LETTER

Increasing fire and logging disturbances in Siberian boreal forests: a case study of the Angara region

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Abstract
Forest disturbances are a critical environmental issue globally and within the boreal biome, yet detailed attribution and trends in disturbances are lacking for many Siberian regions. The Angara region located in the southern taiga of Central Siberia has experienced significant disturbances during the past several decades and is a hotspot of change in Eurasia. Here we estimated fire and logging disturbances using MODIS and Landsat data for the period 2002–2020 across the Angara region and analyzed the resulting trends. Average annual burned and logged area was about 220 and 31 thousand ha or 2 and 0.3% of the study area, respectively. In total, about 4.1 million ha (38% of the region) and 0.6 million ha (6% of the region) were disturbed by fires and logging, respectively. Spatial analysis showed that almost 50% of fires were ignited within 2 km of anthropogenic features such as settlements, roads and logged areas. Almost 5% of the Angara region was burned two or more times during the 19 years of observations. Improved and strictly-enforced conservation and management policies are required to halt continued forest degradation in the Angara region and similarly-affected boreal forests in Siberia.

1. Introduction

The boreal forest is one of the largest terrestrial biomes covering ca. 1.2 billion ha in total, of which some 900 million ha are located in Russia (FAO Global Forest Resources Assessment 2015). Intensification of anthropogenic activities, notably logging and human-ignited forest fires, together with climate change, can lead to significant disturbances that affect the composition, structure, functioning, and ecosystem services of boreal forests, including carbon stocks (Achard et al 2006, Gauthier et al 2015, Thom and Seidl 2016).

Wildfire is one of the dominant disturbances influencing vegetation dynamics, biodiversity and carbon cycling in boreal forests of Russia (Vivchar 2011, Bartalev et al 2015, Leskinen et al 2020). In Russia, several million ha of forested lands, mostly in Siberia, are exposed to fires annually. Burned area across Russia can vary greatly between years depending on weather conditions, with a mean annual forested burned area of 5–7 million ha (Bartalev et al 2015). Climate models project temperature increases in the boreal region to be at least twice the global rate (IPCC 2013).

Logging is another important disturbance in boreal Eurasia (Achard et al 2006). Siberian regions such as Irkutsk oblast and Krasnoyarsk krai are national leaders in timber production, accounting for 15% (35.7 million m3 in 2018 and 31.7 million m3 in 2019) and 12% (28.6 million m3 in 2018 and 25.6 million m3 in 2019) of total timber production in Russia, respectively (Rosstat 2020). The territory of the Angara region encompasses the largest forestry resources in Krasnoyarsk krai. The total stock of wood in the region is approximately 2.2 billion m3,
with mature stands available for harvest comprising roughly 1.7 billion m³ (>77%) (Bezrukikh et al. 2017). The large stocks of high-quality wood and ability to transport timber to other economic regions using river systems of Angara, Yenisei and their tributaries resulted in a number of timber industry complexes in Krasnoyarsk krai.

According to official fire statistics, the Angara region is responsible for about 55% of the total area burned by forest fires in Krasnoyarsk krai (Moshkalchenko 2009). The large footprint of anthropogenic disturbances in the Angara region from logging combined with high natural fire danger (Ivanov et al. 2009) results in large areas being affected by multiple successive disturbances (Moshkalchenko 2009). Repeat disturbances in forest ecosystems are generally reported to have a negative impact on reforestation (Stevens-Rumann and Morgan 2016), potentially shifting forests to an alternative treeless stable state (Turner 2010). This phenomenon has been already observed in the southern boreal forests of Russia where multiple disturbances hampered the reforestation process (Shvetsov et al. 2019) and transformed forests to steppe ecosystems due to inadequate regeneration (Kukavskaya et al. 2016).

The main goal of this study was to evaluate fire and logging disturbances during the past two decades in the Angara region, Central Siberia. Our objectives were to: (a) assess the dynamics of the area disturbed by forest fires and logging and (b) analyze the spatial relationships between fires, logging and anthropogenic features such as settlements and roads. Because of climate change and the increasing human footprint in Angara, we hypothesized that disturbance levels increased during this time period and that most of the fires were caused by humans.

