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Combining community observations and remote sensing to examine the effects of roads on wildfires in the East Siberian boreal forest

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Abstract

The paper is aimed at assessing the associations between the road networks geography and dynamics of wildfire events in the East Siberian boreal forest. We examined the relationship between the function of roads, their use, and management and the wildfire ignition, propagation, and termination during the catastrophic fire season of 2016 in the Irkutsk Region of Russia. Document analysis and interviews were utilized to identify main forest users and road infrastructure functional types and examine wildfire management practices. We combined community observations and satellite remotely sensed data to assess relationships between the location, extent, and timing of wildfires and different types of roads as fire sources, barriers, and suppression access points. Our study confirms a strong spatial relationship between the wildfire ignition points and roads differentiated by their types with the highest probability of fire ignition near forestry roads and the lowest near subsistence roads. Roads also play an important role in wildfire suppression, working as both physical barriers and access points for firefighters. Our research illustrates the importance of local and Indigenous observations along the roads for monitoring and understanding wildfires, including "zombie fires". It also has practical implications for fire management collectively developed by authorities and local communities.

Key words: wildfires, Siberia, boreal forest, community observations, remote sensing

1. Introduction

Wildfires are one of the main vegetation disturbance agents globally, and forests in particular (Thonicke et al. 2001). The effects of forest fires, such as a decrease in air quality, are observed far beyond the forest regions (Kharuk et al. 2021). While fires are natural to forest ecosystems, excessive burning, and particularly human-caused wildfires, disrupts provision of ecosystem services and exacerbates climate change by transforming carbon cycling and storage (Mack et al. 2011; Pan et al. 2011; Gibson et al. 2018; Chen et al. 2021). Meanwhile, with climate change there is an increase of wildfires in the Arctic and boreal forest (taiga) in terms of both spatio-temporal extent and intensity (Kasischke et al. 1995; Flannigan et al. 2009; Kelly et al. 2013; Aponte et al. 2016; Wotton et al. 2017; Masrur et al. 2018). In particular, Siberian boreal forest wildfires became an important topic in global scientific discussions in recent years due to their large scale and linkages to globally and regionally critical environmental changes (Mack et al. 2021).

Usually, up to 90% wildfires in the boreal forest and tundra are attributed to lightning strikes (Veraverbeke et al. 2017; Kharuk et al. 2021), while anthropogenic impact is considered a relatively minor cause (Coogan et al. 2020), although its role often increases with the expansion of human activity in forests (Kasischke and Turetsky 2006; Campos-Ruiz et al. 2018). Yet, a significant knowledge gap remains in understanding human-induced wildfires as manifestations of disruptions in human–nature relations mediated by infrastructure development. Meanwhile, the expanding infrastructure development in the Arctic and subarctic regions has uncertain environmental, economic, and cultural implications (Raynolds et al. 2013; Walker and Peirce 2015; Schweitzer et al. 2017).

Siberia is well suited for examining the role of road infrastructure in boreal forest wildfire dynamics because of its vast forest cover, a variety of human activities, and rapidly increasing infrastructure presence due to growing extractive industry. There is evidence of existing effects of infrastructure on boreal forest wildfires ignition, propagation, and suppression as probability of a fire has been found to have strong correlations with human infrastructure and associated activities (Nami et al. 2018). Moreover, among different forms of infrastructure researchers noted a higher role of human transportation networks than human settlement in fire ignition regime (Gralewicz et al. 2012). In the boreal forest, road networks are formed by a variety of road types, most prominently forestry roads and subsistence trails. In addition, linear clearings that accompany extractive industrial development can also serve as local roadways and as such become the major component of infrastructure (Kuklina et al. 2020). Most roads in the forest are *informal*, i.e., not actively maintained or governed by the state, but rather controlled and managed by private parties (such as forest companies) or local communities.

A more detailed analysis of correlations between different forms of anthropogenic features and thermal anomalies by Kovacs et al. (2004) found the strongest relationship between forest fires and proximity to roads, followed by the proximity to railroads and settlements in Central Siberia. Recent studies of infrastructure and wildfires revealed a linear relationship between the density of forest roads and the density of wildfires in the Irkutsk Region's forest management units (*lesnichestva*) (Boldanova et al. 2017). An increase in wildfire occurrences was also observed near logging sites (Pavlichenko 2017). Moreover, there is evidence that wildfire activity has been exacerbated by illegal logging (Kukavskaya et al. 2013). Deforestation related to mining and logging operations also causes changes in natural fire regimes (Kirillina et al. 2020).

Researchers identified a higher level of the land disturbance and metal structures erected along the roads as contributing factors to lightning-caused fire ignitions (Ivanov et al. 2009; Arienti et al. 2010). In addition, specific biophysical conditions in the near-road areas also contribute to faster spread of fire than in the surrounding area (Ivanov and Moskalchenko 2012).

At the same time, availability of road networks is also important for fire suppression as it allows firefighting teams access to the burning areas. The absence of roads leads to a response failure and fire propagation over larger areas (Arienti et al. 2011; Boldanova et al. 2017). While in the Soviet times the problem of access was solved by the world's largest aerial firefighting system (Pyne 2012), currently the lack of funding increases the reliance on ground transportation for fire extinguishing (Podolskaia et al. 2020). It means that fires in the areas inaccessible by ground transportation are suppressed only if they are in the vicinity of villages and infrastructure.

Understanding wildfire origin and dynamics represents a "wicked problem" that requires multidisciplinary research efforts (Chapin et al. 2008). Local and Indigenous knowledge is crucial for understanding place-based specifics of wildfire biographies: ignition, expansion, and termination, and providing valuable lessons on wildfire governance (Rutherford and Schultz 2019; Roos et al. 2021). Indigenous people and non-Indigenous old settlers are known for protecting forests from wildfires (Kharuk et al. 2021). For example, according to Evenki epistemology, wildfires are provoked by the forest itself addressing the need of the main spirit of natural environment Buya regeneration (Lavrillier and Gabyshev 2017). Moreover, each fire, even the one in the stove, has their own spirits, whom Evenki feed by offering food before meals. Science–Indigenous knowledge collaboration through community-engaged participatory research is needed for wildfire prevention and mitigation (Tymstra et al. 2020). However, there is still a lack of knowledge about co-production between researchers and local and Indigenous communities in Siberia wildfire studies.

Collaboration with local and Indigenous communities is especially important for studies of underground smoldering ("overwintering") fires that are difficult to detect using traditional remote sensing methods and often require additional ground truthing to be captured (McCarty et al. 2020; Scholten et al. 2021). Yet, they may constitute a large share of wildfire activity in some years (e.g., up to $\frac{1}{3}$ of boreal forest fires in 2015 (York and Jandt 2019)), and likely to become more common as climate changes (Irannezhad et al. 2020). That is where the local and Indigenous knowledge is becoming the most useful. Observations by Indigenous peoples, local hunters, and other residents become instrumental in detecting and describing these phenomena.

The goal of this paper is to assess the associations between wildfire ignition, propagation, and termination and informal road network geography in the East Siberian boreal forest. In particular, we focus on the catastrophic fire season of 2016 (Ministry of Natural Resources and Environment of the Irkutsk Region 2021) when the wildfires affected an exceptionally large area in the Irkutsk Region.

We hypothesize that there is a relationship between the function of roads, their use, management, and access regime on one hand, and wildfire ignition, propagation, and termination (either active or passive), on the other. To collect evidence in favor or against this hypothesis, we pursue the following objectives:

1) identify main forest users and road infrastructure functional types in the study area;
2) examine wildfire management practices of the forest users;
3) use remote sensing data to detect wildfire characteristics, including ignition location, propagation, and termination in 2016;
4) use community observations and remotely sensed data to assess the relationship between the location, extent, and timing of wildfires and different types of roads as fire sources, barriers, and suppression access points.

