migration through the gas deposit, explained their migration history, relations with the gas workers, social and environmental changes, and in particular, the effects of gas exploration on everyday reindeer herding and reindeer pastures. Participant observation entailed taking part in every aspect of daily life during this time, as well as during winter at the opposite end of their migration route several hundred kilometers to the south. Printouts of satellite images and topographical maps were used to facilitate interviews. Information from herders was also obtained during participant observation and in-depth unstructured interviews that provided deeper insights about the relations of herders to the land, including its spiritual significance and the impact of industry presence on these relations.

Satellite Imagery and the Scales of Investigation

Data from eight satellite images of different resolution were compared to distinguish their capacity to detect a suite of common anthropogenic impacts. Remote sensing data are considered to be very high-resolution (VHR) if pixel size is less than 5 m (Puissant et al., 2005). The two images from VHR data used in this research were from Quickbird-2 (dated 15 July 2004): a panchromatic image with spatial resolution of 0.61 cm, and a multispectral image (4 channels) with resolution of 2.4 m. The enhanced multispectral image was created by combining the multispectral and panchromatic layers. The six images from high-resolution data were ASTER VNIR (Visible Near Infrared) with 15 m resolution (4 channels), dated 21 July 2001; SPOT panchromatic image with 10 m resolution, dated 19 July 1998; SPOT multispectral image with 20 meter resolution (3 channels), dated 19 July 1998); Landsat TM with 30 m resolution (7 channels), dated 7 August 1988; Landsat ETM+7 with 30 m resolution (7 channels), dated 7 July 2000; and Landsat MSS with 80 m resolution (4 channels), dated 28 July 1984 (Table 1).

GIS data with adequate accuracy were not available. Road networks, individual off-road vehicle tracks, areas covered by multiple tracks (individual tracks were not possible to differentiate), garbage dumps, pipelines, power lines, sand quarries and drilling sites were therefore digitized using Quickbird-2, ASTER VNIR, SPOT, and Landsat TM and ETM+7 images. The spatial extent of the respective impacts was calculated via buffer analysis. Roads and off-road track widths were measured from the panchromatic Quickbird-2 image at 25 different locations, and average road width was calculated. The capacity of the different satellite images to detect the various impacts was compared using field sites, ground photographs, and

TABLE 2. Capacity of imagery to detect different impacts of hydrocarbon exploration in Bovanenkovo, compared to socio-cultural surveys and ground truthing. Rankings: – not visible, x visible with effort, xx moderately visible, xxx clearly visible.

Impact	Socio-cultural Survey	Ground Truthing	Quickbird-2 Panchromatic	Quickbird-2 Multispectral	ASTER VNIR	SPOT Panchromatic	SPOT Multispectral	Landsat ETM+7	Landsat TM
Small Scale (< 0.09 ha):									
Soil contamination[1]	××	××	-	-	-	-	-	-	-
Removal of top soil and vegetation	×××	×××	×××	××	×	×	×	-	-
Industrial waste:									
Metal	××	××	×	-	-	-	-	-	-
Glass	××	×	-	-	-	-	-	-	-
Concrete	×××	×××	××	×	-	-	-	-	-
Wood	×××	×××	×	-	-	-	-	-	-
Single off-road vehicle track	××	××	×××	××	×	×	×	-	-
Vegetation changes:									
Shrubs to graminoids	×	××	×	××	×	-	-	-	-
Peatland to graminoids	×	×××	×	××	×	-	-	-	-
Revegetated barren ground	×	×××	×	××	×	-	-	-	-
Pipelines	×××	×××	×××	××	×	-	-	-	-
Power lines	×××	×××	××	×	-	-	-	-	-
Drilling towers	×××	×××	×××	××	×	×	-	-	-
Trucks/Vehicles	×××	×××	××	×	-	-	-	-	-
Medium Scale (0.1 ha to 1 ha):									
Roads	×××	×××	×××	×××	×××	×××	×××	××	××
Multiple off-road tracks	××	××	×××	××	××	××	××	×	×
Concrete paved yards and roads	×××	×××	×××	××	××	××	××	×	×
Vegetation changes:									
Shrubs to graminoids	××	××	×	××	×	-	×	×	×
Peatland to graminoids	××	×××	×	××	×	-	×	×	×
Revegetated barren ground	××	×××	×	××	×	-	×	×	×
Barren ground on industrial sites	×××	×××	×××	×××	××	××	××	×	×
Revegetated areas	×	××	×	××	×	×	×	×	×
Barracks and built-up areas	×××	×××	×××	××	××	××	××	×	×
Winter roads	×××	××	×××	×××	××	××	×	×	×
Large Scale (> 1 ha):									
Removal of topsoil and vegetation	×××	×××	×××	×××	××	××	××	××	××
Vegetation changes:									
Shrubs to graminoids	×××	×××	×	×××	××	××	××	××	××
Peatland to graminoids	×××	×××	×	××	××	××	××	××	××
Revegetated barren ground	×××	×××	×	×××	××	××	××	××	××
Production and worker settlements	×××	×××	×××	×××	××	××	××	×	×
Quarries	×××	×××	×××	×××	×××	×××	×××	××	××
Impoundment water bodies	×××	××	×××	×××	×××	×××	×××	××	××

