High resilience in the Yamal-Nenets social–ecological system, West Siberian Arctic, Russia

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Tundra ecosystems are vulnerable to hydrocarbon development, in part because small-scale, low-intensity disturbances can affect vegetation, permafrost soils, and wildlife out of proportion to their spatial extent. Scaling up to include human residents, tightly integrated arctic social-ecological systems (SESs) are believed similarly susceptible to industrial impacts and climate change. In contrast to northern Alaska and Canada, most terrestrial and aquatic components of West Siberian oil and gas fields are seasonally exploited by migratory herders, hunters, fishers, and domesticated reindeer (*Rangifer tarandus* L.). Despite anthropogenic fragmentation and transformation of a large proportion of the environment, recent socioeconomic upheaval, and pronounced climate warming, we find the Yamal-Nenets SES highly resilient according to a few key measures. We detail the remarkable extent to which the system has successfully reorganized in response to recent shocks and evaluate the limits of the system's capacity to respond. Our analytical approach combines quantitative methods with participant observation to understand the overall effects of rapid land use and climate change at the level of the entire Yamal system, detect thresholds crossed using surrogates, and identify potential traps. Institutional constraints and drivers were as important as the documented ecological changes. Particularly crucial to success is the unfettered movement of people and animals in space and time, which allows them to alternately avoid or exploit a wide range of natural and anthropogenic habitats. However, expansion of infrastructure, concomitant terrestrial and freshwater ecosystem degradation, climate change, and a massive influx of workers underway present a looming threat to future resilience.

tundra disturbance | *Rangifer tarandus* | reindeer nomadism | oil and gas activities | remote sensing

Certain Arctic regions have experienced more significant and rapid climate warming than others in recent decades. In the Yamal-Nenets Autonomous Okrug (YNAO), on Russia's West Siberian plain, average air temperatures have increased 1–2 °C over the past 30 years (1). Portions of northern Alaska and Canada have warmed to a comparably high level during the same period (1–3). Oil and gas development are also unevenly distributed around the circumpolar Arctic, with a few regions in North America and Russia experiencing extensive impacts, whereas others are virtually untouched (4, 5). Understanding the response of West Siberian social-ecological systems (SESs) (6) to rapid land use and climate change is important because they contain among the largest known untapped gas deposits in the world (7) and are warming rapidly (1–3). The ecosystems of YNAO, in particular, have been subject to widespread terrestrial and aquatic degradation both north and south of treeline (8–11), although the production of gas from the tundra zone is still several years away (12). This article analyzes the past, current, and possible future responses of the Yamal-Nenets SES to the most significant external shocks such as pasture degradation by industry, rapid climate change, the fall of the Soviet Union, and influx of industrial labor migrants. Responses include widespread transformation of tundra vegetation, adjustments of migration routes and timing by humans and reindeer, avoidance of disturbed and degraded areas, and the development of new economic practices and social interaction.

The Yamal Peninsula is home to 10,000 indigenous Nenets, half of whom still practice reindeer herding as a nomadic way of life. The nomadic Nenets and their predecessors first hunted and harnessed reindeer during migrations on Yamal between 500 and 1100 AD (13), herding progressively more intensively after 1600 (14). The longest migrations of up to 1,200 km annually between treeline and the northern tundra take place on the territory of the Yarsalinskii sovkhoz or state farm (Fig. 1) (15). Many regions suffered drastic socioeconomic consequences after the demise of the Soviet Union. Yet according to key economic and social variables of both industry and indigenous livelihood, Yamal has fared quite well compared with other regions in post-Soviet Russia, some of which experienced a near total collapse in reindeer herding (16–19).

SESs emphasize the concept of humans in nature, that the delineation between social and ecological systems is artificial and arbitrary, and require integrated approaches to analysis (20–23). SES are also called coupled human-environment systems (24) and coupled human-natural systems (25). Efforts to understand such systems are still in an exploratory phase (23, 26), with resilience acknowledged to be a difficult concept to work with in the context of managed "ecological economic" systems (27) and surrogates more common than direct measures (26). The humans/nature divide is particularly illusory on Yamal, where Nenets are integral to ecosystem structure and function and fully cognizant of their key role as responsible stewards charged with maintaining a viable system (15). Globally, there is increasing recognition that humans are a major force in ecosystem development and evolution (20). Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to retain essentially the same function, structure, identity, and feedbacks (22, 23, 28). According to some (27), resilience is measured by the size of the displacement the system can tolerate and yet return to a state where a given function can be maintained. Those authors argue that, "in purely ecological systems, this function, such as the ability of a system to capture and store resources, is fairly easy to define. In social-ecological systems, defining this function can be more difficult" (27). The resilience perspective, which focuses on SESs, is essential in the problem of fit between ecosystems and institutions (29) and so it is particularly relevant to this study. In a resilient SES,

