LETTER

Informal road networks and sustainability of Siberian boreal forest landscapes: case study of the Vershina Khandy taiga

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Abstract

Boreal forest landscapes are experiencing various anthropogenic pressures from industrial activity, transportation, urbanization, and recreation compounding already significant changes in regional climate. However, the impact of the transportation infrastructure on boreal forests is rarely considered, and information about road extent is often incomplete, especially in the case of informal roads. Using a combination of landscape observations and interviews with local residents this case study examines the role of informal roads, i.e. vehicular roadways existing outside of the current publicly governed road networks, in transforming Siberian boreal forest landscapes in the Vershina Khandy taiga, Russia. Informal roads constitute 88% of the total road length in the study area and exert significant and multifaceted effects on social-ecological systems and landscape sustainability. Native dark coniferous forests have been disturbed by cutting, logging and human-caused fires proliferated from the roads. In their immediate vicinity, the informal road networks also exacerbate the replacement of primary forests with different successional states. Landscape vulnerability was assessed using three main factors of road-related disturbance: erosion, permafrost degradation and wildfires. Valley landscapes, where roads are prevalent, found to be the most vulnerable to environmental degradation. They are more often located within the wetlands with permafrost occurrences. The impact of informal roads is not limited to environmental changes. Among consequences there are also increased mobilities of local and Indigenous communities, as well an improved access to the area by outsiders: recreational anglers and poachers. The effects on subsistence activities and mobility vary across different landscapes. Further research on natural and social components of landscape sustainability in boreal forests affected by informal road networks is needed to better understand the local, regional and global role of this phenomena.

1. Introduction

Sustainable transportation infrastructure development is an important subject of discussion for policymakers (e.g. United Nations n.d.) and researchers (e.g. Perz 2014). Automobile road network development, while improving economic opportunities and accessibility (e.g. Bryceson et al 2008), contributes to landscape fragmentation, deforestation, geomorphic changes, and pollution threatens biodiversity and traditional land use (e.g. Chesnokova and Lokshin 2016, Sofia et al 2016, Langlois et al 2017, Taubert et al 2018, Hargreaves 2019, Ibisch et al 2016, Shirvani et al 2020).

The density of the road networks significantly affects landscape sustainability. However, the road extent estimates are often outdated or characterized by spatial bias in coverage (Meijer et al 2018). This lack of knowledge is especially evident in remote regions considered to be relatively ‘roadless’
Boreal forests covering approximately 30% of the global forested area serve as one of the largest carbon reservoirs in the world, and their degradation compounds climate change (Harden et al 2002, Pan et al 2011, Gauthier et al 2015). At the same time, the expanding informal road networks inflict considerable and multifaceted impact on boreal forest landscapes, including deforestation, fragmentation, changes in hydrologic regime, permafrost, vegetation, animal migration, and air and water pollution (Daigle 2010, Kivinen et al 2012, Wulder et al 2014, Walker and Peirce 2015, Ackerman and Finlay 2019, Hermosilla et al 2019). Informal road networks in the boreal forest are growing as new linear infrastructures emerge (Daigle 2010, Wells et al 2020). For example, there is evidence of re-use of seismic clearings (trails created for seismic exploration) as roads by all-terrain vehicles (Van Rensen et al 2015, Stern et al 2018, Pattison et al 2020) and an increase of risks of wildfires as a result of expansion of linear infrastructure (Arienti et al 2006, Chen et al 2014, Kirillina et al 2020). Even seasonal vehicle traffic is shown to trigger thermokarst and erosion (Raynolds et al 2020) which in turn promote changes in the carbon cycle (Strack et al 2018). At the same time, extending transportation routes through the boreal forest in support of logging and extractive industries is often promoted by the local authorities as a driver of economic development (Luzgina 2007, Delahova 2016, Bogdanov and Dugarova 2019), and are likely to continue.