[1] Data on soil contamination are from the Varandei oil field in the Nenets Autonomous region.

photographs taken from helicopters. All images were rectified into WGS84 and then synchronized to each other using ERDAS IMAGINE software's Auto Sync module. Impacts at contrasting scales were selected to compare their interpretability from different satellite images (Table 2). Reindeer herders' migration routes and brigadiers' notes were digitized from satellite image printouts. The aim was to produce a map depicting the total area of cumulative disturbance around the Bovanenkovo gas field. Impact areas were estimated by using information from field sites and photographs taken from a helicopter, and by visual interpretation of ASTER VNIR, Quickbird-2, SPOT, and Landsat TM and ETM+7 images.

Walker and Walker (1991) presented a hierarchical approach to analyzing both natural and petroleum industry–related landscape changes in Arctic Alaska based on Delcourt and Delcourt's (1988) spatial hierarchy model from microsite to the global level. In this paper, we investigate the capacity for different satellite platforms to detect impacts at three scales, small (less than 0.09 ha), medium (0.1 ha to 1 ha), and large (more than 1 ha) (Table 2). In our case, large scale extends up to 2000 km^2, which is the size of the gas field in question. Table 1 shows pixel sizes and areas for the eight images, and here the small-scale class is divided into three subclasses (0.0025, 0.01, and 0.09 ha). The threshold value of 0.0025 ha represents a pixel size of 5 × 5 m, which is considered the upper limit of VHR image resolution. The threshold value of below 0.01 ha represents one SPOT panchromatic pixel (10 × 10 m), and the threshold value of 0.09 ha in the small-scale class refers to the size of one Landsat TM pixel (30 × 30 m).

In addition, Nenets reindeer herding was investigated on the basis of both social and ecological field surveys and satellite imagery (Table 3). Here the scales are different and reflect herders' activities. Small scale encompasses phenomena of a size less than 2 m^2, local scale 2–15 m^2, and then mesoscale 15 m^2– 0.09 ha. Visible phenomena varied from reindeer sledges to campsites. These interpretations are

TABLE 3. Capacity to detect phenomena associated with Nenets reindeer herding. Rankings: – not visible, x visible with effort, xx moderately visible, xxx clearly visible.

Phenomenon	Socio-cultural Survey	Ground Truthing	Quickbird-2 Panchromatic	Quickbird-2 Multispectral	SPOTs–ASTER –Landsats
Small scale (≤ 2 m²):					
Reindeer	×××	×××	-	-	-
Nenets sledge	×××	×××	×	×	-
Local scale (> 2 m² to ≤ 15 m²):					
Nenets tent (chum)	×××	×××	×	×	-
Migration routes and trails close to camps	×××	×	×	×	-
Mesoscale (> 15 m² to 0.09 ha):					
Nenets camp (group of tents and sledges)	×××	×××	××	×	-
Sacred sites, graveyards	××	×	-	-	-
Campsite, 1 yr or less old	×××	××	-	-	-
Older Nenets campsite	××	×	×	×	-
Reindeer herd, > 100 animals clustered	×××	×××	××	×	-