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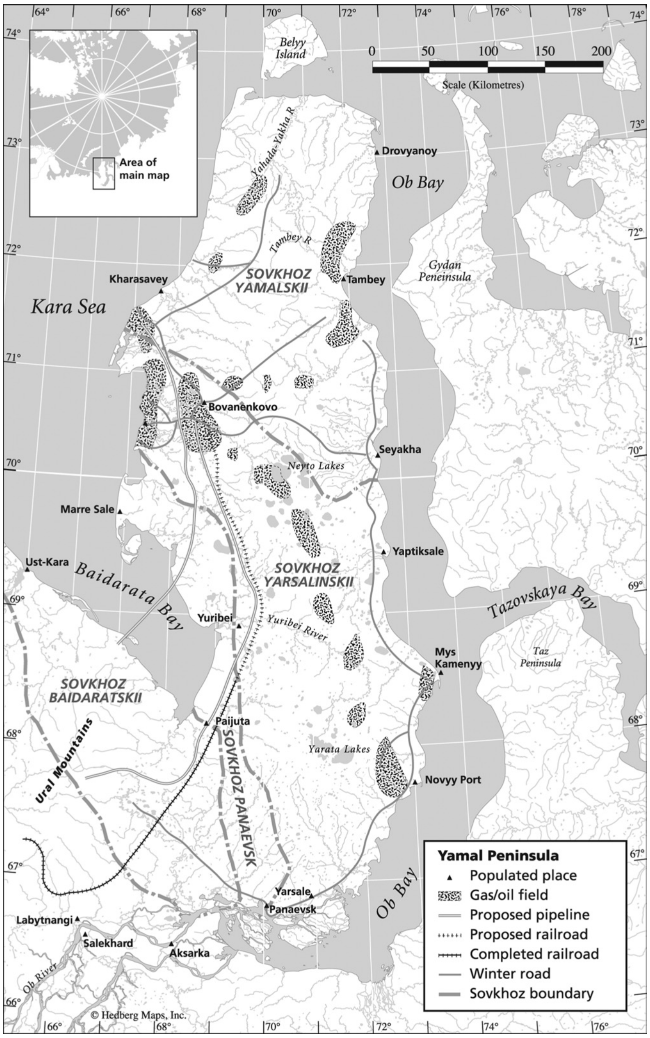

Fig. 1. Reindeer herding districts of Yamal Peninsula encompass primarily tundra pastures (spring, summer, autumn), with winter pastures south of Ob Bay in forest-tundra. Most gas fields lie within territory occupied by the Yarsalinskii sovkhoz and a number of private freelance nomads, who use the area May to November.

disturbance has the potential to create opportunity for innovation and development (6, 23, 30).

Reindeer (*Rangifer* spp.) are important ecologically within the tundra biome via their trampling, grazing, and feces deposition (31–33). The number of animals in YNAO has risen steadily from a historic low of 310,000 after World War II to ≈630,000 reindeer today, 300,000 of them on Yamal Peninsula (15, 34). Meanwhile, the number of nomads on the peninsula has risen, according to official statistics, from 3,552 persons in 1981 to 5,000 currently. According to one estimate, the nomadic population on Yamal has increased at least 3-fold in the last 300 years (16).

The recent transformation from shrub- to graminoid-dominated tundra here and elsewhere in Arctic Russia is acknowledged to be a combination of extensive industrial disturbance and heavy grazing/trampling over several decades by large herds of reindeer (11, 31, 35). At a more local level, highly productive grazing lawns can develop on organic substrates when herbivore activities are concentrated in circumscribed areas (33), such as along Nenets migration routes (see Fig. S1), some of which have been in use continuously for centuries. Dense swards can develop in response to even low-level natural and anthropogenic disturbances, such as camping and pedestrian trampling (Fig. 2) (36). The combination of grazing, trampling, and nutrient inputs from feces/urine favors grasses, sedges, and ruderal bryophytes at the expense of lichens, dwarf shrubs, and *Sphagnum* mosses. Together, these factors set up a positive feedback loop in which swards of nutrient-rich and easily digestible forage foster more intensive localized feeding, further increasing productivity (37).

The goals of this study were to identify critical determinants of resilience in an integrated SES that has experienced significant social/ecological shocks and increasing pressures, yet appears to have reorganized in ways that allow the overall system to continue to function, even thrive. The study required a multidisciplinary surrogate approach to understand the relevant ecological and social drivers and the interplay between them via stakeholder assessment and historical profiling (26). Previous investigations had reported on the extent of serious ecological impacts in the northern forest and forest-tundra zones in YNAO (8–11). Although gas development in the tundra zone is still in its early stages, preliminary work has demonstrated that there are widespread terrestrial ecological problems associated with seismic surveys, exploratory drilling, and new infrastructure, including road and railway construction (10, 11). Herders and scientists have cited the ongoing destruction of vast areas of pastures as an extremely important issue for the future (8, 10, 38). Therefore, we specifically sought to quantify through combined field measurements and remote sensing the amount of terrain affected in the vicinity of Bovanenkovo gas field (BGF), the largest deposit on the Yamal Peninsula (Fig. 1). Exploration of BGF became intensive ca. 1980. After an early post-Soviet lull, development has rapidly accelerated with concomitant impacts on tundra vegetation, freshwater sources, permafrost soils, and reindeer nomads (10, 15). The area comprises summer pastures for reindeer. As such, our focus was on net changes in the key components of pasture quality, including vegetation biomass, with special emphasis on key forage plants (*Salix* spp., Cyperaceae, Poaceae), and relatively free access to migration routes, which necessarily encompasses pastures, fishing lakes, and rivers that remain fully functional.