2. Materials and methods

2.1. Study area and communities

Our study area is in eastern Siberia. It covers 2.4 million ha and has a lot in common with other Arctic and subarctic regions, such as harsh climatic conditions, prevalence of permafrost, isolation, presence of traditional Indigenous cultures and land use practices, and high economic dependence on extractive industries. The mean annual temperature ranges between −3.3 °C and −3.5 °C (Ludi 2008). The winter lasts from October to May with the average January temperature around −35 °C. Winter temperatures below −50 °C are common, and annual precipitation is low (300–400 mm/year). The area is dominated by the Siberian boreal forest (taiga). It is located at the boundary between continuous and discontinuous permafrost zones and exhibits a complex pattern of permafrost conditions. In recent years, the area has been affected by the increased wildfire activity observed across many Siberian boreal forest regions (Kirillina et al. 2020).

The study area is sparsely populated with only two villages in the entire study region: Tokma and Verkhnemarkovo. It is the homeland for Evenki, Indigenous people reliant on subsistence activities such as hunting, fishing, and gathering. In the village of Tokma, population is estimated at 54 people and consists of Evenki and Russian "old settlers". The population of Verkhnemarkovo is about 2000, mostly Russians, but there are also representatives of other ethnicities from different parts of the former Soviet Union who came here in the Soviet period to work in the oil and gas industry. There is a small Evenki population.

2.2. Methods

In our research, we applied a transdisciplinary community-engaged participatory methodology (Alexander et al. 2011) by combining methods of social research (interviews and observations) with the analysis of remote sensing data to obtain comprehensive and nuanced information about wildfires. Integrating community data and remote sensing presents an opportunity to triangulate and contextualize information and thus produces new insights into the relationship between human activity (roads) and taiga fires. The research was conducted in continuous collaboration with local and Indigenous communities and stakeholders in the village Tokma, from the very beginning of the study. Importantly, the topic of this research was chosen based on local concerns that communities expressed to the authors, and research objectives were developed with the community input. Community engagement was maintained at all stages of the study. One of the authors has been a community member and scholar and served as a project liaison.

To understand wildfire management practices in the study area, first, we examined documentation describing rules and regulations on wildfire prevention, monitoring, and suppression by federal, regional, and municipal authorities as well as existing information on wildfire management practices by private companies. We also collected data for the Tokma weather station from the rp5.ru website to provide a context of weather conditions during the wildfires.

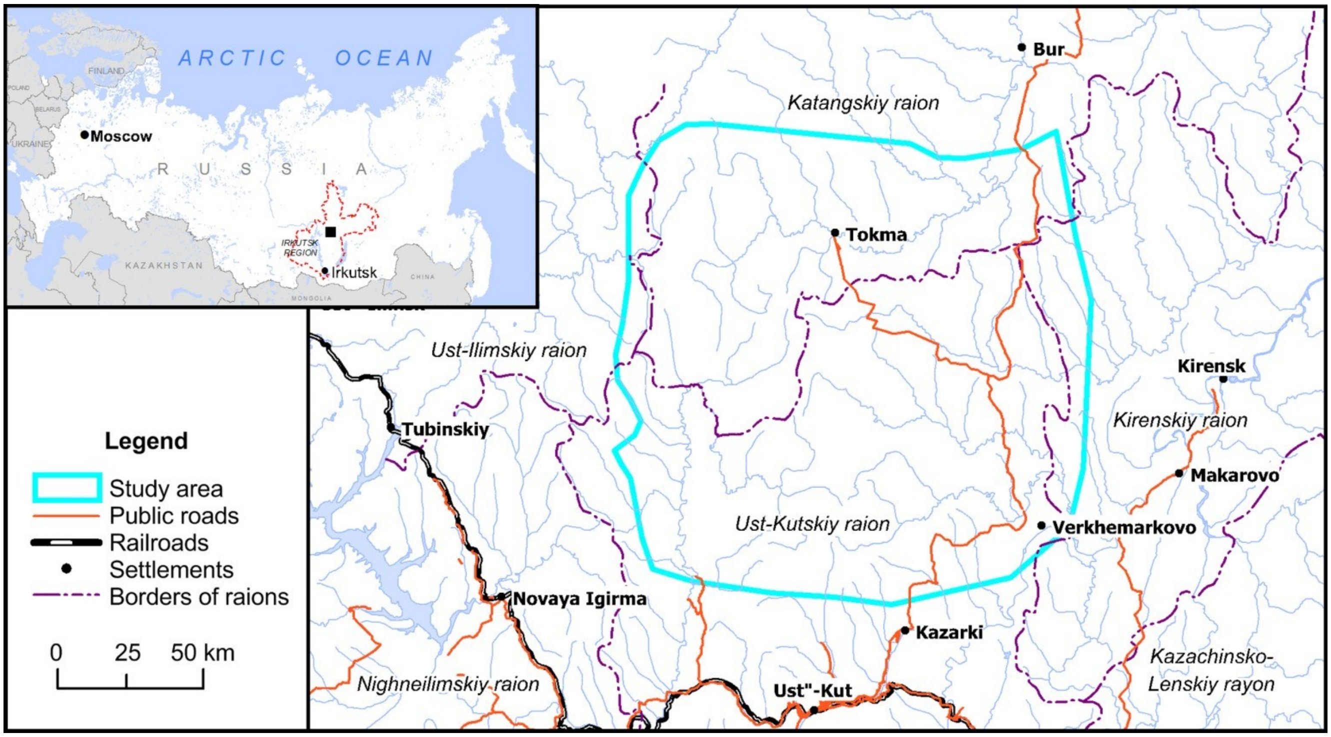
Interviews with local residents formed a major source of information for gathering community observations and concerns. In particular, witness accounts of wildfires were obtained from interviews and observations collected in 2016 (18 recorded interviews with diverse local residents) and 2018 (one recorded interview with a hunter and two unrecorded conversations with hunters). The in-depth interviews, specifically focused on informal road network development and its impact on the environment, including wildfires, were collected in 2020 and included nine interviews with local community members. In addition, we used participant observations travelling by roads in winter. Based on interviews, we distinguished three main areas of local concerns pertaining to wildfires: road network development as a source of fire ignition, road impact of wildfire spread, and roads as barriers for wildfires. We focused on the fire season of 2016, when local residents observed the most destructive wildfires in the area.

In addition to these interviews, information on wildfire control practices along informal roads and further details about wildfire propagation and barriers were supplemented in 2021 by phone conversations with two local hunters and representatives of a forest company and an oil company. These conversations were used to solicit feedback on remotely sensed data analysis (see below), in particular to contextualize remotely sensed observations and identify potential relationships between roads and fire ignition and propagation. We discussed remote sensing data with local residents and solicited community feedback on our initial findings.

We created a 2016 map of roads that includes location, road type and function, and access regimes. The road functions encompass subsistence roads, geological roads (linear clearings of trees and vegetation to allow vehicles driving down the lines and putting explosives in the ground to examine oil and gas underground), forest, and oil service roads. By access regime the roads vary from public access (subsistence and public roads), roads with monitored access (public and private forest roads), and roads with restricted access (oil service roads). To create this map, we used a combination of medium- and high-resolution satellite imagery (Landsat, Sentinel, DigitalGlobe), topographic maps, infrastructure development planning documents (Ministry of Economic Development 2020), and the data from the interviews. We manually digitized roads using the ArcGIS software. We calculated the length of each type of road.