2. Data and methods

2.1. Study region

The Angara region is located in the southern taiga along the banks of the Angara river in Krasnoyarsk krai, Central Siberia. The study region was determined based on forest zoning (Ministry of Natural Resources and Environment of the Russian Federation 2014) which defines the Angara forest region. In this study, we considered the subset of the Angara forest region located within the administrative boundaries of Krasnoyarsk krai (hereafter Angara). Our study region occupies over 10.7 million ha between 56°–60° N and 92°–102° E (figure 1).

The climate of the Angara region is cold continental, with a mean annual temperature of −3 °C and variations between maximum and minimum mean monthly temperatures of 37 °C–44 °C (Bezrukikh et al. 2017). Annual precipitation is 320–380 mm, with a relatively dry spring and autumn (approximately 10% of annual precipitation), and summer accounting for 40%–50% of total annual precipitation. The relief of the study area is hilly upland with a mean altitude above sea level varying between 250 and 350 m (Abrams et al. 2020). The mean length of the frost-free period in the Angara valley is between 80 and 100 d (Valendik 2011). The dominant tree species are Scots pine (Pinus sylvestris) (33% of the study area), with a smaller proportion of larch (Larix sibirica) (25%) and spruce (Picea spp.) (17%) (Bartalev et al. 2016).

The Angara region has experienced severe anthropogenic impacts since the 1970s, such as agricultural clearing and industrial logging, mining and associated road building as well as construction of the Boguchanskaya hydroelectric power station and power lines. These factors led to forest disturbances and an increase in the area of non-forest lands (Andreev 1999, Ivanov et al. 2011).

2.2. Datasets

Landsat data downloaded from the United States Geological Survey (USGS) archives were used to map logged areas (supplementary materials (available online at stacks.iop.org/ERL/16/115007/mmedia), Landsat Data section).

We used the collection 6 MODIS active fire (MOD14/MYD14) (Giglio et al. 2016) and geolocation (MOD03/MYD03) products, which have a spatial resolution of 1000 m, to obtain the locations and dates of active fires. MODIS data were acquired from the Level-1 Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC) collection (https://ladsweb.modaps.eosdis.nasa.gov/).

2.3. Satellite data processing methods

To map logged areas (clear-cuts), we visually identified cut blocks in the Landsat imagery and manually delineated polygons using GIS software. Composite Landsat images were created using red, near-infrared and short-wave infrared bands. We stored the acquisition year of the Landsat image for which each logged site was detected for the first time. This year was considered as the year when the site was logged.

To map fires, we used the MODIS active fire and geolocation products. We converted MODIS data to shapefile format where each active fire pixel was represented as a polygon. These active fire hotspots for each year were then clustered to derive polygons corresponding to larger fire events using several temporal and spatial thresholds. Our fire mapping procedure is described in more detail in the supplementary materials (Shvetsov 2021).

2.4. Spatial analysis of fires and logging

To analyze the spatial distribution of forest disturbances caused by fires and logging, we divided the study area into a rectangular grid with each grid cell occupying 50 thousand ha. Within each cell, we calculated the area of forested territory as well as the total area of burns and clear-cuts on forested lands for each
Figure 1. Location of the study region. The right panel is a detailed map of our study region based on the regional map on the left. Forested lands according to the product of Hansen et al (2013) for the year 2000 are shown in green (Source: Hansen/UMD/Google/USGS/NASA).

year during 2002–2020. Forested lands were defined by the Global Forest Change product (Hansen et al 2013), applying a canopy cover threshold of 25% following Krylov et al (2014). The disturbance degree of the forested area was then calculated as the ratio of the disturbed area to the forested area within each grid cell:

$$DD_j = \frac{A_{\text{disturbed}}(i,j)}{A_{\text{forest}}(i,j)},$$

where $DD_j$ = disturbance degree for the year $j$, $A_{\text{disturbed}}(i,j)$ = disturbed area within the grid cell $i$ for the year $j$, and $A_{\text{forest}}(i,j)$ = forested area within the grid cell $i$ for the year $j$ (Mokeev 1965). Overall disturbance degree for each grid cell was calculated as mean value of annual values.