While the informal road network is expanding (Pattison et al 2020), the overall impacts of these features on boreal forests in Siberia is not well studied. This is particularly true in respect to long-term implications to the sustainability of the boreal forest landscape. At the same time there is existing evidence of infrastructure effects on boreal forest wildfires ignition, propagation and suppression in Canada (e.g. Campos-Ruiz et al 2018), Siberia (e.g. Kirillina et al 2020), and northern China (e.g. Liu et al 2012). Probability of a fire was found to have a strong correlation with human infrastructure and associated activities (Nami et al 2018). Moreover, between different forms of infrastructure researchers note a higher role of human transportation networks than human settlement in fire ignition regime (Gralewicz et al 2012). With more detailed analysis of correlation between different forms of anthropogenic features and thermal anomalies, Kovacs et al (2004) found the highest correlation between forest fires and proximity to roads followed by proximity to railroads and settlements in Central Siberia.

The effects of road network development are most pronounced at the landscape scale where one can distinguish spatial diversity of landscape elements and their role in flow of energy and individuals (Turner 2005, Chen and Liu 2014). Landscape approach allows examining environmental impacts by analyzing sustainability that has both natural and socioeconomic components. Landscape sustainability is defined as ‘the capacity of a landscape to consistently provide long-term, landscape-specific ecosystem services essential for maintaining and improving human well-being in a regional context and despite environmental and socio-cultural changes’ (Wu 2013, p 1013). One option to assess landscape sustainability is to focus on vulnerability, a likelihood of a social-ecological system to experience harm to its structures, functions, and resources, as a result of external stress (Turner et al 2003, Wu 2013).

This paper fuses landscape observations and community-based socio-economic data to examine the informal roadways originated from community reuse of the extractive industry infrastructure, (e.g. seismic clearings, forestry roads), to understand their effects on sustainability of boreal forest landscapes. For this purpose, the following objectives are pursued: (a) examine informal road network and landscape composition and structure in the study area; (b) identify effects of informal road infrastructure on landscape characteristics; (c) assess the vulnerability of landscapes and land-based subsistence activities to informal road development.

2. Study area

The study focuses on the boreal forest (taiga) of north-eastern Eurasia. The study area of 6965 square kilometers (twice the size of Luxembourg) is centered around the Indigenous Evenki village of Vershinina Khandy and includes the town of Magistralny in Kazachinsko-Lenskii District of Irkutsk Region (figure 1). The district is characterized by harsh (and
changing) climatic conditions, permafrost, the prevalence of coniferous vegetation, and susceptibility to wildfires (Geocrilologicheskaya 1979, Antipov et al 2004, Batuev et al 2004).

The traditional Evenki subsistence-based land-use practices (e.g. hunting, fishing, and gathering) were disturbed in 1975 by the construction of the Baikal-Amur Mainline (BAM) railroad and related forestry and geological exploration (figure 1). The depletion of biological resources contributed to the migration of many Evenki families to larger settlements, such as Magistralny located 36 km from Vershina Khandy. However, most of Evenki have retained seasonal hunting, fishing, and gathering activities within the 299,067 hectares area allocated for traditional land use by the Russian government in 1991 (Raspyorazheniiie 2003). As of 2002, out of about 71 Evenki people in the district 48 have been residing in Vershina Khandy. However, most of Evenki have retained seasonal hunting, fishing, and gathering activities within the 299,067 hectares area allocated for traditional land use by the Russian government in 1991 (Raspyorazheniiie 2003). As of 2002, out of about 71 Evenki people in the district 48 have been residing in Vershina Khandy (FREKOM 2002). Kovyktinskoe gas deposit, known as the biggest in the Russian East (Gazprom 2019a), is located within the territory of traditional land use. By 2022 it is expected to become the main source for Power of Siberia gas pipeline, the largest gas transmission system in Russia’s East currently under construction (Gazprom 2019b). Therefore the study of past and present infrastructure development and use is highly important for understanding the sustainability of local social-ecological systems.

3. Materials and methods

Our study of informal roads is based on an interdisciplinary approach which utilizes data from different sources (table 1).

First, we compiled the inventory of informal road networks and examined landscapes in the study area, then we identified effects of informal road infrastructure on landscape characteristics and third we assessed the vulnerability of landscapes and land-based subsistence activities to informal road development.

3.1. Inventory of the informal roads
To compile spatial inventory of roads within the study area we used a combination of medium- and high-resolution satellite imagery from 2017 (see table 1), topographic maps, infrastructure development planning documents (Ministry of economic development 2020), and the data from the interviews. The road functions (such as subsistence roads, seismic line clearings, forest, and roads created by locals informally) were discerned from field studies and environmental impact assessment documents.

