Supporting Information

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SI Text

Demography and Youth Retention Among Herders. As a key indicator of ongoing social resilience, it is important to stress the value of whole families migrating together and that young people continue to choose to make their livelihood in reindeer nomadism. In general, there are no recruitment problems in reindeer herding, except in certain taiga regions of Russia (1). There is agreement among reindeer herders, scientists, and local authorities that reindeer husbandry cannot be learned in institutes or schools. To be a good herder, one must grow up in a reindeer herding family. For the sake of recruitment, it is important that the child spend his/her first years before school in a herding family (2). To obtain a school education, children from herding families can only stay with their parents for a few months a year, during the summer holidays. The school administration accommodates the wishes of children who want to spend more time in the camp with their parents and learn more about reindeer herding and husbandry. These students are allowed to leave before the official end of the school year, and sometimes arrive after it has begun. In this way the schoolchildren can stay in the herding camps up to 5 months a year (2).

Recent research on the structure and size of reindeer herding families in YNAO, Taimyr, and Chukotka has shown that nomadic families have better demographic indices than those who are settled concerning family characteristics such as the average size of the family, average number of children per family, and natural increase (birth rate and death rate). For example, the average size of a nomadic family in Chukotka was 3.9 persons versus 2.8 in a settled family. In YNAO the corresponding ratio was 5.1:4.0, and in Taimyr it was 5.5:3.5. Nomadic families usually consist of married couples with children, whereas populations in permanent settlements often consist of a mix of families and divorced and unwed women with children. This shows that the maintenance of nomadic reindeer herding is an important demographic factor that contributes to the maintenance of indigenous peoples, although herder families are deprived of many material comforts and conveniences. It is important to emphasize that the latest population census (2002) showed that Nenets with close relations to nomadic reindeer herding had the largest population growth among all northern peoples in Russia (2). On the Yamal Peninsula, the official statistics reveal a significant increase in numbers of humans and animals. In 1981 there were 693 households with 3,552 people in tundra managing 137,781 reindeer. By 2007 the figures were 960 households with 5,111 people managing 276,200 animals (municipal statistics, Yar Sale, YNAO).

Reindeer Herd Energetics. If icing events increase in scale and severity, more adult male animals will be needed to break through crust layers so that females and younger animals can access forage. Under severe conditions, first the calves and weak animals die, followed by males and females. Herders know intimately the causal connections between forage availability, accessibility, seasonal weather conditions, and animal health. Sámi herders make similar adjustments, but are constrained by agricultural norms geared to maximize meat production (3). During recent icing events on Yamal, access to immense rangeland territory, mediated by the absence of fences and close relations with neighboring brigades, facilitated rapid migration adjustments. Elsewhere, such options are increasingly limited by infrastructure, land tenure, and political boundaries (4).

Direct Versus Indirect Impacts. As in other parts of the Arctic, the extent of indirect impacts greatly exceeds the physical footprint of an oil or gas field complex (5). It is claimed that if Alaska's Prudhoe Bay Oil Field (PBOF) were developed today using current technology and consolidation of facilities, gravel would cover at least 80% less area and the oil field direct footprint would be less than half its current size (6). In the case of YNAO, most of the damage to date has been in the southern portion of the region. The impact in the northern tundra zone is still in the early stages (7, 8). In southern and central Yamal, much lichen-dominated tundra has been replaced by moss-dominated tundra with increased portions of grasses, becoming more steppe-like (8, 9) (Fig. S1). On summer pastures, anthropogenic shifts from shrub- to graminoid-dominated vegetation (Fig. S2) with increased productivity and nutrient turnover have minimized the net loss of forage to date. However, this must be balanced against remnant trash, petrochemicals, damage to fish and wildlife habitat (Fig. S3), and encroachment by infrastructure (Fig. S4). At present, not all aspects of petroleum development are viewed negatively by Nenets, and herders themselves are strongly in favor of mutual coexistence with industry (10). However, there are indeed limits to what can be accommodated without meaningful consultation and the current imperative is to develop a culture of dialogue with the petroleum companies (11). It is important to note that it is not only a matter of how much territory is affected, but what kind of territory and whose migrations routes are affected by the losses. Our participant observations and interviews have revealed that each territory has its own particular meaning and importance for users.