For each grid cell we also calculated the forested area affected by stand-replacement fires. We mapped stand-replacement fires using the Global Forest Change product (Hansen et al 2013). Following the approach of Krylov et al (2014) we classified forest loss pixels as stand-replacing fires if they were located within 4 km of recorded fire pixels and within 3 years after MODIS-detected fire events.

We also estimated the relationship between the fire disturbance degree and area affected by stand-replacement fires for our 50 thousand ha grid cells. To do so, we calculated the correlation coefficient between the total area of pixels that experienced stand-replacing fires within each grid cell and the fire disturbance degree.

To check whether fires in Angara were caused by humans, we analyzed the spatial proximity between fires and various anthropogenic features such as logged areas, roads and settlements. Roads and settlement data were obtained from Open Street Map (www.openstreetmap.org). We created separate shapefiles containing the dates and locations of initial active fire pixels for each registered forest fire. These files were then used to calculate the distance between a fire ignition point (initial fire pixel) and the nearest logged area, road and settlement. In this analysis, we used a temporal threshold of 10 years between the year of fire detection and the year of logged area detection to detect anthropogenic influence. We thus considered fire events within 10 years post-logging. We chose a threshold of 10 years because the fire danger of logged areas significantly decreases after 10 years due to the formation of a tree canopy, a decrease in the amount of direct sunlight reaching the surface, and decomposition of logging slash (Valendik et al 2001).

Finally, we analyzed successive disturbances considering fires or logging on the same area of land. To this end, we obtained overlapping areas where fires burned the same area several times as well as where logged areas were burned. The analysis was done using ArcGIS software.

3. Results and discussion

3.1. Temporal and spatial distribution of disturbances

The Angara region was highly disturbed by both fires and logging during 2002–2020. The total burned area during this period was more than 4.1 million ha, which represents 38% of the study area (or 42% of forested land). The total logged area during the same period was 596 thousand ha, or 5.6% of the study region.

Annual burned area in the region was highly variable across years depending on weather conditions which resulted in high standard deviation values (figure 2(a)). In almost half of the years (2003, 2006, 2011, 2012, 2014, 2016, 2018–2020), annual burned area significantly exceeded 1% of the study area (i.e. 107 thousand ha) (figure 2(a)), which characterizes fire seasons as extreme following the methodology of Mokeev (1965). The remaining fire seasons are characterized as seasons of high fire activity (i.e. annual burned area varied between 0.1% and 1% of the study area). Average annual burned area was $217.8 \pm 210.4$ thousand ha (mean ± SD) or $2.04 \pm 1.96\%$ of the
study area per year; the largest annual burned area was recorded in 2012 (770 thousand ha), and the smallest in 2009 (13 thousand ha). However, a linear regression did not result in a significant trend in burned area during the study period ($r^2 = 0.07$, $p = 0.27$) (figure 2(a)).

At the same time logged area in the region was considerably smaller, with mean annual value of $31.4 \pm 15.0$ thousand ha or $0.29 \pm 0.14\%$ of the study area. Over the last six years of the study period we observed a significant increase in the logged area in the region. This increasing trend in logged area between 2002 and 2020 was statistically significant ($r^2 = 0.54$, $p < 0.05$) (figure 2(b)).

Comparison with the official logging data from the Ministry of Forestry of the Krasnoyarsk krai (www.mlx.krskstate.ru/) available for 8 years during our study period showed that our Landsat-derived product was on average 13% lower than official estimates. Possible reasons of this mismatch are discussed in the supplementary materials section.

The total disturbed area (clear-cuts and fires) in the region between 2002 and 2020 was almost 3.5 million ha, not considering repeat disturbances. However, not all disturbed areas experienced actual forest loss due to low and moderate severity fires which are common in Eurasia and usually followed by little or no postfire tree mortality (Rogers et al 2015).