3.2. Landscape studies
The landscape mapping within the study area was based on the hierarchical geosystem approach which identifies the elementary morphological units of a geographic landscape. Such elementary landscape units are characterized by unique sets of homogeneous landscape features (Sochava 1978, Antipov et al 2002). Initially, medium- and high-resolution satellite imagery (table 1) was used to identify landscape elements within the study area based on image texture and color. Topographic maps, data from the Shuttle Radar Topographic Mission, and Landsat satellite imagery (table 1) were used to characterize each landscape element according to forms of relief and steepness of the slope. Potential for exogenous processes, such as erosion, was assigned to each landscape element based on slope steepness and available surface geology map (State geological map of Russian Federation 2009). The available hydrogeological maps, empirical data were used to identify landscape elements affected by permafrost. Published materials and data were used to provide additional characteristics (e.g. soils, vegetation) of each identified landscape element (FREKOM 2002, Antipov et al 2004).

The resulting preliminary spatial landscape characterization was validated and refined by field observations along the Magistralny–Vershina Khandy road. Several key study sites, corresponding to landscape elements were selected to provide comprehensive field-based landscape characterization using drone imaging, soil erosion, permafrost, and vegetation surveys. Specific emphasis was made on identifying the environmental effects of informal roads. Results were used to compile a database containing qualitative (type of vegetation, landscape classification, soil, geomorphological conditions, paludification, permafrost, erosion, and other observed anthropogenic disturbances) and quantitative (height, steepness, and aspect of slopes, ground temperature) characteristics of landscape element. The database was used to produce a detailed, landscape map for the Vershina Khandy study area. The map distinguishes landscape elements differentiated by the hydrological regime, subsurface geology, geomorphic features, terrain characteristics, soils, and vegetation cover.
3.3. Social studies
Field studies to identify informal road users, and to characterize road impacts on humans and perceived environmental effects were conducted during the summer of 2019 in the village Vershina Khandy, Evenki summer camp, and along the Vershina Khandy—Magistralny road (figure 1). The members of the local communities were recruited for interviews using a snowball model with the purpose to examine a wide variability of experiences and knowledge of informal road use (Heckathorn 2011). The interviews were taken while going-along (traveling and engaging in local activities) and in the homes and/or camps of the respondents to capture the diversity of sensory experiences of local residents (Kusenbach 2003). Five focused semi-structured interviews of different lengths (from half an hour to two hours) with four males and one female, aged between 30 and 60 years old, were recorded, transcribed, and coded for analysis. The informants were asked about the location, history, use, maintenance, and environmental consequences of informal roads’ operations. The interviews were supplemented by participant observations, including travel by the informal roads, participation in daily activities, photographs, and personal experiences of the project team members in the study area.

3.4. Environmental impact and vulnerability assessment
The environmental impacts of informal roads were examined for landscapes along the Vershina Khandy—Magistralny road. Based on interviews with local residents and field observations, we have identified three most dynamic processes affecting landscapes, local subsistence, and mobility: (a) permafrost degradation; (b) surface erosion; and (c) wildfire-related disturbances. These negative environmental processes are very likely to be associated with the intensive use of the territory in proximity to roads leading to pronounced, irreversible impacts on landscape sustainability, especially in highly vulnerable geosystems (Antipov et al. 2004).

The landscape map developed for the study area was used to evaluate the vulnerability of landscape elements to major disturbances caused by informal roads. The landscape vulnerabilities to disturbance associated with permafrost degradation, erosion, and fire were classified into three categories: low, medium, and high. The level of permafrost vulnerability for each landscape element was assessed based on permafrost extent/continuity, temperature, ice content, disturbance of natural ground cover, and slope exposition. A combination of landscape-specific terrain characteristics (e.g. slope, aspect) and data on geologic structure and surficial deposits were used to evaluate vulnerability to erosion. The nature of the forest stand, wetness of the area, and depth to permafrost table determined the landscape vulnerability to fire. We also assessed the vulnerabilities of access to subsistence resources (Cold et al. 2020) and human mobility associated with each landscape using interviews and ethnographic materials from secondary sources (Ragulina 2000, Herman-Mercer et al. 2019).