Previous studies had also revealed a host of socioeconomic, demographic, and health issues associated with establishing BGF and the road/railway corridor further south (Fig. 1) (10, 39, 40). We involved active nomadic herders directly in the research (Fig. 3) to interpret from their perspective the combination of social and ecological pressures that have most influenced reindeer herding over the past 20–30 years. This time slice coincides not only with the main gas exploration activities, but also with a period of rapid regional climate warming (1, 41). Our aim was to understand the extent of ecological, social, and institutional problems, including fit (29), experienced during the early phases of development. Here, we present data showing that even when subject to extensive and persistent changes in ecosystem structure and state dynamics, coupled with extreme weather events and socioeconomic shocks, the social elements of the Yamal-Nenets SES have adapted surprisingly well. Despite adaptation to a clear ecological threshold crossing, in the shift from shrub- to graminoid-dominated tundra, planned developments and climate change may further degrade key pasture and fishing resources essential to maintaining the system. Significant portions of northern Alaska, Canada, and the East European Arctic contain comparable hydrocarbon reserves, and ongoing developments are expanding. Those systems are similarly characterized by a combination of rapid climate warming and large herds of *Rangifer* spp. dependent on low arctic tundra underlain by continuous permafrost (4, 5). A critical difference is the intensive human management of domestic reindeer among nomadic Yamal-Nenets versus free-range caribou migration in North America, seasonally harvested by hunters based mostly in modern settlements. Given the geographically widespread consequences of industrial production and global change, we expect that lessons concerning the resilience of the Yamal-Nenets SES will have applications to other regions within and outside the Arctic.

Fig. 2. Transient Nenets campsite near BGF (see Fig. S1). Under long-term grazing, trampling, and feces deposition, plant functional types shift from woody plants to clonal rhizomatous graminoids (e.g., *Alopecurus*, *Eriophorum*, *Carex*, *Poa*). Such lush habitats constitute nutrient-rich and easily digestible forage (37, 59), which foster more intensive localized feeding. Photo by B.C.F.

Results

Nenets Responses to Gas Development and Warmer Weather. Besides industrial development and climate, recent socioeconomic shocks to the Yamal-Nenets SES include the collapse of the Soviet Union that led to, among other things, (*i*) rapid reductions in subsidies for herding and meat distribution; (*ii*) an increase in privately owned animals, from 30% in 1965 to the present 80%; and (*iii*) the annual procurement of antler velvet for supplementary income. The post-Soviet era also meant new opportunities followed by increased uncertainty concerning legal rights and future access to lands for herding, hunting, and fishing. Overall, Yamal is the only tundra region with post-Soviet increases in both animals and people (15, 16, 19). Large families remain the norm and most young people choose reindeer herding as their livelihood, so that knowledge continues to be transmitted between generations (see *SI Text*).

According to herders, the main effect of recent warming is an increase in the frequency of unusual weather events, creating conditions that are not predictable. In spring 1999 an icing event rendered significant pasture areas of northern Yamal inaccessible and led to heavy mortality among herds. In spring 2005 the Se-Yakha River, which runs through BGF (Figs. 1 and 4), broke up 2 weeks early, which meant brigades involved in the present study

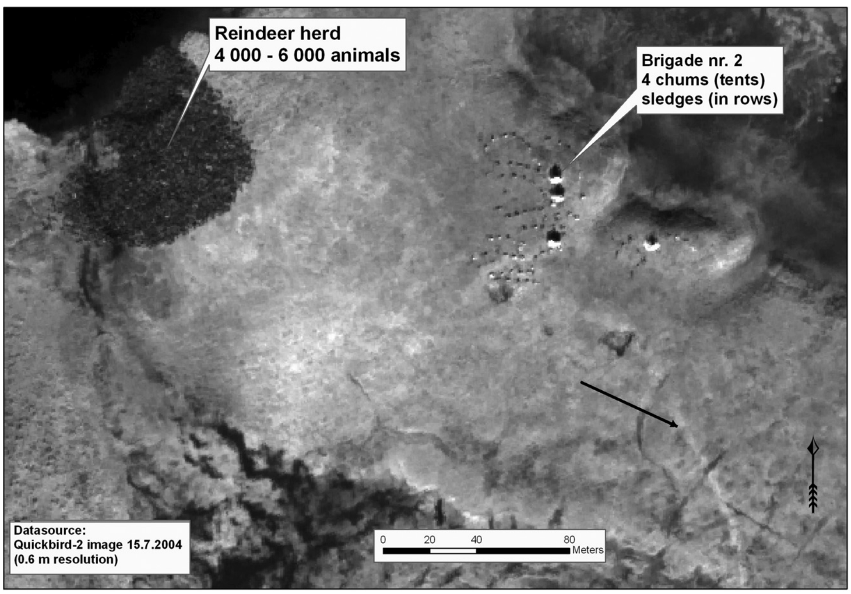

Fig. 3. Very high-resolution panchromatic imagery (Quickbird 2) facilitates qualitative analyses of conditions and management because landscape features and infrastructure are recognizable to all informants. The arrow at the lower right indicates a well-worn track void of shrubs from regular access to this campsite of brigade 2 (see Fig. S1).

migrated more quickly to reach the coast where cool winds, fogs, and salt spray from the Kara Sea foster a combination of insect relief and highly nutritious sedge meadows critical for calf survival and growth. Because the herds already move every 24–48 h after the calving period, the accelerated pace of movement from this event resulted in additional stress to reindeer and herders alike.

In winter 2006–2007 unusual successive icing events occurred on southern Yamal Peninsula over a large region affecting these and many other brigades. During November 8–10, 2006, during fieldwork with brigade 8, consecutive thawing/refreezing periods resulted in two ice layers over an area ≈100 km north–south and 60 km east–west. Two months later, on January 18, 2007, a highly abnormal midwinter icing covered an even larger area of ≈100 × 100 km. Both events constituted systemic shocks requiring intervention to assist animals in reaching forage and changing migration routes after urgent discussions with administrators and neighbors. As a result of these events, the herders that had to cross the iced-over area during their spring migration suffered, according to their own calculations, loss of 25% of their animals, including deaths and still-births resulting from exhaustion and poor nutrition of pregnant females.