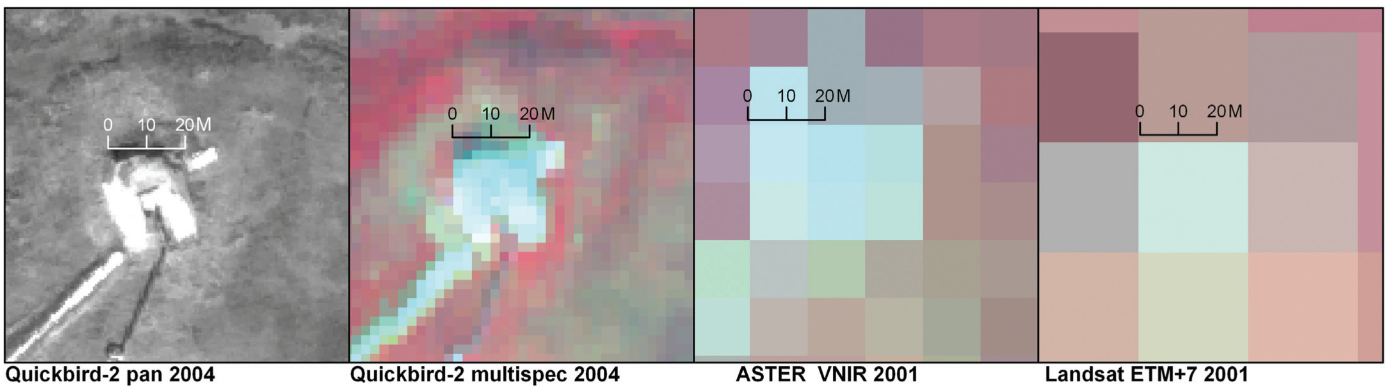

FIG. 2. Detecting small- and medium-scale impacts. With Quickbird-2 panchromatic imagery, the size and the nature of most surface disturbances can be reliably determined. In multispectral Quickbird-2 imagery, details are detectable but more blurry. In ASTER imagery, the size, shape and nature of objects are somewhat unclear, and with Landsat ETM+7 imagery, the impact is barely observable.

based mainly on extensive participant observation (social science survey) with three brigades plus different units of private herders, as well as activities from one campsite in use detected from the Quickbird-2 image.

RESULTS

Detecting the Industrial Impacts at Different Scales

Landscape changes caused by petroleum industry activities appear on various scales from point to small to large. Industrial impacts in oil and gas fields are usually only a few hectares or less in size, composed of fragmented patches and linear transportation networks for access to and from the field and between production settlements. In our approach, the resolution of different types of satellite imagery is compared to other scales: those of data from field surveys (anthropological and natural scientific), reindeer herders' perception of space, and industrial impacts. We have divided the impacts into three spatial scales: small, medium, and large (Table 2).

The size of the Bovanenkovo gas field's active area, interpreted from satellite imagery, is 40 × 13 km. Given our limited resources, we were able to acquire only 120 km² of Quickbird-2 imagery to cover the core area of the gas field. The surrounding field was covered with low-cost or free ASTER VNIR, SPOT, and Landsat TM and ETM+7 images.

Small-Scale Impacts

The capacity to detect impacts from both satellite data used and field surveys is presented in Table 2. Industrial waste such as metal, glass, concrete, and construction wood is difficult to detect because it typically consists of small objects sparsely distributed over the area, which are difficult or impossible to detect even with Quickbird-2 panchromatic imagery. During the field survey we located several dumping places, which we marked with GPS and photographed. Herders provided additional information on the history and cumulative impacts of these dump sites, which we were subsequently able to identify from the combined Quickbird-2 panchromatic-multispectral image. In and around the gas field, it was possible to detect some sizable concentrations of trash from panchromatic Quickbird-2 imagery. Scrap wood remaining on abandoned drilling sites is of high value to reindeer herders, who have to cope with a scarcity of wood for cooking and other purposes. Herders also make extensive, innovative use of other leftovers on