4. Results
4.1. Informal roads in boreal forest landscapes
The predominant types of anthropogenic disturbance in the study area are logging, human-caused wildfires, road construction, and geophysical exploration. Most of the roads have an informal character (figure 1). The public roads for common use exist only in the north of the village with a highway going along the BAM railroad. The analysis of the road network showed that public roads have a length of

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Table 1. List of data and methods.

| Study area                | Data and methods                                      | Sources                                                                 |
|---------------------------|-------------------------------------------------------|------------------------------------------------------------------------|
| Vershina Khandy area      | Road inventory, use, and related challenges           | Interviews with local residents (summer 2019)                          |
|                           | Road inventory & landscapes                           | Landsat 8 (2017), GeoEye (2017), DigitalGlobe (2017), existing published materials (2002–2004) |
|                           | Geomorphology, permafrost                             | Topographic maps (1:100 000); Shuttle radar topographic mission (SRTM); Landsat 8 (2019); geological map (scale of 1: 200 000) (2009); hydrogeological map (Gidrogeologicheskaia 1990) |
| Road Vershina Khandy—Magistralny | Local road use                                       | Interviews while going-along, participant observation (summer 2019)   |
|                           | Road social and environmental impacts                 | Interviews with local residents (summer 2019)                          |
|                           | Road environmental impacts                            | Biogeophysical field observations: measurements of soil erosion, permafrost degradation, vegetation condition and drone imaging |
50.86 km or 12% of the total length of roads, and the informal roads stretch for 375.14 km or 88% of the total road length. The density of the public road network is 49.6 km/1000 km², while the density for all types of roads is 415.6 km per 1000 km², which is more than ten times higher than the regional average road density in the Irkutsk region (40.7%).

The study area is characterized with high probability of erosion, cryogenesis, and karst (Kuzmin and Lopatkin 2018). In particular, for roads on slopes and drainage divides there is a risk of erosion and mass wasting. Depending on slope steepness and aspect, this can be complicated by creep, solifluction, rockslides, landslides, and karst. We identified permafrost occurrences (figure 2) in wetlands associated with river valleys or basins, and on the north-facing slopes. There, frost cracking, ice wedging, ice segregation, and surface frost heaving are common. Permafrost degradation promoted by surface disturbance can cause the formation of negative forms of micro- and meso- relief due to subsidence and thermokarst (figure 2). The most valued by Evenki as a habitat for sable and resource for pine nut gathering cedar-spruce subshrub-green moss watersheds become more rare (figure 3). With wildfires, they are replaced by light coniferous or deciduous forests which are less valuable for the local communities.

4.2. Importance of roads for Vershina Khandy residents
Actively used road networks are associated with subsistence practices, local connectivities, and current industrial development. Based on the analysis of interviews with local residents, we distinguished the following subsistence activities mediated by informal roads: gathering wild plants for nutrition and medicinal purposes (pine nuts, berries, and herbs), as a source of energy (firewood), hunting and fishing for nutrition and medicinal purposes (moose, deer, badger, and fish), materials (fur animals for cash income), and groundwater, streams and lakes for water supply in respect to subsistence. Based on customary law and the Soviet planning system, the Evenki’s territory of traditional land use was divided between families into hunting plots. Each family usually has several hunting huts on those plots for accommodations during hunting seasons. For fishing, Evenki have a summer camp with permanent houses.

Connectivity with the towns of Magistralny and Kazachinckoie is important for all Evenki in the district. The village residents go to the towns for shopping, administrative functions, medical services, and for selling the products generated by subsistence activities. The Evenki from urban settlements use the informal Vershina Khandy—Magistralny road to visit relatives in the village and get to their hunting and fishing grounds.

Industrial activities, such as geological exploration, forestry, and natural gas extractive infrastructure development, affect the evolution of the local informal road system and its use. The industry users contribute to the expansion of the network and regulate access to certain road segments. They also utilize heavy vehicles and generate most of the traffic in proximity to their operations. In addition, these roads are travelled by recreational fishermen and hunters from other regions.