Relevant to this discussion is the striking contrast between the extent of impacts in conjunction with hydrocarbon development in YNAO and northern Alaska. Bovanenkovo Gas Field (BGF), the largest gas field on central Yamal, is approximately double the size of PBOF (6, 7) (Table S1). On Alaska's North Slope, the most extensive impact has been gravel fill for pads and roads (6, 12). On Yamal, the three most widespread anthropogenic disturbance types are off-road vehicle traffic, exploratory drilling, and sand excavation (13). A ban on summer tundra travel since 1989 is routinely ignored, resulting in further surface disturbance (8).

Construction of the entire 1,288-km TransAlaska Pipeline (TAPS) directly disturbed 785 km^2 of land (14). By 1994 disturbed terrain comprised an estimated 6,000–7,000 km^2 for YNAO. Most of the damage to date has been in the southern portion of the region. The impact in the northern tundra zone is still in the early stages (7, 13), but includes intensive terrestrial and aquatic impacts in the BGF area on the territory of the Yarsalinski sovkhoz. At that time BGF encompassed >200 km^2, of which half was severely disturbed (13, 15). In southern and central Yamal, much lichen-dominated tundra has been replaced by moss-dominated tundra with increased portions of grasses, becoming more steppe-like (9, 13).

Officially, 13.5–14% of the territory (≈277–287) km^2 around BGF was severely disturbed as of 2005, whereas our estimate of visibly disturbed terrain from the same year was 448 km^2 (Table S1). The former figure is already >30 times greater than the total of severely disturbed terrain for PBOF (6). In the immediate future 743 new wells (in 56 clusters) will be drilled for gas extraction in the vicinity of BGF and Kharasavey (7) (Fig. S3). Each drilling denudes vegetation over an area of ≈120–200 m in diameter, with moderate impact beyond that distance (13); ≥135 km^2 will be occupied by infrastructure (well clusters, roads, pipelines), and the directly disturbed area will nearly double to ≈500 km^2 within which vegetation will be completely destroyed. In addition, relatively intensive disturbance typically occurs within an area three times larger than the area of direct impact and minor disturbance within an area 10 times larger (7).

In North America and Russia, official statistics estimate only part of the overall impacts. Within each region, central and outlying areas of petroleum developments are affected by the cumulative impacts outlined above, including blowing sand and dust, impoundments, and wetland drainage resulting from altered surface hydrology, thawing permafrost, and oil and petrochemical spills (8, 9, 12, 16, 17). Another key difference between PBOF and BGF is the pattern of historic land use and occupancy. Although both areas are populated by *Rangifer* spp., the role of caribou in Alaska harvested at certain times of the year but otherwise unmanaged is very different from the Yamal domestic reindeer supervised by herders year-round. On Yamal, summer reindeer grazing pastures and fishing lakes have traditionally served as critical resource areas for tundra-dwelling Nenets around BGF since pre-Soviet times (18, 19). Calving for domestic reindeer on Yamal occurs in the course of rapid spring movement of the herd northwards, at a distance from the current BGF site. In Alaska, calving grounds of caribou are in the more immediate vicinity of PBOF, and it has been argued that calving grounds for caribou are the most stable and important places (20). The coastal Iñupiat have lived in the vicinity of PBOF for 700+ years and subsisted on bowhead whale for four of five winters in the precontact era. Niuqsut, the closest modern settlement to PBOF, has become more dependent on fishing and hunting caribou in the oil era (12). The people of Niuqsut historically harvested resources on lands that partly encompassed the territory of PBOF. Although the initial relocation away from PBOF agreed to in their land claim ca. 1971 was considered a relatively minor sacrifice at the time, residents have subsequently experienced a progressive encroachment on their territory by new roads and infrastructure (21).

The indigenous population of the North Slope is generally believed to have benefited a lot from the presence of the extractive industry, and the extent of damages is significantly less than on Yamal, as outlined above. However, today's political representatives of the North Slope warn their colleagues in other areas, such as Yamal, not to forget the cumulative cultural and spiritual impacts of industrialization, even when the environmental footprint is reduced to a minimum. Alienation from the land reduces fitness to adapt to a future after the extractive industry, when traditionally land-based livelihoods may become more important again.