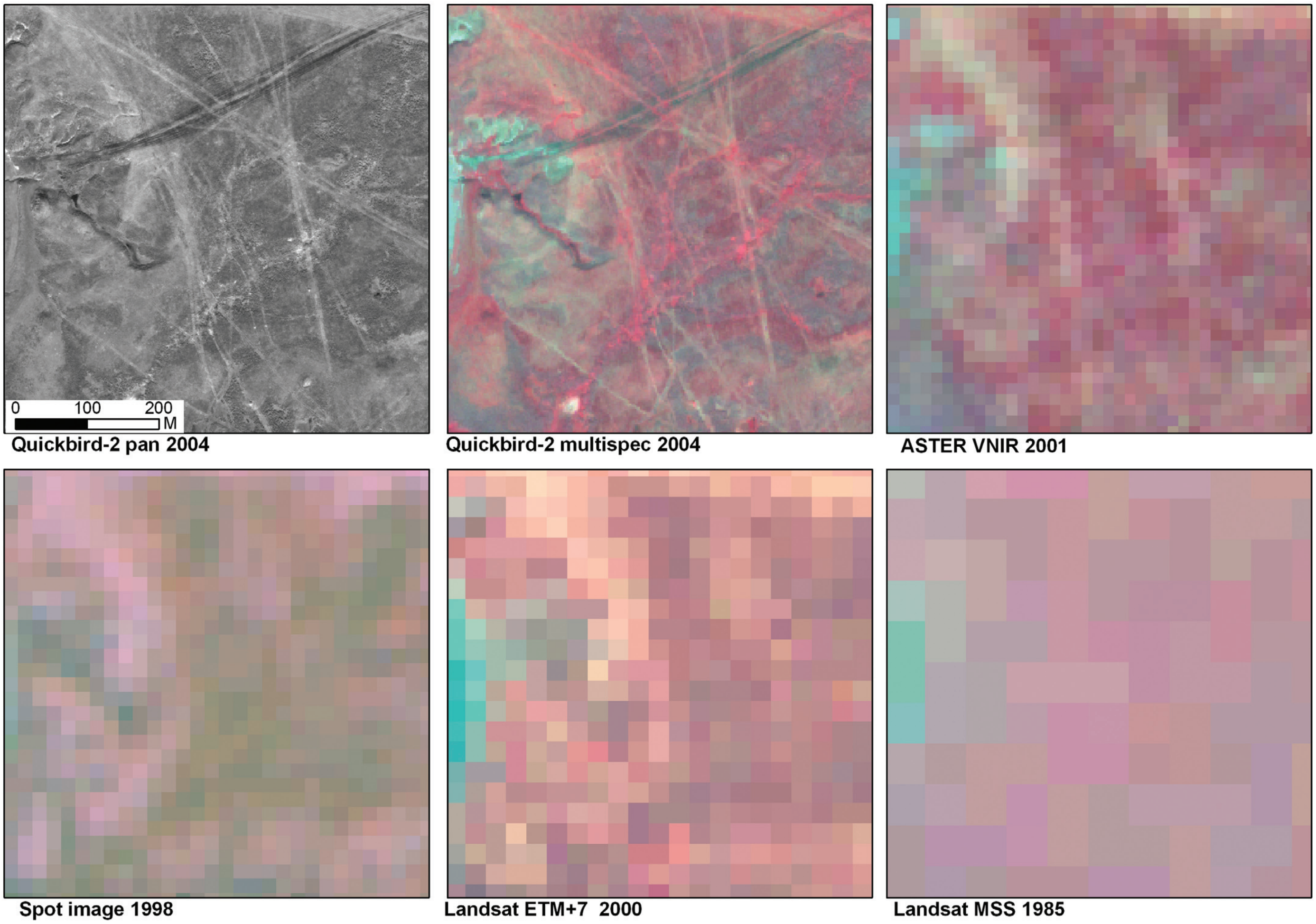

FIG. 3. Small- and medium-scale impacts: The capacity to detect single and multiple off-road vehicle tracks. When individual vehicle tracks are multiplied and spread out, they appear as medium-scale impacts and are therefore possible to detect from coarser imagery.

former industrial facilities, and by doing so, contribute to a certain extent to the recycling of waste (Stammler, 2002). Sparsely distributed wastes can be partly or completely covered by vegetation. Such hidden waste is one of the forms most harmful to reindeer, according to herders. Reindeer can injure their hooves from glass or sharp metal and hence be exposed to infections that may even become fatal.

We did not find a clear instance of soil contamination caused by oil spills in or around Bovanenkovo, which is a gas condensate field. Instead we used our experience from the Varandei oil field in the Nenets Autonomous Okrug, where we found one small spill of a few square meters around a well capped in 1988. This revegetated drilling site was just scarcely detectable from Quickbird-2 images, but oil could not be identified. Contamination of the soil from oil and various chemicals is difficult to detect even in field surveys if the contaminated area is small or if the accident occurred some time ago and the area has become revegetated.

ASTER VNIR and SPOT images with a resolution of 10–20 m are capable of determining the spatial extent of changes, but they cannot provide detailed information on the cause of change. Landsat TM and ETM+7's resolution allows the identification of changes less than 30 × 30 m in size. Patches even smaller than a single pixel can sometimes be identified (Fig. 2), especially if vegetation in such locations has been removed and bare soil is exposed, because the spectral reflectance of bare ground is significantly different from that of the surrounding vegetation.

Pipelines and power lines are reasonably detectable in panchromatic and multispectral Quickbird-2 imagery. Quickbird-2 panchromatic resolution was high enough to identify power line poles. The enhanced Quickbird-2 multispectral image was most effective for identifying off-road vehicle tracks and revegetated areas (Fig. 3). Vehicles can also be identified from multispectral Quickbird images. Some of the larger drill towers and barracks can be detected even with ASTER VNIR imagery.