Migratory Nenets must maintain a considerable base of castrated male reindeer to transport households. Over the subsistence minimum, the ratio of productive females is increased for meat production (see *SI Text*). Conscious management decisions on overall herd size also influence the capacity to respond to shocks and disturbance. Large herds are generally preferred by sovkhozes and their successor enterprises as the most efficient way of managing reindeer and producing meat. However, smaller herds and camps are able to respond more flexibly to ecological changes because they can exploit smaller patches of pastures, including those surrounded by industrial installations. Such patches are too small to be accessed by large herds as whole units.

Socially Significant Direct Impacts. One of the main effects of industrial development is loss of territory, with diverse ecological and cultural significance. Since the onset of industrial development brigades 4 and 8 have lost eight important campsites in the immediate vicinity of BGF, which they were able to replace only through spatially flexible responses. In addition, brigade 4 lost a small cape just south of the Se-Yakha River in 2007 to a sand quarry. This was the brigade's last undisturbed site on elevated ground, crucial for staging the northbound river crossing. The site also contained a sacred spot where the spirits could be asked for good success during the worst insect harassment time in summer or for a good autumn migration on the way back. When the site was fenced in and the quarry dug around, the site lost the importance that it had held because of its strategic embeddedness in the environment.

Another direct impact is the loss of fish because of the ongoing degradation of freshwater sources. Herders do not slaughter reindeer for food in summer and rely mainly on fish present in the lakes, plus those caught migrating from the Kara Sea up the numerous rivers on Yamal Peninsula. This staple food is being rapidly depleted. First, many rivers are functionally blocked during the period of fish migration in the course of bridge construction (see *SI Text*), which deprives entire inland areas on the peninsula of their main staple food source in summer. Second, lakes are used as construction sites, be it for sand quarries or e.g., airports. According to Gazprom, the planned Bovanenkovo airport might well be on the site of a lake and surrounding mire, the location of which is classified information (ref. 42; www.rosbaltnord.ru/2008/06/11/493324.html).

Socially Significant 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 (see *SI Text*). Every direct loss of territory has additional indirect social impacts, which are not identifiable by remote sensing. The availability of fish is influenced by direct loss of fishing grounds but also by competition of tundra nomads with industrial workers, for whom fishing is a preferred activity during off-work hours. Nomads report that industrial workers who lack knowledge of fish migration position their nets in an unsustainable way or leave the nets in place, thus blocking fish migration for an extended time. Workers also take dogs with them to the production sites and into the tundra. These pets often remain behind, become feral, and attack weaker reindeer. Herders are required to hunt feral dogs for herd protection at their own expense via snowmobile. Because gasoline and ammunition are not for sale on the tundra, except through the black market, herders are forced into illegal activities to eliminate the threat.

Infrastructure contributes to positive and negative indirect impacts. Each additional road opens up larger areas of the tundra to newcomers who rarely possess either the ecological or cultural knowledge required to behave there in a sustainable manner. Beyond work-related purposes, industrial workers readily exploit roads for illegal hunting and fishing, recreational trips, or trading. Untrained for interactions with herders and reindeer, they can behave in inappropriate ways, e.g., wandering uninvited into camps with cameras, alcohol, etc. Roads are thus significant for herders and animals well beyond the immediate corridor of pastures subject to direct and indirect ecological impacts. However, surface or air connections may facilitate access to markets in town and so reduce costs of trading for herders. An example of the influence of lower transportation costs is the velvet antler trade. Although this business has been discontinued in most other Russian regions, in Yamal the access to gas company helicopters allows the continuation of this trade. Only because flights of workers and supplies to "gas villages" can be used for flying out antlers are the otherwise high costs of this business bearable, which enables gas workers to engage in business with herders. The ability to barter for goods and supplies at their camps on the tundra in summer is a luxury that herders had not enjoyed before.

Most contact between herders and workers takes place within the gas villages herders migrate through, stopping to trade for staples and socialize. Despite these positive interactions, personal freedom on both sides to shape beneficial relations tends to diminish, because rules designed in cities do not always meet the needs of tundra residents. The enforcement of such rules restricts the scope for local agency at the drill rig/gas village level, for example, when gas workers are forbidden to sell fuel to herders for snowmobiles and lamps. This shows how socially significant impacts may be both positive and negative.

Compared with other regions, which have experienced modest to steep post-Soviet declines in people, herded reindeer, and overall economic stability, Yamal has been markedly successful. We identified flexible pasture use and access, along with functional continuity in private animal ownership, as crucial determinants of this success. Nenets further stressed importance of the large number of families and, particularly, youths who chose to live in the tundra. Social capital (including trust and social networks), memory (including experiences of dealing with change), and intimate human–animal–plant relations through continuous movement on the land all were deemed central to the overall resilience of the Yamal-Nenets SES.

Remote Sensing of Impacts. Combined field surveys, image analysis, and interviews with gas field workers yielded detailed information about the extent of different anthropogenic land cover types. The prevailing disturbance regime on the ground and detected in satellite imagery was off-road vehicle traffic, mostly from the early to mid-1980s (see Fig. S2). Change detection procedures determined visible impacts within 22% and 25% of the respective summer territories of brigades 4 and 8 of the Yarsalinskii sovkoz, which pass directly through BGF (Fig. 4). In contrast, $<1\%$ of the adjacent territory of brigade 2 (Fig. 3), south of BGF, has been