To explore this further, we compared our estimates of disturbed areas with the Global Forest Change product (Hansen et al 2013), which reports forests with tree cover loss. Using this product, we found that the area estimated to transition from forest to non-forested lands was 1.8 million ha between 2002 and 2019. At the same time, our data reported 3.3 million ha of total disturbed area for the same time period (2002–2019). Thus, about 45% of the study area had little or no postfire change in forest stand structure.

Figure 3 shows the spatial distribution of the disturbance degree caused by fires and logging within the Angara region. During the last decade (2011–2020), the majority of burned area (more than 1.5 million ha) occurred in the central and northern parts of the study region (figure 3(a)); major logged areas (150 thousand ha) also extended to northern and northeastern parts of the region (figure 3(b)). This indicates an expansion of burning and logging to the northern previously undisturbed territories due to depletion of forest resources in the southern regions that have already been subjected to anthropogenic pressure and deforestation since the 1970s.

Approximately 32% of the study area was characterized by high fire disturbance levels ($0.1\%–1.0\%$) according to the classification of Mokeev (1965). Extreme disturbance degrees (more than 1% of the area) were observed for almost 68% of the Angara region, with 44% of the area experiencing a fire disturbance degree exceeding 2.0% (figure 3(c)). High fire activity in the forests of the study region is associated with both significant disturbance by logging and dry and warm weather during the spring and summer (Ivanov and Ivanova 2010).

The spatial distribution of highly disturbed areas was generally in good agreement with areas affected by stand-replacement fires. The correlation coefficient between disturbance degree and area affected by stand replacement fires was $r = 0.73$. Most of the study area (more than 66%) experienced a disturbance degree from 0.1% up to 1.0%, whereas only 6% of the territory experienced disturbance degree higher than 1.0% (figure 3(d)). Logged areas were found to be significantly lower compared to fires.

We also compared our spatial distribution of fire disturbance with the fire disturbance levels map of Moskalchenko (2009) made for the eastern part of the study region using fire data from 1992 to 2006. The comparison showed that in our classification, the area characterized by strong and extreme fire disturbance has considerably increased. For instance, the northeast portion of the study area in Moskalchenko (2009) is characterized mainly by a weak to moderate degree of fire disturbance levels. However, our estimates show extreme fire disturbance for most of this area. This difference seems to be attributed to large fires here after 2011 (>70% of the total burned area between 2002 and 2020). Thus, these results confirm...
our hypothesis that the disturbance level in the region had increased during the last two decades.

3.2. Spatial relationships between fires and anthropogenic features
The proximity of fires to anthropogenic features such as roads, settlements and logged areas may be a useful indicator of the likely origin of the fire (Yang et al 2008). We therefore performed an analysis of spatial relationships between fire occurrence locations and these features in Angara. We found there was an increase in the frequency of fires near anthropogenic features. Over the 2002–2020 period, 20% of all fires occurred within 2 km of settlements and 27% within 2 km of roads, and half of all fires detected in the region had at least one logged area within 2 km (figure 4).

In Central Siberia, forest fires tend to show a strong positive spatial correlation with the distance from roads, indicating that forests near roads are more likely to burn than other forests in the area. This is also true for railroads, settlements, and industry locations (Kovacs et al 2004).

Roads in the Angara region are mainly represented by unpaved logging roads with an uneven density varying between 76 and 400 km of roads per 100 thousand ha (Ivanov and Moskalchenko 2012). According to Moskalchenko (2009), over 60% of forest fires in the Angara region are located within 20 km of the roads, with most of them having an anthropogenic origin. According to our data, the proportion of fires within 20 km of roads is even higher—almost 75%. This proportion can differ between different forestry districts within the study region. For instance, in the woodstries with a high population density and a well-developed road network, most of the fires (56%) are within 5 km of roads, while in the regions with low population and a poorly developed road network, only 22% of fires are located within 5 km of roads. These figures mostly agree with the results of Moskalchenko (2009), who found that roughly 80% of fires occur near the roads in the woodstries with a high population density.