Medium-Scale Impacts

Medium-scale signs of impacts are generally detectable with all satellite imagery we used. In off-road vehicle tracks, which in Bovanenkovo are mainly from the period 1988–95, the original willow shrubs (*Salix* spp.) have been destroyed and graminoids are now dominant (Fig. 3). Such tracks are mostly detectable from the multispectral

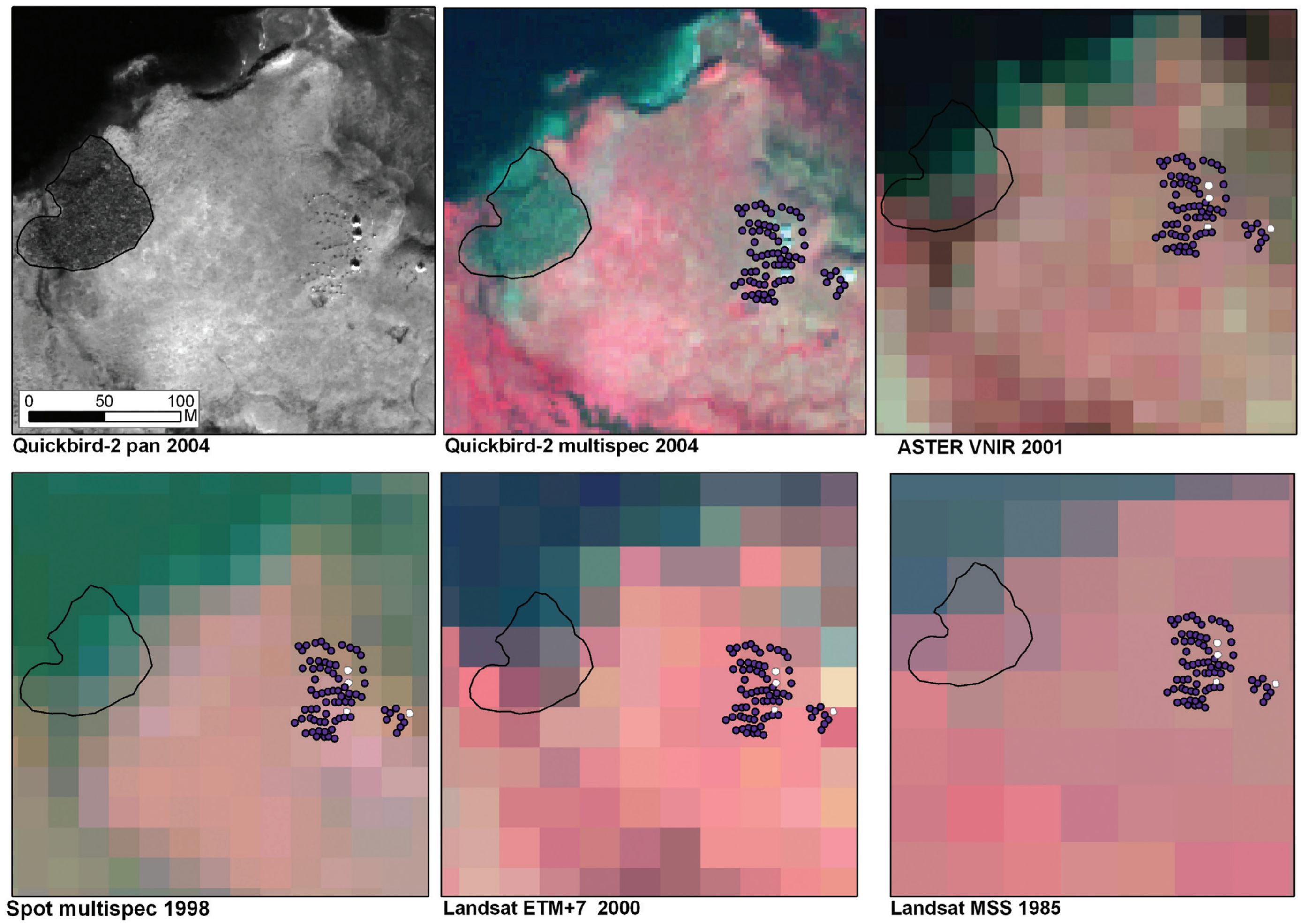

FIG. 4. Detecting reindeer herders: From the panchromatic Quickbird-2 image, tents (white dots), sledges (purple dots), and reindeer herd (black polygon) were identified. From multispectral images these might have been unrecognized, but could be identified after being noted from the panchromatic image.