For detecting wildfire characteristics, extent, and timing during the 2016 season, we used several remote sensing sources and methods. First, we located active fires using data on thermal anomalies from Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) imagery (Justice et al. 2002; Schroeder et al. 2014; Giglio et al. 2016). The archived data from these images were obtained from NASA's Fire Information for Resource Management System (FIRMS) (https://earthdata.nasa.gov/firms), part of NASA's Earth Observing System Data and Information System (EarthData 2021; Fire Information for Resource Management System 2021). The data were documented in a point-based vector data format (i.e., shapefile) with information on fire occurrence, fire location, the logical criteria used for the fire selection, detection confidence, fire radiative power (FRP), and numerous other layers describing fire pixel attributes. These data were aggregated by dates and locations for the detection of the ignition points' location and timing. The FRP information was used to determine the fire intensity (Wooster et al. 2003). We manually removed gas flares that take place in the oil production sites as they have stable temperatures and locations in contrast with wildfires. We estimated the burned area extent of each wildfire using object-based image analysis (OBIA) methods based on Sentinel-2 and Landsat-8 data. Sentinel-2 and Landsat-8 data, having spectral channels in the mid-infrared range, accurately reflect the burned areas (Quintano et al. 2018). OBIA methods provide a more reliable and realistic border compared to pixel classification methods (Blaschke 2010; Sizov

Fig. 1. Study area (created using the ArcGIS software with basemap from ESRI (projection WGS84/UTM48N)).



et al. 2020*a*, 2020*b*). The web service Sentinel Playground was used to search for archived cloudless and snowless images (Sentinel Hub 2021). During the search, the images were obtained for the period preceding ignition, during the wildfires, and after the wildfires have ended. We downloaded selected images within the boundaries of the extent of each burned area using the GoogleEarthEngine geo-platform, which contains the complete archives of the Sentinel-2 (S2) and Landsat-8 (L8) surveys available for analysis and processing (Earth Engine Data Catalog 2021*a* (Sentinel-2) and Earth Engine Data Catalog 2021*b* (USGS)). A significant advantage over the Copernicus Open Access Hub (ESA) service is that all datasets are available online (Copernicus 2021). For each scene, all multispectral channels of processing level 2A (CEOS) were downloaded in GeoTiff (16 bit) format with the original spatial resolution (10 m/S2; 30 m/L8) in the UTM48N (WGS84) projection.

To obtain the boundary of each burned area, we used segmentation of the corresponding S2 image (the closest in date to the end of the fire) using the Large-Scale MeanShift tool with the 50-pixel minimal size of the segment in the open OrfeoToolbox 7.0.0 software (Orfeo ToolBox 2021). The tool is based on the MeanShift algorithm, which is sensitive to spatial resolution and adapted for processing volumetric rasters (Comaniciu and Meer 2002). From the resulting vector line layer, a spatial sampling of segments was carried out based on comparison with points of thermal anomalies from FIRMS products, a synthesized image using medium IR channels, and the NBR index (Normalized Burn Ratio). Segment selection was performed using spatial queries and visually in manual mode using the ArcGIS software. In some cases, manual editing of segment boundaries was carried out, mainly in terms of their division into smaller fragments and removal of areas with preserved vegetation within the burned area.

To determine the role of roads as barriers for wildfires and its variation by road type, we identified the share of roads as the terminal boundaries of the wildfires (burned areas). In addition, for each burned area we analyzed distance from ignition locations to different road types and length of wildfire boundaries formed by different types of roads.

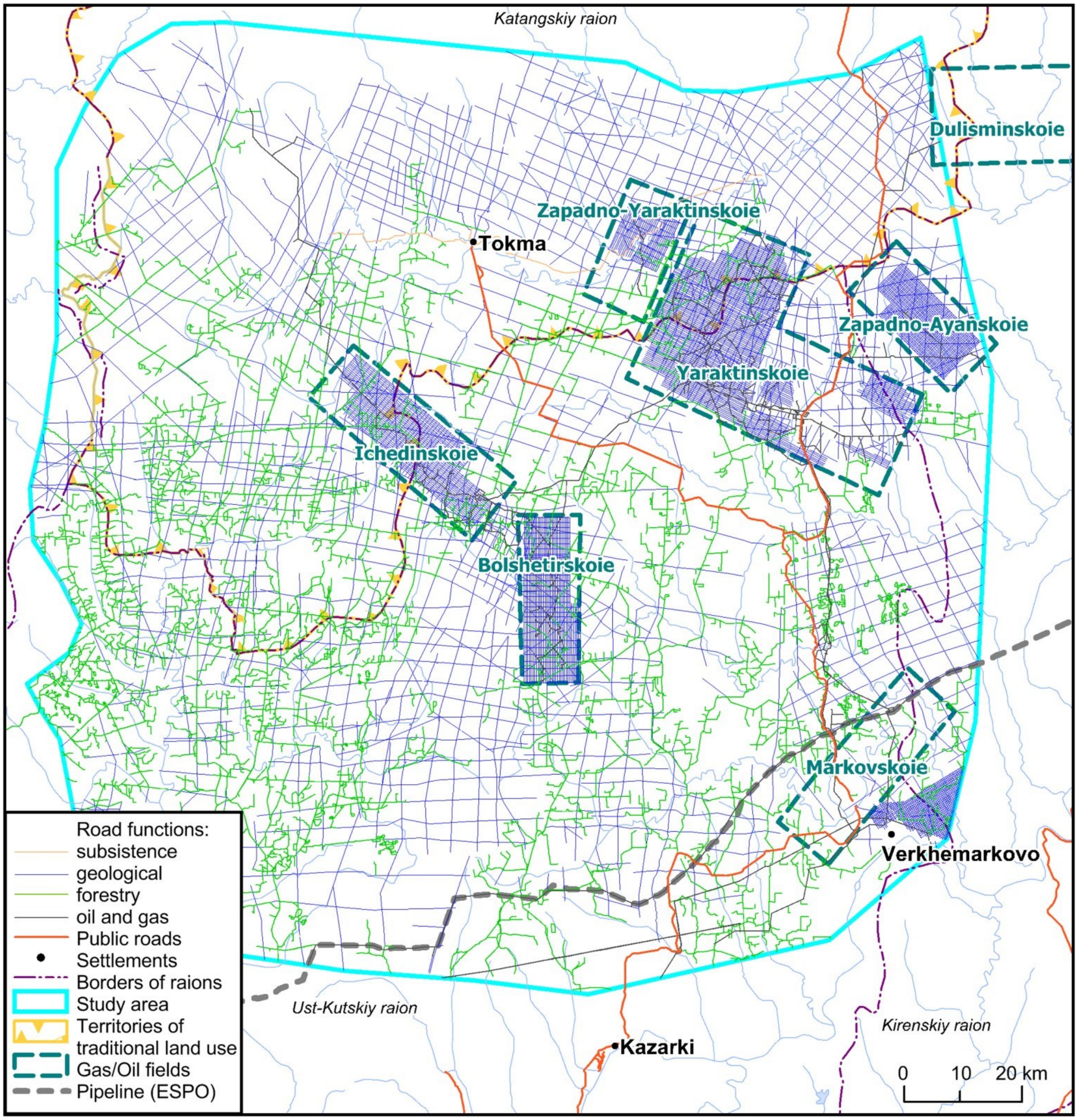
3. Results

3.1. Main forest users and road infrastructure in the study area

According to the official estimates, the study area has sparse infrastructure development with the density of public roads only 16.2 km per 1000 square km. The village of Tokma has seasonal transportation access by an official 100 km-long municipal winter road connecting the village with the federal winter road “Mirninskii” (Fig. 1). However, the region is experiencing a boom of extractive industrial development (oil and forestry), which significantly changed the landscapes by developing new infrastructure, including informal roads (Kuklina et al. 2020). To cope with the lack of public infrastructure, each of the forest users developed a distinct system of roadways that co-exist in space and may overlap, although such overlappings are rare. While most informal roads have seasonal character, they can be used year round by all-terrain vehicles (Fig. 2).