4.3. Vulnerability assessment of informal road impacted landscapes
Based on environmental and social studies we identified vulnerability levels to erosion, permafrost and wildfire activity (as leading drivers of disturbance) and of subsistence activities and human mobility (as the main subjects of concerns for local communities) in each landscape (figure 4). Vulnerability varied across the study area, but it is notable that most of the road networks fell within medium or high vulnerability categories in respect to permafrost (80.5%), erosion (87.8%) and wildfires (92.6%). 50.9% of all roads crossing landscapes are highly susceptible to permafrost degradation. Resultantly, local roads were
under considerable risk of being affected by hazards while boreal forest landscape demonstrated a potential exposure to road-induced environmental impacts.

Levels of vulnerability to different hazards sometimes contrast each other. In particular, the lowest vulnerability to erosion is detected in valleys dominated by larch, where the risks of permafrost degradation and wildfires are high. In most landscapes, fire risk is rated as medium because the vegetation has already been burnt or cleared by logging, while reforestation of these areas proceeds slowly forming sparse birch forests. Meanwhile, high wildfire vulnerability landscapes coincide with highly vulnerable subsistence resources, in particular in cedar-spruce subshrub-green moss watersheds. Wetland landscapes in valleys have high vulnerability to permafrost degradation and low vulnerability to wildfires due to abundance of water. These complexes are replaced by birch shrubs on waterlogged meadows of sedge and reed grass.

With the development of informal road networks there are various risks for vulnerable subsistence resources in different types of landscapes (supplementary table 1 (available online at stacks.iop.org/ERL/16/115001/mmedia)). Increased logging and fires due to road network development lead to shrinking subsistence resources and changes in wildlife habitats (figure 5(a)). In addition, seismic lines and forestry roads intersected with hunting trails create noise pollution, destroy or remove traps, and/or make hunting trails impassable (Illmeier and Krasnoshtanova 2021). Subsistence roads are increasingly used by outsiders that are blamed for depleting fish resources, littering, and poaching. The road dust along the gravel roads affect near-road vegetation and human health. Finally, local communities note increased occurrences of forest fires along informal roads used by recreational anglers and geological exploration workers.

Different regimes of access and methods of laying tracks have also disrupted local mobilities. The issue of access often depends on extractive companies policies and types of landscape. For instance, private forest companies arrange check-points to control access and protect the area from illegal logging and forest fires. At the same time, local mobility is vulnerable to landscape changes, especially due to erosion, permafrost degradation and wildfires (supplementary table 1). For example, boggy areas (supplementary table 1: 1, 2, 4, 5) prone to multitracking and paludification may be impassable for portions of the year (figure 5). The road width there can reach up to 100 meters.

4.4. Effects of informal roads on landscapes: Vershina Khandy-Magistralny transect case study

The village of Vershina Khandy has no official road connection. The existing informal road from Vershina Khandy to Magistralny (figure 1) plays an important role in providing connectivity between these settlements and is a characteristic example of an informal road in the study area. It is officially considered a winter route, however, even in winter it is not maintained by the local municipality due to the lack of funds. The road incorporates an old subsistence trail (7.2 km), an abandoned seismic line clearing (5.3 km), a road created by locals informally (4.0 km), a private forest road (18.4 km), and a public road to the town of Magistralny (4.7 km) (figure 6). In winter, it is accessible by any vehicles, while in summer only heavy off-road or light all-terrain vehicles can be used. The road traverses an
area with various levels of vulnerability to erosion and permafrost degradation which makes it suitable for more detailed studies of landscape sustainability (supplementary table 1).

Nearly two thirds of the area adjacent to the road have secondary birch forbs, with larch and spruce-larch moss forests in the background (figure 6). The affected area increases with growing vehicular use. Artificial surfacing appears to limit the anthropogenic impact on the landscapes.

The slopes of different steepness are prone to erosion. Erosion is observed on the road surface where slope steepness reached 10°. In 8 km from the village road runs over permafrost-affected wetland where paludification, and subsidence of soils take place. The moss cover is supplanted by sedges and reed grass. Erosion of the riverbanks is evident where the road crosses streams.

The road segment with gravel surfacing consists of a forest road maintained by the forest managing company tenant and the public road maintained by municipality (figure 6). Forestry companies are major users of this segment: logging and lumber transportation takes place along the road. Despite intensive use, no major impacts on relief are observed along the road: the footprint is determined by the initial width of the paved road and its shoulder (up to 20 m).