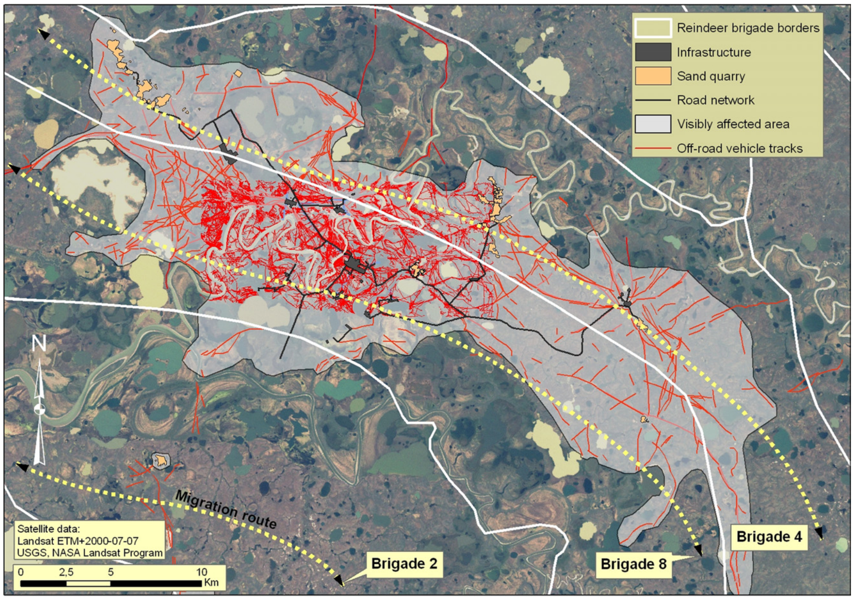

Fig. 4. Visible impacts digitized onto false color Quickbird-2 image from July 2004 and an overlapping ASTER image from July 2001. These, in turn, are overlapped onto a Landsat image from July 2000 for spatial context. Shading delineates moderate–heavy anthropogenic disturbance. Migration routes of brigades 2, 4, and 8 are indicated.

transformed. The main trend is a shift from erect shrub-dominated (*Salix* spp.) to graminoid-dominated (*Cyperaceae*, *Poaceae*) tundra vegetation cover. Certain features, e.g., naturally revegetated vehicle tracks (see Fig. S2) and larger areas of bare soil that had been revegetated completely, were easier to detect from multispectral Quickbird-2 imagery. Approximately 2,500 km of vehicle tracks occupied ≈25 km^2 as of 2005.

Some vehicle tracks impossible to detect in the field showed up clearly in satellite imagery because of the contrasting spectral reflectance characteristics of graminoids versus shrubs. However, garbage and petrochemicals were extremely difficult or impossible to detect remotely. From lower-resolution Landsat images (see Fig. S3) it was possible to discern significant cover of bare ground in the mid to late 1980s. Few roads had been built then and vegetation cover was completely destroyed in places from activities like quarrying for sand and extensive vehicle traffic, exposing relatively high albedo mineral soils beneath. By the mid to late 1990s most of these areas had been completely revegetated by graminoids, which greatly reduced their surface reflectance.

Permanently transformed areas are those occupied by roads and infrastructure. The active road network in 2005 was 79 km and covered 143 ha. Although only ≈18 m wide, the actual affected zone around roads is much broader because of the indirect impacts of blowing sand, dust, and altered hydrology (36). The total area of impact was calculated by outlining areas inside BGF that had signs of human disturbance visible in the ASTER TERRA and Quickbird-2 images (Fig. 4). The area covered ≈450 km^2. Inside this zone visible changes were widespread compared with the original vegetation cover, yet there remains a significant amount of terrain relatively unaffected by direct mechanical disturbance.

Changes in Vegetation Biomass. The main trend in vegetation has been the large-scale shift from shrub- to graminoid-dominated tundra. We concentrated on linear paths in willow shrub vegetation denuded by vehicle traffic, especially multipass tracks. These had regenerated for ≈20 years at the time of sampling. There were significant differences in biomass between the prevailing cover of erect willow shrubs and the tracks that traverse them. Live leaf biomass in undisturbed willow thickets at BGF was 119.4 ± 71 $g \cdot m^{-1}$. For purposes of reindeer rangeland assessment this translates into 1.19 ± 0.71 $t \cdot ha^{-1}$, the standard for YNAO (31) and phytomass studies in Arctic Russia (43). Another study at BGF determined annual aboveground production in such willow thickets to be ≈0.72 $t \cdot ha^{-1}$ (44). Some 20 years after disturbance, we found *Salix* leaf biomass in fully revegetated tracks with closed plant cover (≥100%) was only 0.10 ± 0.22 $t \cdot ha^{-1}$, significantly less than adjoining undisturbed willow vegetation ($P < 0.0001$). On the contrary, graminoid biomass in revegetated tracks was significantly ($P < 0.0001$) higher (3.78 ± 2.09 $t \cdot ha^{-1}$) compared with undisturbed willow thickets (0.56 ± 0.71 $t \cdot ha^{-1}$).

The reduction of *Salix* was two orders of magnitude, whereas the increase in graminoids was ≈7-fold. As a consequence, total live biomass actually increased slightly, from 4.74 ± 2.73 $t \cdot ha^{-1}$ to 4.79 ± 1.74 $t \cdot ha^{-1}$, of which 79% was made up of graminoids. The reduction in bryophyte biomass, from 2.12 ± 2.28 $t \cdot ha^{-1}$ to 0.71 ± 0.84 $t \cdot ha^{-1}$, was one order of magnitude ($P < 0.02$). At the same time, litter decreased from 1.00 ± 0.74 $t \cdot ha^{-1}$ to 0.04 ± 0.12 $t \cdot ha^{-1}$, nearly two orders of magnitude ($P < 0.0001$), resulting in lush and highly productive meadow-like vegetation, the so-called "green belt" effect (45) (see *SI Text*). Reinvasion of *Salix* spp. was negligible, with few seedlings counted, and only minimal visible lateral regrowth from intact shrubs bordering tracks. Dwarf shrubs had disappeared almost completely.