The subsistence forest use by Tokma villagers is mostly controlled by an *obshchina* (a noncommercial organization formed by Indigenous and other local residents for conducting traditional subsistence activities) with 1.7 mil-

Fig. 2. Road network by type (created using the ArcGIS software with basemap from ESRI (projection WGS84/UTM48N)).



lion hectares of land (Fig. 2) allocated for traditional use (e.g., hunting, fishing, and gathering). This land is composed of hunting plots managed by 20 hunters from Tokma and 33 hunters from the neighboring Evenki village of Bur. The hunting plots are connected by the system of subsistence trails that have widths of 2–6 m. In Verkhnemarkovo, hunting plots are managed by the local branch of the Irkutsk regional public organization of hunters and fishermen.

Geological exploration has been present in the area since the 1960s. The traditionally used territories around the villages have been explored by applying the 2D seismic reflection method that requires straight clearings to create roads every 4–5 km for heavy machinery along which the testing is carried out. The first oil and gas field in Eastern Siberia was discovered near the village of Markovo in 1962, and therefore received the name Markovskoye. To develop this field, the village of Verkhnemarkovo was formed on the opposite bank of the Lena River and large-scale exploration work began in this area (Saxinger et al. 2018). In the 1970s near the territory of traditional land use of Tokma residents, geologists discovered the Yaraktinskoie oil deposit (Irkutsk Oil Company 2019). Currently, geological exploration is conducted by 3D seismic reflection methods, under which the seismic lines form grids with cells 150–300 m wide. The width of seismic clearings is 4–6 m. Currently, hundreds of workers of geological exploration companies conduct geophysical line clearings in the study area.

Forestry followed geological exploration: the Forest State Service and later private forestry companies have made use of abandoned seismic lines adding their own forestry roads. In the 1980s, the forest industry started to develop near Tokma. At the end of the 2000s, the forest lands were rented by Transsiberian Forest Company (TSLK). Nowadays, the names of renting forest companies are constantly changing; however, local residents believe that the owners are the same people avoiding taxation (Illmeier and Krasnoshtanova 2021). The forest near Verkhnemarkovo is rented by BEKoil-Igirma Ltd. Private forest companies, while renting land, are required to make use of already existing infrastructure and, if needed, develop their own roads. They arrange checkpoints to monitor road access and protect the area from illegal logging and forest fires. According to the rules of design and construction, forest roads have a width of 6.5–10.5 m (Ministry of Construction and Housing and Communal Services of the Russian Federation 2016).

Oil and gas extraction in the study area is conducted by the Irkutsk Oil Company (INK) that has been developing its own infrastructure (pipelines, drilling sites, access and service roads) for oil exploration on the Yaraktinskoie, Ichedinskoie, Zapadno-Yaraktinskoie oil deposits spanning across hunting areas near Tokma. The East Siberia–Pacific Ocean oil pipeline construction in 2006 accelerated the oil extraction and included the construction of new power gridlines, more geological exploration, and modernization of the nearby Baikal–Amur railroad. Oil exploration and extraction are carried out by the fly-in fly-out method with thousands of employees based in the shift work camp of Yaraktinskoie (40 km from Tokma) that has been the largest oil exploration site of the company. The width of oil and gas industrial roads varies between 4 and 20 m. These roads have restricted access, and can be used only with the permission from the corporate office.

3.2. Wildfire management practices

Almost all forest in Russia is state property governed by the Ministry of Natural Resources and Environment through the Federal Forestry Agency (FFA). In the Irkutsk Region, the FFA is represented by the regional Ministry of Forestry that includes 37 forest districts managed by forestries (*lesnichestvo*). Fire suppression plans are being developed for each forestry district (Kirillina et al. 2020). The wildfire management coordination between forestries is carried out by the Department of Forest Protection of the Irkutsk regional Ministry of Forestry. The department also establishes the timing of the wildfire hazard period, bans or restricts public access to the forests during that period, and drafts consolidated plans for suppressing wildfires in the region. Forestries are responsible for maintaining forest roads for fighting fires, arranging and maintaining firelines, detecting fires and extinguishing them using ground-based means, and installing stands and signs containing information on fire safety (Forestry Agency of the Irkutsk Region 2008). Extinguishing wildfires using aircraft, monitoring fire hazards, and implementing wildfire-prevention measures are carried out by the Irkutsk Aerial Forest Protection Service (*Avialesookhrana*). The Avialesookhrana is responsible for monitoring the fire situation using airborne technologies, receiving and recording messages about forest fires from different sources, sending alerts to population and firefighting services, and giving an operational assessment of the fire dangers in weather conditions and actual forest fires (Federal Forestry Agency 2011; Federal Forestry Agency 2021*a* (Control Zones); Federal Forestry Agency 2021*b* (FBU Avialesookhrana)). The southern part of the study area is located in the zone where both air survey and satellite monitoring of wildfire are implemented, and the northern part is the area where authorities conduct only satellite monitoring unless wildfires threaten settlements and (or) important infrastructure (Forestry Agency of the Irkutsk Region 2008).

Any organization or an individual operating in the boreal forest has to rent forested lots from the Federal Forest Fund. According to the current legislation, each owner and tenant maintain their means for preventing and suppressing wildfires. Forest users are obliged to maintain wildfire safety, which includes fire prevention, monitoring, and development of the wildfire response plans (; Government of the Russian Federation 2020*a*). If a wildfire is detected, tenants must immediately report this to a specialized dispatching service and take all possible measures to prevent the spread of a wildfire. If they fail to act, they could face administrative and civil liability for the damage caused to the forests. Also, lease agreements with these users may be terminated by the government.

The main challenges arise with situations when one forest plot is rented out to different users for different types of forest use, e.g., leased concurrently for timber harvesting, construction and operation of power, communication and pipelines, oil extraction, and hunting (Forestry Agency of the Irkutsk Region 2020). The current legislation does not determine the division of responsibility for wildfire safety measures between different tenants. In this case, informal agreements apply. As a private forestry company worker explained:

> *"We are not a specialized firefighting company, we do not have to extinguish, but only prevent the spread of wildfire, although when we can we also do extinguishing. There are no signed agreements between forestry and oil companies. In the event of a wildfire on the territory, oil workers directly contact the local responsible for monitoring wildfires lesnichestvo. Oil company workers are engaged in preventing the spread of fire only in case of a threat to their production facilities. Although there was a case when oil workers came to help us, the support was informal, outside the documents, since they do not want unnecessary problems that next time they will be called again to extinguish/prevent a wildfire. In cases of large wildfires, the lesnichestvo asks for help in extinguishing, and we help. There are talks about compensation for expenses, but it is unlikely, we do everything at our own expense"* (male, 40, Novaya Igirma, 31 March 2021).

The Irkutsk Oil Company (INK) has also participated in monitoring and extinguishing wildfires on the rented and adjacent territories when the extent of wildfires was especially high (Irkutsk Oil Company 2016, 2017, 2019). How-

Table 1. Characteristics of wildfires observed in 2016 in the study area based on satellite data (FIRMS).