According to our data, the relationship between the number of fires and the distance from settlements and roads is exponential. The coefficients of determination for log-transformed data were $r^2 = 0.88$ for settlements, $r^2 = 0.90$ for roads and $r^2 = 0.69$ for the logged sites (figure 4). Approximately 70%–75% of all fires were located within 10–15 km from settlements. These results are in line with other studies which have also shown strong relationships between fire frequency and distance from roads and settlements for the study region, with correlation coefficients varying between 0.81 and 0.95 (Andreev 1999, Ivanov et al 2011).
Economic development within the study area, and logging in particular, tends to increase fire danger. Logged areas are characterized by an increased risk of fire occurrence due to high fuel loads (up to 135 t ha\(^{-1}\)) combined with the availability of anthropogenic sources of ignition, and often experience higher severity fires than unlogged forests (Kukavskaya et al. 2013). The presence of roads and easier accessibility of logged areas also increases risk of human-caused ignition (Moskalchenko 2009). Forest cover removal due to clear-cuts increases direct sunlight leading to higher temperatures and earlier drying of forest fuels and, therefore, increased fire danger compared to adjacent forests (Valendik et al. 2011).

Fires often start in recently logged areas, where drier fuels become flammable earlier than fuels under forest canopies, and then spread into neighboring primary forest (Moskalchenko 2009, Ivanov et al. 2011). Because of this, approximately 50% of all fires detected in the region had at least one logged area within 2 km, and more than 60% of fires were detected within 4 km from previously logged areas (figure 4). This suggests that the majority of fires in the region are likely ignited by humans. Nevertheless, a significant number of fires were detected at a distance of 30 km or more from anthropogenic features (settlements, roads, and logged areas). According to an analysis of forest fires and thunderstorms (Ivanov and Ivanova 2010), a significant number of fires are caused by lightning in the study region, which is a result of high thunderstorm activity, high natural fire hazard of forests, and orography.

The number of fires and burned area as a function of distance to human activity are shown in figure 5(a). Unlike figure 4, where anthropogenic features were considered independently, figure 5 considers the distances to the feature nearest to fire. According to our data, about 90% of fires, which account for almost 79% of burned area, were detected within 10 km from anthropogenic features (settlements, roads, and logged areas). According to our data, about 90% of fires, which account for almost 79% of burned area, were detected within 10 km from anthropogenic features, although this corresponds to only 49 ± 11% of the area of the study region. The relationship between mean fire size and distance from anthropogenic features can be approximated by an increasing linear trend with reasonably high accuracy.
The Angara region is characterized by high fire and logging activities, with repeat fires occurring in subsequent years, indicating a very short fire return interval of 1–2 years, or even twice a year (Kukavskaya et al 2016). The influence of human activity on the forests of the region results not only in an increase of probability of fire ignition but also facilitates fire suppression. For example, roads not only increase the risk of human-caused ignition, but also hinder the spread of fire, and facilitate the delivery of fire suppression forces and equipment (Ivanov and Moskalchenko 2012). Anthropogenic activity in the region results not only in the increased probability of fire ignition, but also facilitates fire suppression. For example, roads not only increase the risk of human-caused ignition, but also hinder the spread of fire, and facilitate the delivery of fire suppression forces and equipment (Ivanov and Moskalchenko 2012). The presence of humans in the region and the possibility of quick fire reporting also reduce the risk of late fire detection. Consequently, fires are more likely to be controlled efficiently when small and in closer proximity to anthropogenic features. Studies in interior Alaska also showed that human-caused fires are generally smaller in size compared to remote fires of natural (lightning-caused) origin (DeWilde and Chapin 2006).

Multiple successive disturbances were quite common in the study area, affecting approximately 650 thousand ha during the period of observation (Table 1). Most of these disturbances were multiple fire events, affecting 514 thousand ha (5.0% of the study area), while areas affected by both fire and logging accounted for 150 thousand ha (1.3% of the study area). The maximum number of repeated fires over the 19 year period was six; however, most of the area (>80%) affected by repeated fires only burned twice. While we might slightly overestimate the amount of repeated fires due to low spatial data resolution, resulting in unburned patches within fire pixels that burn in subsequent years, some Siberian forests have been found to experience very short fire return intervals of 1–2 years, or even burn twice during the same year (Kukavskaya et al 2016).