Discussion

Alternative States. The general response of tundra to anthropogenic disturbance is a reduction in floristic richness (36). Around BGF, <40% of the local flora occur in anthropogenic habitats and just 8% are active colonizers (10). Unlike North American oilfields, where mitigation and rehabilitation regulations are strictly enforced, disturbances on Yamal often expand with no legal consequence (40) and most are left to regenerate naturally rather than actively revegetated (46). The result is a steady "nibbling" away of territories essential for reindeer nomadism (see *SI Text*). Although floristic reductions can persist for decades or centuries, and intensify with increasing latitude (9, 36), species diversity within the most productive habitats is not necessarily the key to quality forage for reindeer in summer (33, 37). Of the green forage occurring in undisturbed Yamal summer pastures, *Salix* and *Betula* leaves comprise 30–40% of the total fodder in deer rumens, with much of the remainder being graminoids and forbs (31). Two decades after extensive surface disturbance, the contrast between willow habitats versus those with graminoid-dominated cover is visually striking (see Fig. S2) and the transition often occurs over very sharp boundaries of ≤1 m (see *SI Text*). Despite substantial cover of bare ground in the early years of development, because of rigorous regeneration there has been a slight increase in live leaf biomass, meaning no net loss of available green fodder. However, the presence of trash, petrochemicals, noise, and feral dogs means that much territory is functionally lost (see *SI Text*). This degradation of territory is in addition to the indirect effects of roads and infrastructure, such as degradation of vegetation, freshwater systems, and increased poaching. We documented the consequences of extreme weather events consistent with climate warming scenarios (2, 3). Nenets played down their importance and stress hydrocarbon development as the main long-term threat to their existence (47, 48), but the potentially negative synergy of rapid climate and land-use change, coupled with an influx of workers, cannot be ignored (see *SI Text*).

Our ecological findings demonstrate that the dramatic transition from shrub- to graminoid-dominated tundra pastures related to development is steadily increasing from the local to the regional scale. Transitions between woody- and graminoid-dominated rangelands have been proposed as alternative stable states in which the disturbance is normally grazing pressure. Resilience is the property that mediates transition among these states (49, 50). The ecological resilience concept presumes the existence of multiple stability domains and tolerance of the system to disturbances that facilitate transitions among stable states (30). In the case of rangelands, alternative states are classified according to dominant plant forms and the disturbance is grazing pressure. However, alternative ecosystem states in tundra can result from both anthropogenic and zoogenic disturbance (33, 36). In such an endlessly dynamic context, herders themselves stress that pastures must be not only ecologically, but also socially and culturally suitable (15, 51) (see *SI Text*).

While we can observe an alternative ecosystem state because of the changes in vegetation in the vicinity of BGF, the alternative state of the social-cultural system (30) would imply a significant reduction of reindeer nomadism in the area, if more attention is not paid to building a constructive dialogue for the future (52). Such a state would reverse Nenets nomads' generally supportive approach to mutual coexistence with industry. The likely outcome for newly sedentary herders would be resignation, alcohol abuse, suicide, and domestic violence (53, 54).

Territorial Loss as a Trap. Reduction of pastures through industrial pollution, land withdrawals, and infrastructural encroachment must be understood via their ecological, economic, and social significance for reindeer herding as a nomadic livelihood (see *SI Text*). The ongoing loss of high ground for campsites, sacred sites, and migration routes, often accompanied by erosion, is particularly critical in a land dominated by mires and wetlands. Overall, flexible use of the area is a key component of the SES, which has enabled it so far to respond successfully to outside pressures. For example, the introduction of discrete herding areas for each brigade during Soviet times was accepted in general but flexibly negotiated in practice. Another factor easing the transition to post-Soviet management is that Yamal was characterized by the uninterrupted continuity of private herd ownership, which helped Nenets 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 below 30% during Soviet times, compared with 5% on Chukotka (15, 55). This is an example of path dependency (56) (see *SI Text*). The difference with industrial development, however, is the massive ecological transformation of territory we have documented here in combination with reduced spatial flexibility. With gas extraction rapidly appropriating new territories, the traditional mechanisms of Yamal Nenets herders to absorb outside shocks are likely to be severely threatened, because in the near future more land areas and freshwater sources will be permanently lost or degraded to the point where they may no longer support tundra nomadism.

Considering recent events raises the concept of "socio-ecological carrying capacity" (15) of the area, and a potentially lethal trap (57), in which the capacity for Nenets to adapt moves beyond their control. Since 2006 there has been a massive regional influx of labor, which is projected to amount to 50,000 shift-workers on Yamal Peninsula and will increase the industrial population of humans 10-fold over the nomadic herding/fishing population. At the current rate of terrain/freshwater disturbance, the ecological footprint of this influx would be so significant that herders will effectively be socially and culturally "alienated" from the area (see *SI Text*). Any exogenous transformation of a place has ecological, social, cultural, and spiritual consequences (see *SI Text*).