5. Discussion

The landscape scale is where the impact of transporta-
tion infrastructural development on social-ecological systems is the most prominent (Wu 2013). The studies of specific landscape components most sensitive to disturbances associated with the road network development and use are instrumental for understanding impact and potential vulnerability of affected social-ecological systems.

Our study confirms a strong relationship between infrastructure development and landscape change. First, geomorphic change is manifested by surface erosion and permafrost degradation in boreal forest landscapes (Walker and Peirce 2015, Sofia et al 2016). Second, there are significant changes in vegetation composition in the study area. Native dark coniferous forests are disturbed by cutting, logging or human-caused fires associated with these roads, and being replaced by larch, pine-larch and larch-pine fruticulose-green moss forests. As such, the informal road network exacerbates the replacement of primary forests with the secondary ones in different stages of succession.

In addition, informal road network development negatively affects ecosystem services. Interviewees mostly draw attention to the roads’ impact on subsis-
tence resources (pine nuts, berries, and herbs gathering). Roads also altered wildlife habitats and provided better access to some animals and fish species while imposing access barriers to others. The road-related loss of regulation and maintenance services, such as surface erosion and permafrost degradation was observed. However, similarly to existing research (e.g. Hatton MacDonald et al 2013), these impacts were mentioned less frequently by local residents. Although road dust can have significant biological and geomorphic influences on landscape (e.g. Walker and Everett 1987, Myers-Smith et al 2006) more studies are needed to understand its effect in boreal settings. The indirect impacts are related to development of extractive industries along informal roads, which could be part of benefit-sharing agreements. Affected by industrial development, fragmented landscapes provide less subsistence resources (Kivinen et al 2012). Increase in landscape disturbance negatively affects subsistence activities and may cause the loss of traditional ecological knowledge and spiritual
value of non-human beings. Therefore, the issues of informal roads network development have similarities with Amazon forest unofficial roads (Barber et al. 2014, Arima et al. 2015) as well as with the Arctic winter roads networks (Ibisch et al. 2016). The effects extend beyond the initial disturbance with the use of these roads for mobility by diverse users.

While the level of vulnerability to anthropogenic impacts is already high in the boreal forest (Reynolds and Tenhunen 1996, Wulder et al. 2011, 2014, Hermosilla et al. 2019) the informal roads network development may exacerbate landscape disturbance due to additional stress imposed by increased human activity and regional climate change.

In particular, most roads examined in this study traverse landscapes characterized by high and/or medium level of vulnerability. As a result, the roads are subjected to increased natural hazards risks and contribute to further landscape disturbance. This creates a challenging situation when the functioning of both natural and technological is adversely affected. With the impending construction of the Power of Siberia Pipeline the impact on local landscapes will be exacerbated by the more intensive use of existing roads and by road network expansion.

6. Conclusions

Although the impacts of the transportation infrastructure, and informal roads in particular, are rarely considered, this study provides evidence of substantial and multifaceted effects these networks exert on social-ecological systems and landscape sustainability and serve the major drivers of boreal forest degradation.

The expansion of the informal road network can be considered an indirect consequence of industrial development in the region because it follows and extends the life of the industrial road system that otherwise would have had temporary character. The social-ecological impact of these roads is not limited to extractive industry operations since roads are used by local residents and recreational travellers. Meanwhile, the effects on subsistence activities and mobility vary across different landscapes.

This study indicates that informal roads play an important role in transforming boreal forest landscapes, and this influence will likely increase due to the expansion of industry operations in Siberian boreal forests and be further exacerbated by climate change. Yet these impacts are difficult to assess due to the lack of official data (and they are not typically included in Environmental Impacts Assessments of industrial projects and in government development plans). Therefore, as demonstrated by this study, meaningful collaboration between researchers and local and Indigenous communities provides an opportunity to develop a comprehensive and detailed understanding of complex boreal forest social-ecological-technological systems.

Further research involving extensive data collection using high-resolution remote sensing, field observations and community-based work is required to advance our knowledge of the social-ecological systems changes inflicted by sprawling informal transportation networks. Also there is a need to consider technological domains, such as maintenance practices, road surface character, and use of different vehicles that affect social-ecological systems, their adaptation and resilience.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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