Quickbird-2 image. Here the advantages of near infrared (NIR) channel versus panchromatic for vegetation differentiation become clear. These linear tracks appear significantly more reddish than the surroundings.

At the medium scale, the utility of ASTER VNIR and SPOT emerges, and direct impacts are readily detected. Identifying areas with transformed vegetation from surrounding landscape requires greater efforts. Landsat's TM and ETM+7 are also possible to use but are lacking somewhat in terms of detection capacity. Winter roads and off-road tracks are just barely visible in Landsat TM and ETM+7 images. However, as resolution becomes coarser more detail is lost, and identifying the impacts is less reliable overall. Essentially, what can be detected is a basic differentiation between disturbed and undisturbed terrain, but field observations are needed to determine the cause of impact.

Large-Scale Impacts

Although VHR images are also most accurate for detecting large-scale impacts, the size of the area under investigation is an important limiting factor. If industrial activities are distributed over vast areas, the cost of VHR data may become prohibitive. Research projects typically have limited funds to spend on satellite imagery. The cost of Quickbird-2 imagery is US$20/km^2.

When the average size of impacts is greater than one hectare, the detection potential of ASTER VNIR, SPOT and Landsat TM and ETM+7 images becomes more reliable. What is lost in detail is gained in acreage. The largest sand quarry in the Bovanenkovo gas field, for example, is one square kilometer (1211 Landsat ETM+7 pixels). Large-scale impacts are represented by impoundments or drained water bodies resulting from industrial infrastructure. Even Landsat MSS is capable of identifying such changes accurately (Table 2). When impacts are in this size range, the advantages of VHR imagery, compared to ASTER VNIR or even to Landsat TM, are not sufficient to make its use cost-effective.

Phenomena Associated with Reindeer Herding

Somewhat unexpectedly, we were able to identify one of the Yarsalinksi sovkhoz campsites from both Quickbird-2

FIG. 5. Left: Brigadier Vasili Serotetto explaining the migration routes, campsites, and pastures of Brigade No. 2 with a false-colour composite of ASTER VNIR imagery. Photo: Timo Kumpula, 14 July 2005. Right: Camp of Brigade No. 4 close to Bovanenkovo. Notice chums and sledges in the middle and slightly clustered reindeer herd on left side (circled with black line). Photo: Bruce Forbes, 11 July 2005.

images taken 15 July 2004. This brigade had four tents (chums) that were first noticed from the panchromatic Quickbird-2 image as an unusual group of whitish spots. At first, these were interpreted as patches of bare soil. Closer inspection revealed four chums and 72 sledges in rows and 4000 or more reindeer clustered together near the camp on the shore of a nearby lake. During the fieldwork in July 2005, we came across the same brigade in a different location, and the brigadier verified our interpretation. He was able to provide the exact date and time when the image was taken. He explained that the herders of the camp were with the reindeer herd starting to catch draught males to be ready for migration to the next camp (Figs. 4 and 5, Table 3). He also told us that when the image was taken, there were four chums (tents) in the camp, "but as you can notice, that fourth chum is little bit farther away from the others: that's because there was disagreement between them and the rest, but nowadays the people of this chum have moved to a different brigade."

Herders' and Workers' Interpretations

Interviewing reindeer herders and participating directly with them in their migration route through the Bovanenkovo gas deposit was essential to the holistic understanding of the impacts of oil and gas development on humans and animals. Information on the history of exploration that has taken place in the area would have been difficult or impossible to gain from other sources. All informants were able to interpret satellite image printouts extremely efficiently (Fig. 5). False colour composites did not cause problems for identifying the exact locations of lakes, rivers, campsites and migration routes. Herders, through their perceptions of the migration route and the industrial area, added an important level of historical depth and detail to our understanding of recent changes in the area. Gas workers also provided useful details about the area and history from their point of view. Furthermore, they provided information concerning the future of oil and gas exploration in the area. Interviews and participant observation with both groups of people in the tundra revealed well the various mental maps of people with different interests in the area (Stammler, 2005). The mental map of most herders consists of a complex set of migration routes, pastures, fishing grounds, and campsites, presenting a detailed image of the surface resources. The gas workers' mental map in the Bovanenkovo area was also very detailed and in many cases covered several decades, consisting of a diverse mix of drilling sites that provide access to different layers of the gas under the permafrost, and pipelines, roads, and camps dispersed across the entire territory of the gas deposit. Gas workers had also developed an intimate knowledge of the rivers and lakes throughout the decades; they have been using some of these for fishing for a long time, and some are now being negatively affected by the construction of new roads, which in some cases lead right through the water bodies.