Extreme Weather and Climate Change Impacts. So far very few practitioners on the ground, neither herders nor administrators, attribute the extreme weather events we witnessed to climate change. Scientific discourses about this gradually trickle down to herders, who have noticed changes over many decades. However, their own analysis of such events goes along different lines. Some argue that nature or the spirits correct from time to time a degree of balance among grazing reindeer and available pastures by reducing the overall number of animals through natural disasters. The most frequent and best known are hoof-rot epidemics and icing events such as the ones documented in this study. Indeed, there is a long memory based on oral history among nomads concerning these events.

There are aspects of extreme weather and destructive processes associated with climate change (22, 23) that are expected to, or are already, affecting the region. These include: icing events leading to hard crusts on snow; earlier spring thaw; later autumn freeze up; increased harassment of reindeer, people, and fish populations from insect pests, parasites, and diseases that develop faster and are more prolific in warmer and moister conditions; sea-level rise; sea ice retreat; and coastal erosion. To take the latter point, if the western shore of Yamal Peninsula were to erode as heavily as has been predicted (24), the sovkhoz Panaevsk would lose a significant portion of its territory critically important for summer reindeer forage and insect relief for yearling calves from onshore winds. All of these processes, while ostensibly slow moving, have potentially serious implications for the future of the Yamal-Nenets SES. This is especially the case when taken together with the rapidly expanding industrial workforce and the accelerating pace of land cover change (e.g., new infrastructure and degradation of tundra pastures, lakes, and rivers).

Negative consequences are still buffered by a specific system of flexible allocation of labor and property rights for animals among families, and cooperative territorial behavior, particularly between families with fewer and those with more reindeer (19). This management system of a flexibly maintained "social carrying capacity" has always been and continues to be crucial for absorbing shocks. The current main concern for Yamal herding, however, is the combination of direct and cumulative impacts of industrial development in the area (25). Although extreme weather events are more difficult to capture on satellite imagery, the steady advance of industry and its various consequences in terms of land cover change (26) can be well documented with a combination of remote sensing, ground-truthing, and participant observation.

Pasture Quality and "Grazing Peace." Nenets responses to gas development balance the needs of reindeer for clean and peaceful grazing conditions against the needs of people for market outlets and interaction. Pastures thus have to be ecologically, socially, and culturally suitable (19, 27). Nenets sovkhoz-brigades have reorganized their migration to move as quickly and carefully as possible through BGF (Fig. S4). Through trial and error, new migration paths are narrowed to the minimum and routed to attempt to steer clear of dangerous trash and petrochemicals. This allows animals to avoid injuries that may lead to infection, while at the same time providing access to productive and safe forage. For private reindeer herders, particularly those of the central Yamal Peninsula with smaller herds, the interactions with gas workers have become a part of their everyday life for half of each year. From early summer to November they can remain in the area, regularly calling on the gas villages for bartering. Private herders from the neighboring northeastern Se-Yakha tundra visit BGF for supplies even in winter, although the area is reportedly poor in lichen pastures.

For the BGF case, the concern is that science might not take into account the varying combined social and ecological suitability of pastures. Reindeer herders argue that further industrial development hurts most on transit routes that are used in spring and autumn by numerous herds one after another. Cutting off transit routes means cutting off also the subsequent grazing areas that are accessed through these transit routes. The cumulative effect is even stronger in areas where calving takes place on a transit pasture. The suitability of a place for calving is crucially determined by its peacefulness and remoteness from human presence, which is what is seriously diminished by the presence of industry. Evidence from fieldwork suggests that reindeer herds and nomads can adapt to completely new calving grounds. However, these must be located in areas compatible with the overall seasonality of the reindeer migration, i.e., they have to be accessed by the herd by May to be suitable. This demonstrates that significant outside pressures can be accommodated by Nenets reindeer nomads. Despite major environmental changes experienced within the lifetime of active herders, the reindeer economy still succeeds where others have failed. Herders actively and skillfully manage their animals amid ongoing gas and oil development and infrastructure that is considerably more intrusive than similar developments in the North American Arctic. However, this adaptive capacity is constrained by certain social and ecological limitations, beyond which coexistence becomes increasingly difficult.