Managing for Resilience. Adaptation means developing new social-ecological configurations that function effectively under new conditions (22, 27, 58). Adaptive capacity (30) in the Yamal-Nenets SES lies partly in the complex ecology of reindeer, which feed on >400 species (31) and continue to forage successfully despite rapid large-scale anthropogenic habitat transformation. Hence, it is not the number of species *per se* that help sustain an ecosystem in a certain state. Rather, the existence of species functional groups with different, often overlapping characteristics (23), such as high biomass, digestibility, and energy value (59), enables regeneration and successful foraging after disturbance across diverse scales. Despite major industrial and climate change experienced within the lifetime of herders, the Nenets' reindeer economy still succeeds where others have failed, actively managing herds amid ongoing gas activities and infrastructure that are considerably more intrusive than similar developments in Arctic North America. Thus, adaptive capacity lies also in economically, socially, and culturally specific practices of Nenets tundra nomads. We have revealed how they carefully manage herd demography for different needs based on animal energetics and socioeconomic conditions. Therefore, we argue that the adaptive capacity of smaller herds to "land change" (60) by gas development is greater than that for larger herds.

Conclusions

We have demonstrated a clear ecological threshold crossing in the shift from woody- to graminoid-dominated tundra. Visibly affected rangeland, in which the disturbance is industrial impact rather than grazing and trampling pressure, extends over hundreds of square km and represents an alternative stable state. Institutional drivers were evident in virtually all aspects of ecological and social change, both positive and negative. Formal institutions for mitigating ecological damage remain weak and constitute a "misfit" (29), because enforcement of existing laws is minimal. The same problem of fit (29) characterizes the norms governing consultation and legal land rights that either largely exclude herders or are not implemented because of diverse interests of government, companies, and indigenous representatives. However, institutions controlling movement of people and animals in space and time remain flexible and allow Nenets to retain possession of their herds, which are able to exploit a wide range of ecologically variable natural and anthropogenic habitats. We emphasize that this flexibility is highest among smaller privately managed herds. We note in certain cases what were originally intended as formal governmental institutions, such as the Soviet concept of brigades, have become redefined according to local particularities and culturally embedded needs of nomads (15). This shows that, in principle, they have the capacity to be reformed according to new exogenous changes, e.g., pasture compartmentalization by industry.

In conclusion, we have shown the Yamal-Nenets SES to be remarkably resilient and capable of reorganizing in the face of diverse systemic state changes over the past two to three decades. We have revealed that free movement of people, animals, and goods increases herders' capacity to respond to combined ecological and social change and facilitates contacts between nomads and incoming workers with all associated favorable and problematic consequences. Nenets themselves stressed the importance of the large number of families and youths who chose to live in the tundra. We identify flexible pasture use and access as a crucial determinant of Yamal-Nenets resilience. We note that the significant reductions in shrub biomass at BGF were compensated for by net increases in productivity among highly nutritious and digestible forage species, although herd access is increasingly restricted. Herders expressed strong concern about the potential loss of fish as an essential source of protein during the long summer migration when they do not slaughter reindeer. Based on a careful review of the trends observed, industry plans, and specific ongoing and potential problems perceived by the Nenets, we speculate on limitations of the observed resilience. We envision a looming threshold related to the sheer scale of future expected needs of industry for territory, concomitant pasture, and lake/river degradation, coupled with a rapidly growing industrial workforce at the same time as climate is warming. We highlight problems of fit for key governance institutions because SESs are vulnerable not only to changes in the physical environment (61), but also to shifting or static policy and institutional environments (62) and potential rigidity traps (57). If land change (60) continues at current rates, reconfiguration of movement in time and space will be impossible and the entire SES may become highly vulnerable. However, if any system in modern Russia is in a position to survive such an onslaught it is the Yamal-Nenets SES because of its accrued experience with coexistence, financial wherewithal from gas and oil revenues, and a widely acknowledged vibrant nomadic culture.

To conclude, historical experience and current Nenets agency could serve as a stable basis to continue the decades-old coexistence of industrial development and nomadic pastoralism, if a certain number of conditions are met. Investments by industry must undergo a cost-benefit analysis for the ecological and socio-cultural situation in the tundra, rather than focusing on development of sedentary communities. If nomads' suggestions are considered, money would be redistributed away from village housing to increase ecological safety of tundra infrastructure, raising pipelines (see Fig. S4) to allow free movement of humans and animals, more air-based supplies instead of an extended road network, concentration of sprawling infrastructure to minimize ecological damage to tundra pastures and freshwater fish sources, and strict implementation of codes of conduct for herders and workers (48). The region is experiencing a pattern of activity that is likely to be repeated elsewhere in the Arctic and have feedbacks to the global system. Now that the conditions for successful coexistence are known, and a reliable knowledge base on both sides exists via this and previous studies, proper implementation could turn the region into an exemplar of global relevance for the future.

Materials and Methods

Study Sites. Yamal Peninsula occupies a low (30–70 m above sea level) sedimentary plain, extending over three bioclimatic subzones (63), with fine-grained Pleistocene sand underlain by saline marine clay with widespread ice-rich permafrost. Alkaline substrates are rare (9). The combined social and ecological fieldwork was conducted at a few key locations within the Yarsalinskii sovkhoz, which extends from the mainland forest-tundra zone in the south (≈65°30′N) to the ''typical'' tundra in the north along the coast of the Kara Sea on western Yamal Peninsula (≈71°30′N) (Fig. 1). These end points of the longest reindeer migration routes correspond, respectively, to Circumpolar Arctic Vegetation Map subzones E and D (63). Our ecological and geographical measurements focused on the vicinity of BGF (70°17′N, 68°54′E). Occupying lowland and relatively moist substrates with clayey soils, the prevailing vegetation at BGF is a dense cover of willows (*Salix* spp.). These can be 50–60 cm high in hollows and other microsites with protective snow cover, but tend to average 30–40 cm. Slightly higher ground with better drainage is characterized by low-lying dwarf-shrub heath dominated by *Betula*, *Ledum*, and *Empetrum*. The wettest sites are *Sphagnum* mires dominated by sedges (*Carex* spp., *Eriophorum* spp.) with lesser amounts of grasses and herbs.