The bridge-building technology of blocking off small rivers or lakes completely for the duration of road works has been heavily criticized by herders. Larger areas around these blocked rivers can become flooded and turn into extremely saturated wetlands that are not suitable as reindeer pasture or migration routes anymore. Blocking rivers, even temporarily, also has an impact on fish migration, resulting in a loss of potential fishing lakes for tundra residents. However, the herders were surprised how quickly the fish came back after the rivers had been unblocked and the wetland could be used as pasture again. These flooded areas, as well as drained lakes, can be readily detected on satellite images, and herders added historical depth and detailed descriptions of events for these areas.

DISCUSSION

Studies of hydrocarbon exploitation impacts should be holistic, encompassing all possible effects on the environment and other forms of land use. In northern Russian oil and gas fields, effects on reindeer herding communities must also be studied, and several authors have argued that impact studies should shift away from spill response and impact and damage compensation to focus on preventing spills, minimizing negative impacts, and making development plans for local populations (Meschtyb et al., 2005; Spiridonov, 2006; Stammler and Wilson, 2006).

Environmental impacts in oil and gas fields are numerous and range in scale from small to large (e.g., Walker et al., 1987, 2009; Truett and Johnson, 2000; National Research Council, 2003). Usually they are clustered in patches around active or abandoned drilling sites, and they include sand quarries, housing, barren grounds on industrial sites, and areas with mechanically disturbed or otherwise altered vegetation cover. Many of the impacts, like winter roads, pipelines, power lines, and off-road vehicle trail networks, have linear forms. Patch size can range from a few square meters to several hectares, and linear forms range from a few meters to hundreds of kilometers in length and may be up to tens of meters wide (Forbes et al., 2001; Khitun and Rebristaya, 2002).

Remote sensing imagery provides a crucial data source for assessing both the environmental and social impacts of oil and gas development and land cover changes in the vast Arctic (e.g., Walker and Walker, 1991; Stow et al., 2004; Walker et al., 2009). Since the launch of the Landsat program in 1972, numerous satellite programs have been established. The amount of available data is growing fast. Since the U.S. Geological Survey released its entire 35-year Landsat archive free of charge as of January 2009, the possibilities for cost-efficient land cover classification and monitoring applications have improved significantly (USGS, 2009). Landsat TM and ETM+7 represent the highest resolution (30 m pixel size) imagery available from the Landsat platforms that can be used to detect medium scale and larger changes (≥ 0.1 ha).

In Landsat TM and ETM+7, SPOT, or ASTER VNIR imagery, the resolution is generally not high enough to make detailed environmental impact assessments regarding oil and gas, except when an oil spill is large enough, like the Kolva River disaster in NW Arctic Russia in 1994 (see Walker et al., 2006). VHR imagery like Quickbird-2 has the capacity to detect even small-scale (less than 0.09 ha) impacts (Stow et al., 2004). However, when assessing large oil or gas fields, VHR data may be too expensive. Visible impacts in the Bovanenkovo gas field at present spread over an area of about 500 km^2. If it is necessary to prioritize areas because of cost limitations, those with the most intensive activity (hot spots) could be interpreted with VHR data and the surrounding areas with coarser resolution imagery, such as ASTER VNIR, SPOT, and Landsat.

VHR imagery alone does not enable environmental and social impact assessment of an oil or gas field. Field surveys provide necessary data for image interpretation, classification, and accurate estimates. For truly accurate image interpretation, field experience is essential to avoid gross errors. Some features, like revegetated areas, were easier to identify from image printouts or from a helicopter than at ground level. In the infra-red channel, revegetated areas have higher albedo because they are usually dominated by fresh grasses and sedges that reflect more intensively than shrub- or sedge-dominated surroundings. In satellite image false colour printouts, different intensities of infra-red signatures were readily apparent. On the other hand, not only the socio-cultural significance of industrial development and its cumulative impacts, but also certain material impacts cannot be detected with satellite imagery. It was remarkable that from Quickbird-2 images it was possible to detect some of the everyday activities of Nenets reindeer herders: for example, even an individual reindeer herd clustered together could be identified.