| Area, thousand ha | % of study region | % of total disturbed area |
|-------------------|-------------------|--------------------------|
| Multiple fires    | 514.0             | 4.8                      | 14.7                      |
| Burned 2 times    | 430.8             | 4.1                      | 12.3                      |
| Burned 3 times    | 70.1              | 0.6                      | 2.0                       |
| Burned 4 and more times | 13.1          | 0.1                      | 0.4                       |
| Fires and logging | 146.2             | 1.3                      | 4.2                       |
| Fire and logging in the same year | 23.2        | 0.2                      | 0.7                       |
| Logged then burned | 123.0          | 1.1                      | 3.5                       |
| 1–5 years between logging and fire | 77.3       | 0.7                      | 2.2                       |
| 6–10 years between logging and fire | 45.7       | 0.4                      | 1.3                       |

4 Conclusions

Our research provides an analysis of the spatial and temporal patterns of forest disturbances in the Angara region in the southern taiga of Central Siberia. The analyses of satellite-derived burned and logged area estimates for two decades from 2002 to 2020 revealed the following:

- The Angara region is characterized by high fire and logging disturbances. The total burned area in the Angara region between 2002 and 2020 was more than 4.1 million ha. Annual burned area varied from 13 to almost 800 thousand ha with a mean value of almost 220 thousand ha. Total logging area during the same period was estimated at 596 thousand ha, or 31 thousand per year on average.
- The number of forest fires increased with proximity to anthropogenic features, whereas mean fire

Lake in southern Siberia, where 13% of the region experienced repeated fires during 20 year study period (1996–2015) (Kukavskaya et al 2016). We assume this can be attributed to the drier climate and higher fire risks, as well as the greater anthropogenic pressures and forest accessibility in the Zabaikal region compared to the Angara region. Fire regimes and dominant tree species within the forest can affect the likelihood of successive fires. For instance, Russian boreal forests are generally characterized by low severity surface fires (Wooster and Zhang 2004, Rogers et al 2015), which reduce surface fuel loads by only 15%–20% (Kukavskaya et al 2016), providing enough fuel for successive fires.

The influence of humans on the forests of the Angara region due to logging and fires was found to increase in recent decades. Such disturbances have multiplicative effect on the consequences of climate anomalies (Achard et al 2006) considering relationships between climate and forests (FAO 2013). The use of satellite imagery could allow monitoring of boreal forests state and disturbances which is essential to improve understanding of interactions and feedback among processes (Gauthier et al 2015) and to develop appropriate climate and forest conservation policies (Funk et al 2019).
size decreased. The relationship between the number of fires and the distance from settlements and roads is exponential with $r^2 = 0.7–0.9$. About 90% of fires, accounting for almost 79% of burned area were detected within 10 km from anthropogenic features.

- Multiple successive disturbances affected 650 thousand ha. Most of these disturbances were repeated fires, which affected about 5% of the study area.

Boreal forests provide critical ecosystem services to local, regional, and global populations and play an important role in climate regulation through the exchange of energy and water (Gauthier et al 2015). Evaluation of the current state of boreal forests and their disturbances by both natural and anthropogenic factors is essential for developing sustainable forest management strategies and preserving primary forests. Siberia’s vast boreal forests can have a substantial impact on the global carbon cycle, climate change, and availability of forest products. An increasing number of Siberian forests such as those in the Angara region are facing extreme pressures of increasing logging and fire (Achard et al 2006, Kukavskaya et al 2013, 2016, Kirillina et al 2020). Our analysis underscores the importance of developing large-scale remote sensing-based assessments of boreal forest disturbances, particularly for logging since global fire products currently exist. Continued and repeated disturbances will significantly alter ecosystem dynamics, forest regeneration, wildlife populations, and, ultimately, negatively impact a suite of valuable ecosystem services. With climate changes, wildfires will play an increasingly important role in the structure and carbon storage capacity of the Siberian boreal forests.

**Data availability statement**

The data that support the findings of this study are openly available at the following URL/DOI: [https://github.com/data-store-a/angara-data](https://github.com/data-store-a/angara-data).

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