Continuity in Reindeer Management. In general, both herders and workers have good memories of coexistence during the stages of geological exploration and experimental extraction in the 1980s and 1990s. Despite significant environmental footprint of the industry, relations were reliable and friendly because of personal continuity, mutually beneficial trading, and assistance in solving everyday

problems (10). However, in any social science it is necessary to consider the tendency for nostalgia and emphasizing the positive when people discuss the past, especially when compared with the present situation: with the influx of large numbers of gas extraction workers, and high turnover among field personnel, the personal continuity characteristic of the exploration time is rapidly ending.

Another important aspect of continuity in reindeer management concerns private herd ownership and the nomadic practice of keeping several generations together in the tundra. These two crucial "ingredients" of path dependency (28) help to explain why Yamal nomadic society fared so well after the end of the Soviet Union and how Nenets were able to kick start their private herding activity after the Soviet system collapsed. It is considered highly significant that the number of private reindeer on Yamal never dropped <30% during Soviet times, compared with 5% on Chukotka (19, 29). One of the key aspects of the Soviet-era administration of Yamal is that they did not cut back on private ownership of animals. Other regions had lost most of their own adaptive capacity because it was effectively destroyed by the intrusion of the Soviet system, confiscation of private property, and forcefully sedentarising nomads (29, 30). In Yamal, this influence has been comparably less pronounced because local Soviet bureaucrats succeeded to incorporate Nenets needs while still showing conformity to central Soviet policies on paper (19). The essence of this informal contract between the Nenets and their Soviet administrators is encapsulated by a pointed comment from one herder to F.S.: "You pretend to work on our terms, and we pretend that we believe you."

From a reindeer management perspective, the relatively productive and seamless transition from the Soviet to post-Soviet eras on Yamal therefore has two important elements: (*i*) the uninterrupted continuity of private herd ownership, by which people remain keenly interested in keeping their own animals intact to sustain their own livelihood; and (*ii*) generational continuity because sedentarisation was not enforced as hard as in other areas (see refs. 19 and 29). The reality is that old people continue to migrate until they are physically unable to do so and in the process teach their grandchildren how to actively manage the herds.

Displacement and Relocation of Herders. Herders were told in 2005 that the area between BGF and Kharasavey (Fig. S3) will be effectively inaccessible for migration by reindeer and nomads in the future. The usual strategy for nomads would be to avoid these places or speeding up migration through them, but given the increased densities of industrial installations and tundra population of humans and animals, this may no longer be an option, once the projections by Gazprom and the municipality (7) materialize. Pastures will then be neither ecologically nor socio-culturally suitable for nomadic use. This would be a particularly heavy shock for private herders that are not organized within the sovkhoz system, whose use of the pastures in the area is not codified anywhere on paper. To acquire funding for their housing program, the municipality of Yamal argues that at least 167 nomadic families will have no choice other than agreeing to what is called "voluntary" relocation to villages. Following from what was outlined above, this accelerates the process of the tundra becoming an industrial landscape, which is what both industry and the municipality are envisioning for the future. We thus acknowledge that there are physical limits to the SES's capacity to respond, even though all previous attempts to quantify these limits (7, 31, 32) proved to be premature, because they had not properly accounted for the complex socio-cultural practices and drivers within the system (19, 33).

Sense of Place Among Workers and Herders. In fact, the footprint by both reindeer herding and gas extraction around BGF is influential for herders and gas workers alike. Some of those gas personnel who began service at BGF during the era of early geological exploration and are still working there have become personally attached to the area of the deposit over the decades. They have influenced the characteristics of the place through their industrial footprint, but also through their discourse, e.g., by the particular names they have given to their installations. For reindeer herders, gas workers places such as Kekh, SU16, or third quarry have become part of their holistic universe with their corporeal and incorporeal features, as points of reference, landmarks in the landscape, and as stations to call in and socialize. On the other side, the presence of reindeer herders and their nicknames have become part of the social environment for the gas workers when they operate in the field. As of 2006, it could be argued that both ways of using the land around BGF have led to a mutually acknowledged coexistence, despite the direct and cumulative impacts described above. The area acquired footprints of both practices, which led to certain adjustments among members of both user-groups.