ID	Area, square km	Period of burning	Duration of fire days	Cumulative fire radiative power (FRP), MW	Max FRP in a single day, MW
T2016_01	555.46	09/05–09/28	24	281 831	87 066
T2016_02	249.56	07/15–08/18; 08/30–09/28; 09/07–09/28	63	199 699	23 260
T2016_03	257.45	07/22–08/19; 08/29–08/30; 09/04–09/28	53	73 780	15 351
T2016_04	13.17	08/06–09/28	30	3636	558
T2016_05	64.76	09/07–09/28	20	11 390	3833
T2016_06	27.65	09/07–09/28	21	5153	2282
T2016_07	1427.36	06/10–07/09; 07/15–08/08; 08/15–08/22; 09/05–09/28	82	402 926	62 962
T2016_08	576.74	07/01–08/08; 15/08–09/28; 10/19–10/25	66	224 174	59 087
T2016_09	565.17	07/15–08/09; 14/08–09/28	61	275 776	87 893
T2016_10	359.40	07/20–08/23; 08/29–09/28	57	133 707	36 013
T2016_11	319.56	07/20–08/08; 15/08–09/28	51	85 298	33 236
T2016_12	111.03	07/25–08/08; 09/09–09/28	27	14 220	4023
T2016_13	0.86	06/28–06/29	2	78	51
T2016_14	152.79	07/24–08/08; 08/16–08/19; 08/29–09/28	46	47 538	15 061
T2016_15	29.92	07/02–07/03; 07/26–08/08; 08/16–08/19; 09/06–09/27	31	6650	2882
T2016_16	3.42	07/22–07/25; 09/14–09/27	14	1106	322
T2016_17	0.79	06/24–06/28	3	17	14
T2016_18	0.61	09/27–09/28	2	43	23
T2016_19	8.59	09/14–09/27	7	5096	2524
T2016_20	29.08	09/13–09/28	10	20 099	10 528
T2016_21	1.93	07/20–07/27	7	213	156
All 2016	4755.31	06/10–10/25	104	1792 429	374 581

ever, these efforts do not have a systemic or coordinated nature.

3.3. The fire season of 2016

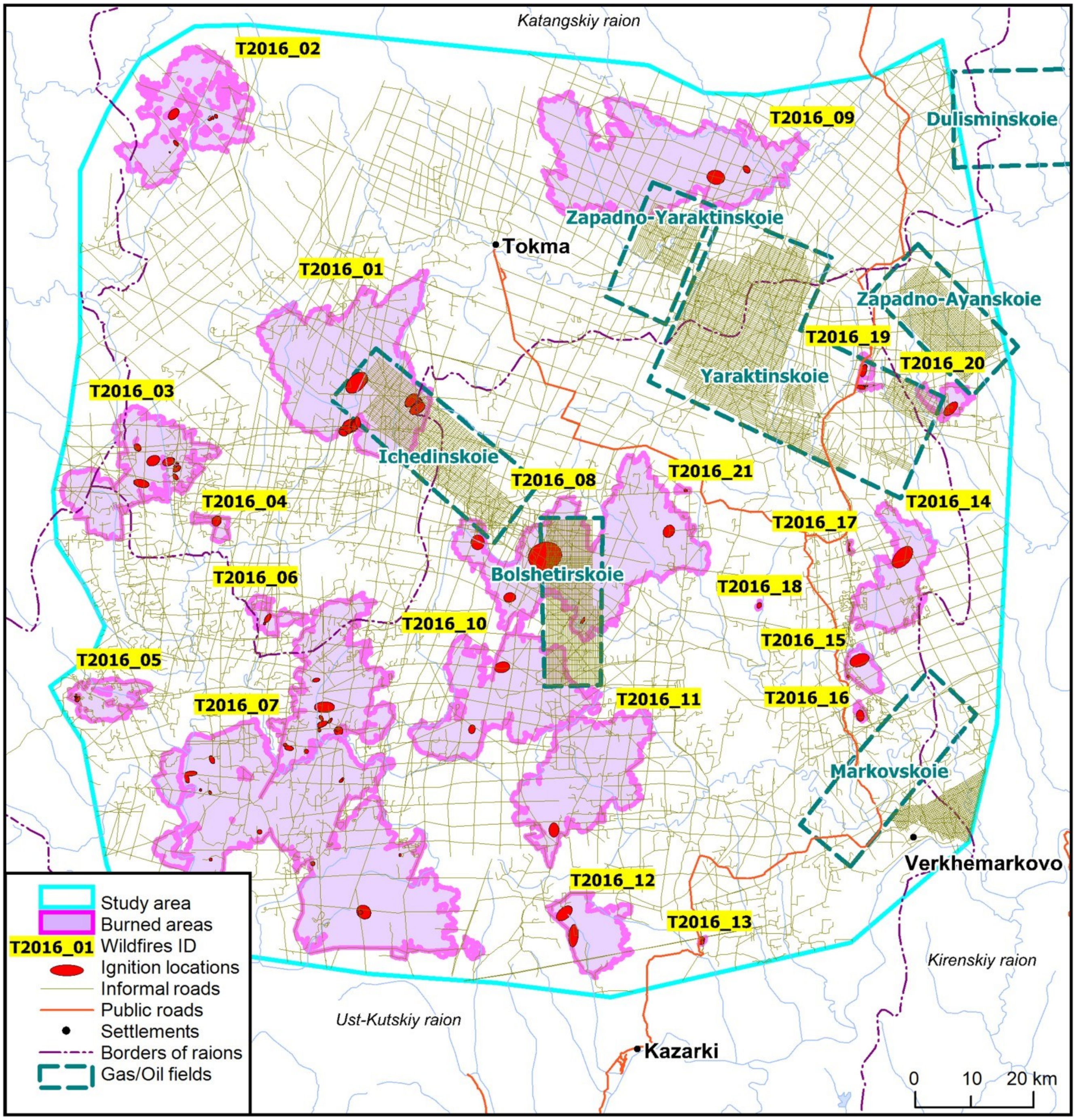
The fire season of 2016 was one of the most damaging in East Siberia boreal forest in recent years (Ministry of Natural Resources and Environment of the Irkutsk Region 2021). The fire hazard period, when thermal anomalies were recorded, lasted from 10 June to 25 October 2016 (a total of 104 days). In our study region, 21 burned areas were identified and mapped, with a total area of 475 531 ha (Table 1). Thus, the wildfires consumed 20.1% of the entire study area in just one season (Fig. 3).

Comparing the interviews with the data from MODIS and VIIRS, we identified wildfire hotspots in 2016 and found that the cumulative FRP in the 2016 fire season was the highest in the last 20 years (Fig. 4). Higher FRP corresponds to more intensive fires. Although the cumulative FRP values did not exhibit a similar trend with temperature anomaly values at the Tokma weather station, the analysis of precipitation detected a strong correspondence between negative precipitation anomalies and high FRP. In the last 20 years, the driest conditions were observed in 2016 when the cumulative FRP was also the highest in the study area (Fig. 4).

3.4. Roads, ignition locations, and wildfire boundaries

While forest wildfire propagation is significantly determined by weather conditions, landscape characteristics, and accessibility of the area for fire suppression, there is also evidence of the significant role of the informal roads. According to the interviewees, the activity of outsiders (nonlocals) who use the roads was the main cause of forest fires. Wildfires have been one of the consequences of forest logging, oil extraction, and infrastructure development damaging local subsistence resources and natural habitats of game animals. There was also a strong community perception of an existing link between the practices of forestry companies to burn unwanted wood in early spring (March–April) and wildfires. This practice has been promoted by federal regulations requiring forestry companies to clear logging sites (Ministry of Natural Resources and Environment of the Russian Federation 2016; Forest Code of the Russian Federation 2020; Government of the Russian Federation 2020*a*). In particular, the locals pointed to a specific wildfire that started in May 2016 near such burning

Fig. 3. Areas burned in 2016 and informal road networks in the study area (created using the ArcGIS software with basemap from ESRI (projection WGS84/UTM48N)).