Land Cover Classification. Two expeditions to BGF were made in July 2004 and 2005. A total of 220 field sites were surveyed for satellite image interpretation spread over ≈15 land-cover classes. Each site was marked with GPS and the vegetation was characterized. A total of 5–10 quadrants of 50 × 50 cm in each of the main vegetation types, depending on the degree of heterogeneity, were identified, and cover and height were estimated for all plant groups; grasses, sedges, shrubs, lichens, and bryophytes. Bare soil and litter cover were measured with special attention to visible signs of human impact.

Satellite images with varying spatial resolution were used to compare the visibility of the different impacts. Very high-resolution remote sensing data (Quickbird-2) was acquired July 15, 2004 with a spatial resolution of 2.4 m on the multispectral channels (blue, green, red, and infrared) and 0.63 cm on the panchromatic channel. Data are stored in 11-byte format. High-resolution data used were ASTER TERRA with 15-m resolution (four channels from July 21, 2001), Landsat TM with 30-m resolution (seven channels from August 7, 1988), and Landsat MSS with 80-m resolution (four channels from July 28, 1984).

Road networks, off-road vehicle tracks, areas saturated with tracks (no identifiable individual tracks), garbage dumps, pipelines, powerlines, sand quarries, drilling sites, herders' migration routes, and brigadiers' notes were digitized by using Quickbird-2, ASTER TERRA, and Landsat TM images. Total area of impacts was estimated by using buffer analysis. Average road and off-road track widths were measured from 25 locations in panchromatic Quickbird-2 imagery. Visibility of different impacts was compared among images using field sites and photographs from helicopter and ground level. Various-sized impacts were selected to test the detection capacity of different satellite platforms. The aim was an accurate estimate of the total area of direct and indirect impacts encompassing all visible signs of disturbance.

Vegetation Biomass. Vegetation biomass measurements were made in the vicinity of BGF, situated on lowland clayey substrates subject to extensive anthropogenic disturbance and included within the Quickbird-2 satellite coverage described above. The prevailing erect shrub cover at BGF corresponded to the vegetation type ''*Salix lanata-Brachythecium mildeanum*'' recently described for the area (64). The shrub layer consisted mainly of *Salix glauca* L. and *S. lanata* L. averaging 40–50 cm high.

At the growing season peak in mid-July 2005 we sampled vegetation biomass in three random off-road tracks in willow-characterized shrub vegetation. (see *SI Text*). We placed quadrats systematically 12 m apart from one another beginning from a random point along transects running along the track center. Parallel transects were established 12 m apart from the track center in relatively undisturbed vegetation. In total, there were 38 plots on tracks and in undisturbed vegetation. The above-ground plant material was clipped from a 25 × 25-cm plot and sorted by growth form (deciduous shrubs, evergreen shrubs, graminoids, forbs, bryophytes, lichens). Leafy and woody material were separated, oven-dried at 60 °C for 48 h, and weighed. From these data we calculated estimates for available green forage in the disturbed and undisturbed vegetation as verified in the satellite imagery. The statistical analyses were conducted in R statistical environment (version 2.6.2) using generalized linear models with quasipoisson error structure (www.R-project.org).

Participant Observation and Interviews. Yamal reindeer are intensively managed 24 h a day, 365 days a year by whole families through generations. Historical profiling (26) via participant observation entailed taking part in every aspect of daily life through all seasons. This fieldwork adhered to the Guiding Principles for the Conduct of Research published by the International Arctic Social Sciences Association (http://www.iassa.gl/principles.htm). Although the main ecological and geographical fieldwork concentrated on summer pastures around BGF and Lake Khalevto, intensive social anthropological fieldwork also encompassed autumn, winter, and spring pastures. Discussion topics included experiences with ecological, socioeconomic, and industrial influences on their ability to maintain nomadic herding as a viable livelihood. Special attention was paid to decision-making for coping with real and perceived risks and future prospects. Participant observation included trading activities between reindeer herders and gas field workers at various levels, which included visits with herders to BGF and visits with the gas workers to reindeer nomads' camps. Long-term (≥18 years) gas field workers were interviewed to understand how their relations with reindeer herders have developed in the last 20 years. Color and panchromatic satellite images were interpreted in the field with herders and workers, who were easily able to recognize landscape features, migration routes, and even nomadic campsites (Fig. 3). The overall time spent with participant observation among all groups from March 2004 to July 2007 was 29 person months, plus a stakeholder assessment (26) workshop in December 2007 (48) and follow-up interviews in March and November 2008.

Within the Yarsalinskii sovkhoz we focused on three ''northern brigades'' or collective herd management units for in-depth participant observation and interviews. These three encompass herds that have either direct or indirect contact with the main oil and gas infrastructure at BGF. The aim was to learn from the contrast provided by herding units that have lost considerable amounts of their territory versus those that have lost little. One brigade (no. 4) was accompanied during its migration through BGF in July (see Fig. S4), and another one (no. 2) passing ≈20 km south of it (Fig. 4). A third (no. 8) also crosses BGF, but was accompanied outside of the immediately affected area for 200 km of their migration in autumn 2007 toward the slaughterhouse at Yar Sale (Fig. 1). Each nomadic group consisted of 10–90 people comprised of two to nine nuclear families managing from 3,000 to 8,000 animals. The area being rapidly developed lies north of the Se-Yakha River, between BGF and Kharasavey (Fig. 1) (see *SI Text*).

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