Different practices on the land have been called "modes of dwelling" (34), referring to northern land-based livelihoods. We suggest broadening this perspective to include reindeer herding and gas extraction. In peoples' perception, places have their own experiences and memories of actions that happened there. Place names among Nenets, long-term gas workers, and many other societies across the Arctic reflect these transformations to the characteristics of a particular landscape (35).

Vegetation Disturbance. We did not include sand quarries or roads in the analysis because after two decades these remained generally void of any significant vegetation cover and have no real value as reindeer pastures. Although vegetation cover initially tends to be partially or completely destroyed by heavy vehicle traffic (17), most sites visible on the ground and in satellite imagery had revegetated naturally in the intervening years since the original impact. Typical multipass tracks along well-traveled routes away from the central settlement and associated infrastructure at BGF tended to be linear. The importance of deciduous shrubs leaves as forage for reindeer motivated us to concentrate on shrub thickets in our vegetation analysis.

Private Herders and the Antler Trade. The area between BGF and Kharasavey (Fig. S3) is also used by private reindeer herding households that do not belong to the sovkhoz structure at all. Information about their camp and herd size and their migration route does not exist in written form. We made a series of exploratory flights by helicopter in July 2005 to visit most of these camps. The flights were organized to facilitate the collection of antler velvet, which is a side activity by employees at BGF. This provided GPS readings of their locations and allowed extensive participant observation of the modern barter-based system of trade in antlers. The area covered reaches beyond the immediate BGF development into the summer pastures of the northern brigades of another sovkhoz. The latter are going to be particularly affected by the ongoing construction of the railway connecting BGF with Labytnangi-Moscow, and by the pipelines that will transport gas to European markets. Future development plans were taken into account, but the research was carried out at a time of rapid industrial development, the details of which are usually not disclosed to people outside the immediate circle of decision makers. This made it difficult to incorporate scenarios into the analysis.

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Fig. S1. Active migration route near campsite seen in Fig. 2. These look like ruts from off-road vehicles (see Fig. S2) but paths are formed and maintained by the repeated passage of reindeer-drawn sledges. The graminoid sward contrasts sharply with shrub-dominated vegetation visible to either side. Both the corridors and campsites are large enough to be visible in satellite imagery (Fig. 3). Photo by B.C.F.

Fig. S2. Graminoid-dominated strip characteristic of off-road vehicle tracks. Disused for ≈20 years these are visible as linear features in satellite imagery. Photo by B.C.F.