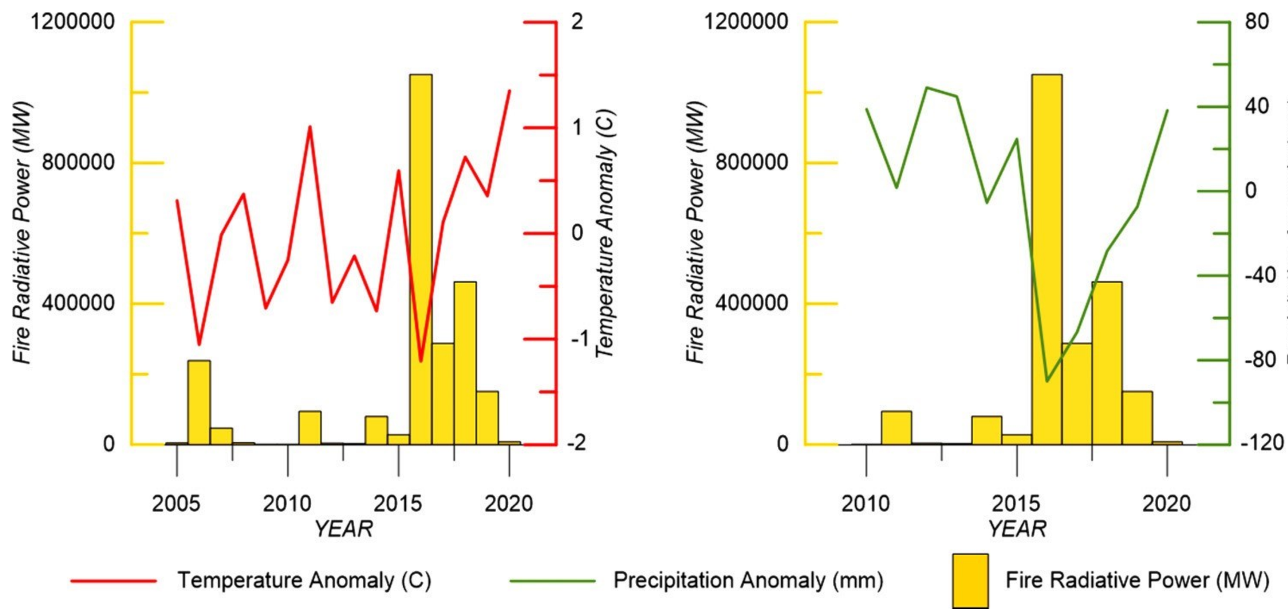
sites. They believed that the fire smoldered for a couple of months in this boggy area and intensified during the dry season:

> "And after the lumberjacks [arrived], these fires started. We then believe that it is they who are to blame for these fires. They throw so much wood there, well, how much they take there … half of the wood is left, arranged in heaps. They begin to burn [these *heaps], … well, maybe it would be possible to burn them, if there was a guard. It is necessary to keep an eye on burning wood so that the fire would not spread. And how can you control it in summer? It would be another matter in winter. Well, that's all, and all these conflagrations begin precisely near logging areas for some reason"* (male, 70, Tokma, 9 March 2020).

The residents also drew attention to the activities of geology exploration companies. While forest companies mostly operate in wintertime, seismic line clearings take place throughout a year:

> *"These Geotecs (name of the geological exploration company), they make profili (seismic line clearings) in summer. And in winter too, of*

Fig. 4. FRP and temperature and precipitation anomalies in Tokma (May through October).



course. Once one told me: "We are all year round". Because the volumes are large, they work. And the main thing is that someone gives them permission to do this work anyway during a fire-hazardous period" (female, 60, Tokma, 10 March 2020).

In support of these community-based narratives, the analysis of the distances from the ignition points to the nearest road using remote sensing data showed a strong spatial correspondence: a large proportion of fires (37%, or 46 out of 125) were within 300 m from existing roads, and the number of ignition points decreased with the distance from the roads (Fig. 5). Forestry roads and geological clearings appeared to be particularly closely associated with wildfires: among all ignitions detected within 300 m from roads, 50% were in proximity to geological clearings and 43.5% were near forestry transportation infrastructure. A possible indication of this relationship is that the ignition points were 3.5 times more likely to occur within 300 m of forestry roads and geological clearings compared to a randomized point sample, although the result was not significant due to a small sample size and requires further data collection.

In sharp contrast, wildfire ignition points were not found near subsistence roads (0–300 m). The oil and gas roads appear to have moderate association with wildfire ignition, which may be explained by more strict regulation of traffic along these roads.

According to local residents, the access restrictions to the informal road infrastructure imposed by industrial operators, particularly the oil companies, are beneficial for local communities since there are fewer poachers who can get to the area. Reduced traffic is viewed as limiting human-caused fire ignitions. However, the access of local residents to these roads is also not formally guaranteed, which represents the downside of the restricted regime.

3.5. Roads, wildfire propagation and termination

The local residents drew particular attention to roads as barriers for low-intensity fires:

"The first year they (roads) still hold back the fire, if the fire is low … Two years ago there was a blaze. It was stopped, localized by a mineral belt, two weeks passed… It was actually extinguished, but somewhere the stump remained in the middle. And here the needles have already dried up. And it was undergrowth … There, along the road on which you were traveling, everything was torn to the ground … low fire stopped. Undergrowth, needles remained, and dried up. Heat, wind, fire climbed up and flew like gunpowder and flew across the road" (male, 70, Tokma, 7 March 2020).

Table 2 shows that 2016 wildfires in most cases appeared to stop spreading naturally in roadless areas. However, the barrier role of the roads, i.e., the proportion of the terminal fire boundary coinciding with a road, was also noticeable: roads were estimated to coincide with 15.9% of terminal fire limits. However, in some cases (T2016_04, T2016_17) the share of roads in burned area borders exceeded 70%; i.e., the roads effectively contained the fire. This pattern was predominantly observed for small fires that occurred in areas with relatively developed road infrastructure.

Among various types of roads serving as burnscar boundaries (Table 2), nearly 75% belong to logging roads (including logging sites), which may be explained by their wide prevalence near burned areas (with a lot of ignitions in close proximity to this type of roads) and their larger width compared to seismic line clearings. Both a physical barrier and access point role of the roads appear to be important. For example, the analysis of the images with wildfire propagation in the burned area T2016_19 (Fig. 6) shows how the wildfire that started on 1 September 2016 near the drilling site and roads maintained by an oil company was quickly contained by creating firelines (light colored mineralized belt is visible

Fig. 5. Distance between ignition points and roads.

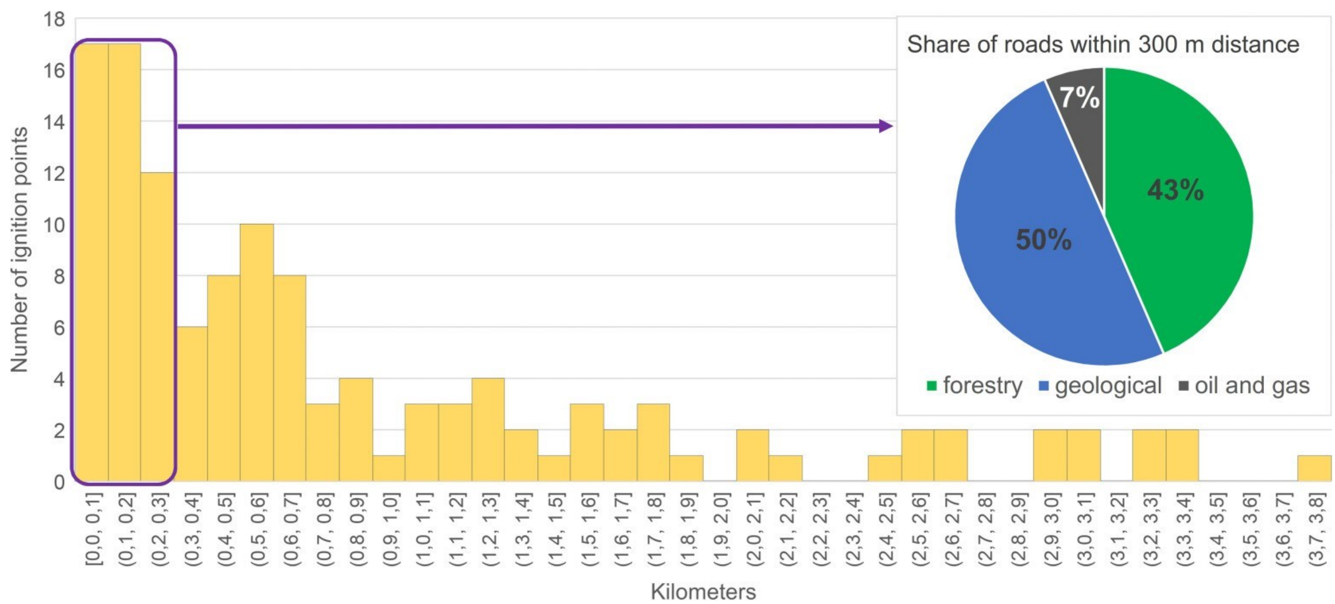


Table 2. The length of boundaries of the 2016 burns, km.