Field surveys remain the most useful way to identify different direct and indirect impacts (Tables 2 and 3). The social scientific survey relied on herders' knowledge of the area as many of them had experienced the times before and during the gas field development. Information on when and where certain impacts have occurred was important to understand how activities in the gas field have developed. An ecological field survey with an inventory of ground cover was essential to study the changes in vegetation on disturbed sites (Forbes et al., 2001). Some objects, such as revegetated old vehicle tracks, seldom used off-road tracks, and areas that have been revegetated completely, were easier to detect and outline (for example) from multispectral and panchromatic Quickbird-2 images. It is noteworthy that some tracks were difficult to detect in the field before we checked the satellite image printout.

Clearly identifiable zones of impact make it easier to combine ground-truthing of land cover with social anthropological fieldwork in the same area with the different groups of affected residents. The added value for researchers of being in the same area simultaneously during fieldwork is that interdisciplinary data analyses can be facilitated, leading to better integration of research results. A few groups have attempted to include herders' participation and knowledge directly into their research, and their results to date have been promising (Rees et al., 2003; Forbes et al., 2006, 2009; Walker et al., 2009).

In general, local and indigenous peoples' assessments add a different level of interpretation to changes on the tundra by ranking events, developments, and trends and evaluating them in terms of their positive or negative impact on their respective livelihoods. Thus, satellite images and ground-truthing of land cover provide an important factual basis and information about the significance of these processes for the lives of humans and animals on the tundra. Herders are able to provide qualitative data (testimony from active and retired herders) on the degree of environmental and socio-economic change during recent decades. They provide information on the current variation in the vegetation, soils, and reindeer habitat types and how they are ranked according to quality. They can also estimate what proportion of the habitat has been lost as a result of oil and gas development and how the herders and reindeer have or have not adapted to this loss. Herders also have a good idea where areas of potential or likely future degradation may occur (e.g., desertification from heavy grazing, thawing of permafrost). Herders' expectations or scenarios for the future under oil and gas development are important factors that should be considered in research topic development. Nenets have devised specific strategies for mitigation of predicted negative impacts and scenarios of future reindeer management in conjunction with oil and gas activities.

More difficult or impossible to detect with satellite imagery are the potential and actual positive social and economic impacts of industrial development on reindeer herders. During fieldwork, participant observation with the Nenets revealed that, in principle, herders of the area welcome the presence of industrial workers and their facilities, and their perception of the negative effects is partially offset by the benefits (Stammler, 2005; Forbes, 2008). Examples they cited include the workers' settlements as a source of staple food to resupply brigades during the long summer migration, the use of roads for the supply of herders, the settlements as a market for reindeer meat, and the helicopters of the gas company as a means of transport and as a means to collect velvet reindeer antlers to be sold on far eastern markets for cash (Stammler, 2004). In the case of the private herding camps not belonging to officially registered reindeer brigades, the gas company has become the most important trading partner (see Stammler, 2005:300–305).

Together the applied results from these assessments provide a potentially powerful tool for regional planning and policy development. The results will be of interest to scientists in several disciplines (e.g., anthropology, geography, biology/ecology, political science, international relations, conservation biology), as well as to indigenous groups elsewhere in other Arctic and subarctic regions.

CONCLUSIONS

Oil and gas development in the Russian Arctic is increasing rapidly. Nenets reindeer herding on the Yamal Peninsula is experiencing increasing pressures from hydrocarbon exploitation. Environmental impacts of such activities affect the quality, quantity, and accessibility of reindeer pastures. In the near future, social impacts may present even greater threats to the long-term viability of Nenets nomadism in the Yamal tundra (Forbes and Stammler, 2009; Stammler et al., 2009).

In this paper we have focused on detecting environmental impacts from different types of satellite imagery. Scales varied from small to large, and types of impact from patch to linear form. VHR imagery like Quickbird-2 had the best capacity for detailed impact assessment. With VHR imagery most of the impacts could be identified, while with coarser resolution imagery it was in many cases possible to say that there was some change or activity, but not to determine its nature. High price limits the use of VHR imagery. Landsat TM and ETM+7, SPOT or ASTER VNIR imagery can be used together with VHR imagery when interpreting large or multiple oil and gas fields.

Field surveys remain essential for reliable satellite image interpretation. The social scientific survey that relied on local herders' knowledge provided information on the period prior to and including the ongoing gas field development, which was not achievable with satellite imagery alone. Assessing the ecological impacts of oil and gas activities requires a combination of remote sensing, detailed ground-truthing, and social science field surveys. Local and indigenous peoples' assessments add a different level of interpretation to changes on the tundra. Such an interdisciplinary approach leads to better integration of research results and more comprehensive understanding of combined social and environmental impacts.

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