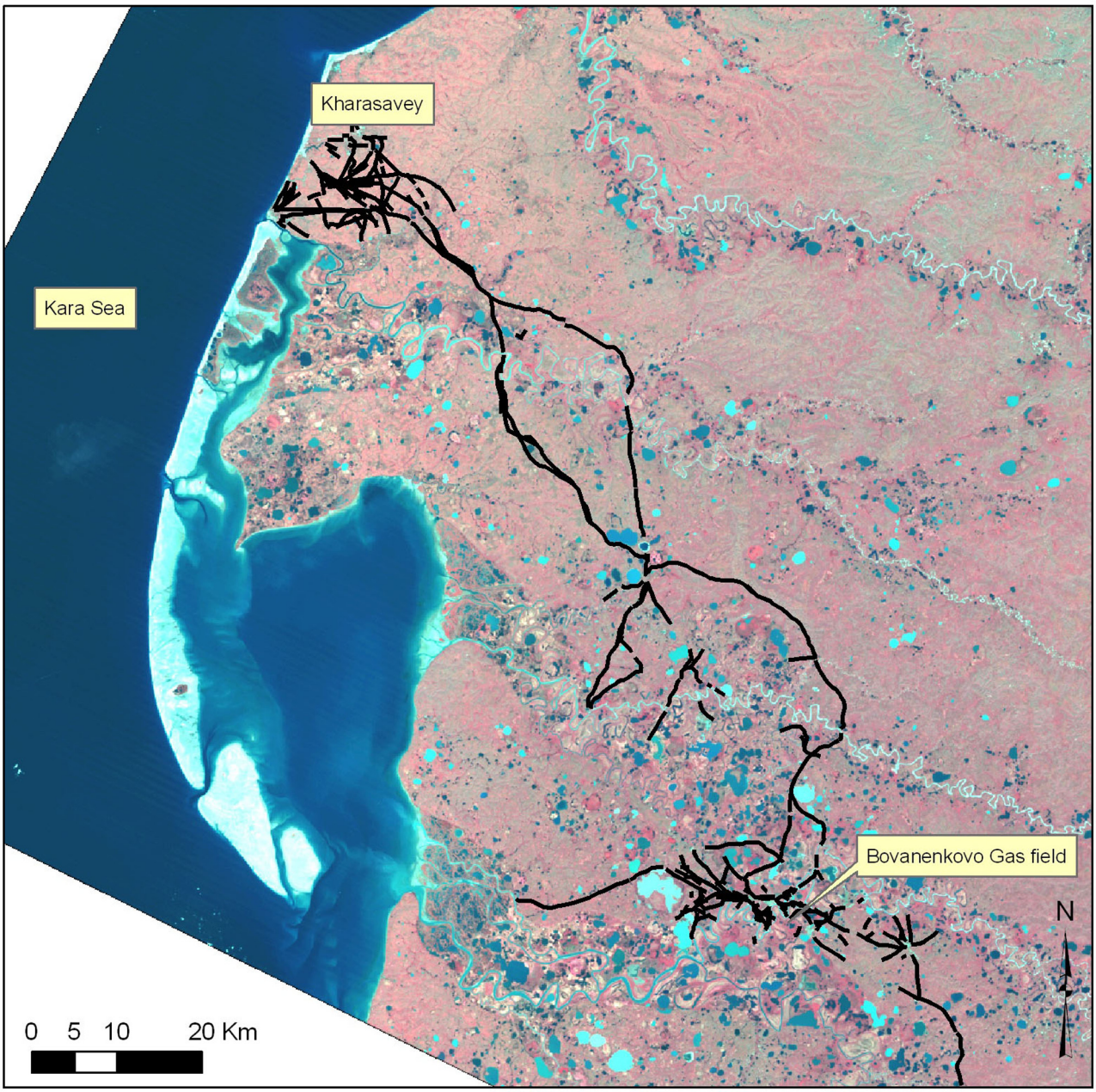

Fig. S3. Low-resolution Landsat TM image (30-m pixels) showing the transport corridor between Kharasavey and BGF. Approximately 80 km^2 of terrain were visibly affected as of 2001. Ongoing construction of ≈130 bridges has degraded key rivers and lakes so the supply of fish for daily subsistence, especially critical during summer migration, is less reliable now. The ongoing influx of gas workers is certain to increase fishing pressure and accelerate this process.

Fig. S4. Nomadic caravans crossing under a pipeline during migration through BGF. Nenets have in many ways successfully adapted to the gas field, in part by carefully steering reindeer through as quickly as possible. Photo by B.C.F.

Table S1. Summary of terrain categories in northern Alaska and northwest Siberia

West Siberia	km²	Alaska	km²
Yamal-Gydan Region (8)	235,000	Arctic Coastal Plain (6)	230,000
Yamal Peninsula (13)	112,000	Canning to Colville River (6)	71,000
Total area disturbed (Yamal-Gydan) (8)*	6,000–7,000	Total area disturbed (TAPS) (14)†	785
Bovanenkovo Gas Field (7)‡	2,052	Prudhoe Bay Oil Field (6)‡	991
Bovanenkovo Gas Field (13)§	200	Prudhoe Bay Oil Field (6)§	16.9
Severely disturbed terrain (7) (BGF)	277–287	Severely disturbed terrain (PBOF) (6)	8.8
Indirect impact zone (BGF)¶	448	Indirect impact zone (PBOF)	na
To be disturbed in the near future (7)‖	500	To be disturbed in the near future	na

na, not available.
*Estimate from 1994.
†Includes territory south of the Brooks Range.
‡Above-ground facilities.
§ Below-ground lease area.
¶ Estimate from this study.
‖ Includes territory between BGF and Kharasavey.