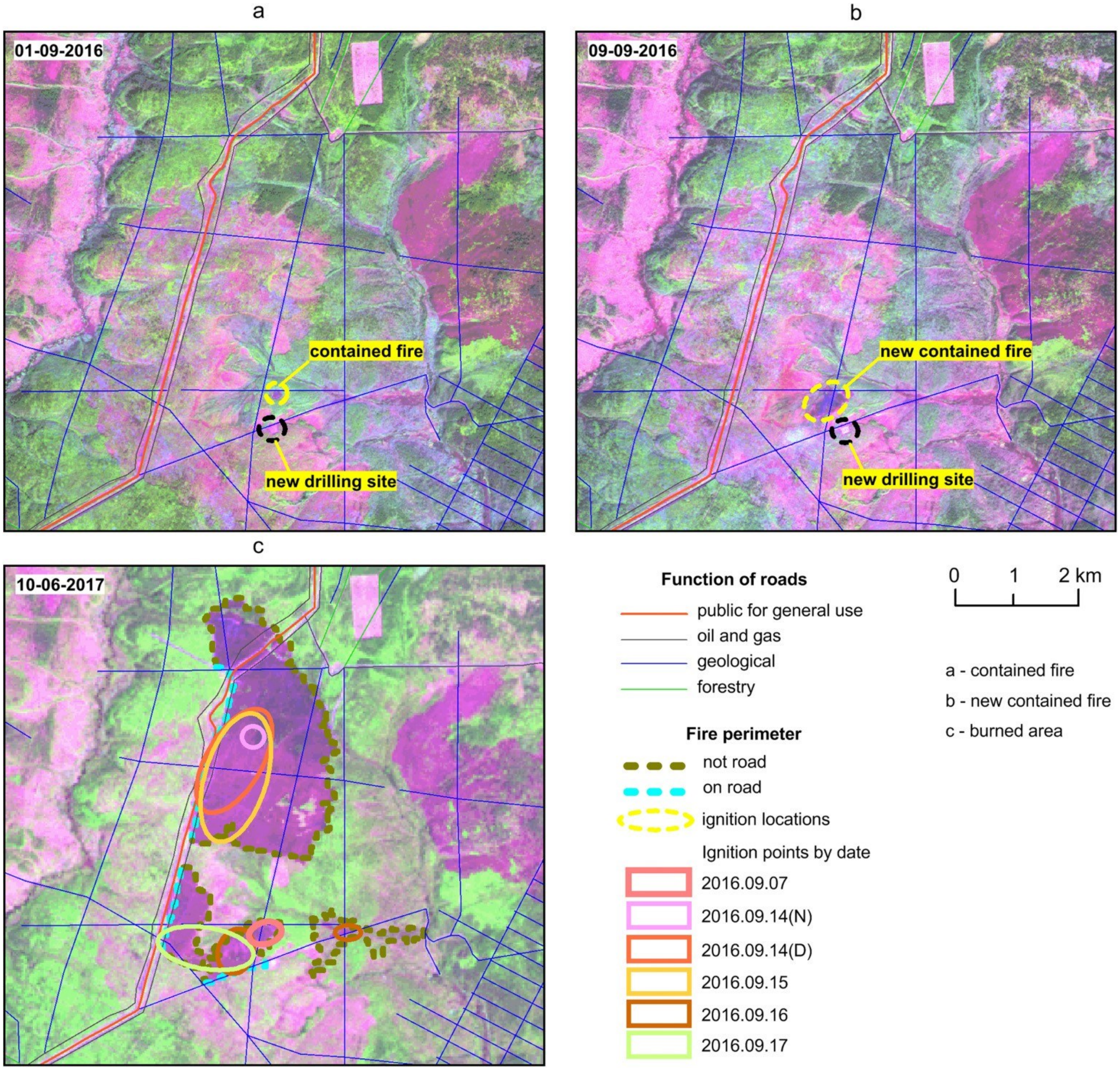
ID	Not road	Road				
		Total	Forestry	Geological	Oil and gas	Public for general use
T2016_01	237	42.6	32.9	9.5	1.2	0
T2016_02	610.3	3.7	0	3.7	0	0
T2016_03	204.8	124.1	111.7	12.4	0	0
T2016_04	8.9	21.7	21.7	0	0	0
T2016_05	90.2	22.2	22.2	0	0	0
T2016_06	53.7	19	18.6	0.4	0	0
T2016_07	1362	223.1	175.3	19.2	28.6	0
T2016_08	269.2	89	61.3	14.7	13	0
T2016_09	377.3	11.1	0	11.1	0	0
T2016_10	260.2	31.6	7.8	23.8	0	0
T2016_11	178.2	39.4	30.7	8.7	0	0
T2016_12	80.3	33.4	22.4	0.8	10.2	0
T2016_13	2.2	4.9	0	0	4.2	0.7
T2016_14	113.1	41.9	34.8	4.1	3	0
T2016_15	20.9	15.2	0	0	15.2	0
T2016_16	9.2	4.6	4	0.6	0	0
T2016_17	1.4	8.9	7.8	0	1.1	0
T2016_18	5.8	0	0	0	0	0
T2016_19	28.9	7.2	0	1.4	1.7	4.1
T2016_20	57.4	3.7	2.9	0.8	0	0
T2016_21	1.8	6.3	3.5	2.8	0	0
All 2016	3972.8	753.6	557.6	114	78.2	4.8
All 2016 (in %)	100	100	74.0	15.1	10.4	0.6

at the Sentinel-2 imagery) (Fig. 6*a*). On 9 September, another fire was contained in proximity to the previous one (Fig. 6*b*). However, from 14 September to 17 September several new ignition points emerged within a few kilometers from the oil operation, and no artificial barriers for fire propagation were formed. The fire ended naturally on 27 September (Fig. 6*c*).

3.6. "Zombie fires"

In our case study, the local residents described a large number of occurrences of fires smoldering through winter, i.e., "zombie" or "overwintering" fires (McCarty et al. 2020; Scholten et al. 2021), that they witnessed while travelling along their subsistence roads. A hunter in 2016 saw

Fig. 6. Wildfire propagation in the burned area, site T2016_19 (created using Landsat-8(c) USGS and ArcGIS software with basemap from ESRI (projection WGS84/UTM48N)).

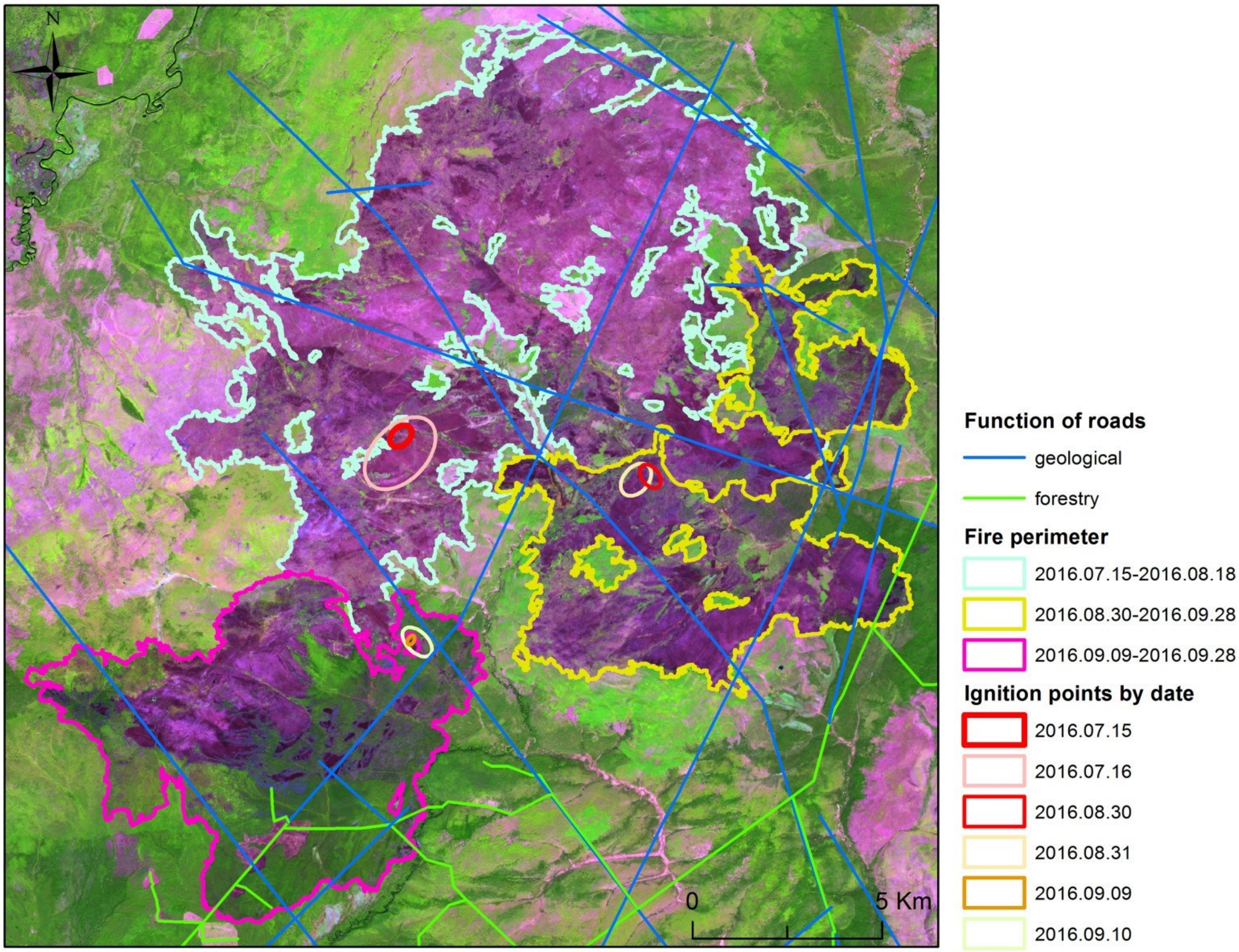


flashes across the river that looked like lights of an oncoming vehicle. He went to check and saw underground burning in the form of openfire and smoke. Another hunter saw smoke coming from underground that was initially remote, but in a few months approached his subsistence trail. All these winter fires took place near the areas of summer wildfires.

However, "overwintering" fires described by these witness testimonies are not readily detectable by the conventional remote sensing methods. A comparison of autumn 2016 and spring 2017 images has not provided enough evidence to conclude that something has changed. In other words, capturing "zombie fires" without human account is extremely challenging, especially given the fact that we are only beginning to understand this complex phenomenon (McCarty et al. 2020).

Another interesting type of wildfire dynamics we identified in the 2016 season was the "compound fires". We found several instances of such fires that re-ignite multiple times during one summer season. For instance, on the site T2016_02 (Fig. 7) it is clearly seen that initially the fire started on 15 July and by 18 August a vast area burned out. After that, no thermal anomalies were observed for 12 days until the end of August. The areas of smoldering peat bogs could have remained in the lowlands, and on 30 August and 7 September, when the necessary conditions were formed, became the source of two new fires developing independently of each other. As a result, the burned area almost doubled.

Fig. 7. An example of a "compound wildfire", site T2016_02 (created using Landsat-8(c) USGS and ArcGIS software with basemap from ESRI (projection WGS84/UTM48N)).



4. Discussion and conclusions

Our research emphasizes the necessity to include diverse forms of knowledge in wildfire research and management (Sherry et al. 2019) and Indigenous knowledge in particular (Christianson 2014). It is especially important in the boreal regions with rapid industrial development that exacerbate the extent, severity, and frequency of wildfires (Aponte et al. 2016). By examining the relationships between roads and wildfires, we were able to better understand the role of different forest users in wildfire ignition and propagation.

Our study confirms a strong spatial relationship between the wildfire ignition points and roads. A more detailed analysis demonstrates the differentiation by road type. We found much higher probability of fire ignition near forestry roads than near geophysical line clearings. Very few wildfire ignition points were found near the oil and gas serving roads (3% of ignitions versus 5.3% of general share of oil service roads in the transportation network), which can be explained by the restricted access regime to these roads. Interestingly, no wildfire ignition points were found within 300 m of roads exclusively used for subsistence by local residents. This may indicate that the existing practices of local residents do not serve as a major human-made cause of forest fires in the area and may even reduce the likelihood of fires.

Roads also play an important role in wildfire suppression, working as both physical barriers and access points for firefighters. All types of roads may block or impede wildfire propagation: roads coincide with 15.9% of terminal fire limits, and some fires appear to be largely stopped by roads. This pattern is prevalent for smaller fires near relatively developed road infrastructure. Logging roads are especially frequent wildfire barriers as they are wider than geological clearings and more present in the landscape compared to other road types.

Analysis also reveals the lack of coordination between wildfire management practices, infrastructure development, and road access. Poor coordination increases the risks of wildfires since diverse forest users can blame each other for the fire ignition and do not have developed a strategy for collaborative efforts on wildfire monitoring and extinguishing.

Our research illustrates the importance of local and Indigenous observations along subsistence roads for monitoring and understanding wildfires, especially when they are smoldering in peatlands. These witness accounts are particularly instrumental for learning more about "zombie fires" (smoldering fires continuing into the next season) and "compound fires" (smolder with multiple reignitions in one season). Peatlands store an estimated 30% of the world's soil carbon pool while covering only 2%–3% of the land surface. Moreover, researchers expect more byproducts such as CO, CH4, CH3Br, CH3Cl, and Hg in case of smoldering fires that can take place underneath snowpacks (Flannigan et al. 2009). In addition, these peatlands are often also the areas of permafrost occurrences. The active layer thickness of permafrost increases after wildfires (Michaelides et al. 2019). The consequences of permafrost degradation are also associated with carbon release (Turetsky et al. 2019; Irannezhad et al. 2020). The local observations of holdover fires could help to estimate the underground wildfire propagation and impacts.

Future research on Siberia wildfires needs to incorporate more collaborative work with local and Indigenous communities combined with detailed analysis of permafrost conditions, vegetation, climate change, topography, and hydrology as well as changes in land use. These efforts will result in better understanding and forecasting of wildfire events and discerning their impact on carbon emissions and possible contribution to global climate feedback. It also has practical implications for improvement of fire management and preventing fires through road use restrictions collectively developed by authorities and local communities.

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Data availability

Geospatial data generated or analyzed during this study are available from the corresponding author upon reasonable request.

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Competing interests

The authors declare there are no competing interests.

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