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Remote sensing estimates of stand-replacement fires in Russia, 2002–2011

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Abstract

The presented study quantifies the proportion of stand-replacement fires in Russian forests through the integrated analysis of Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) data products. We employed 30 m Landsat Enhanced Thematic Mapper Plus derived tree canopy cover and decadal (2001–2012) forest cover loss (Hansen *et al* 2013 High-resolution global maps of 21st-century forest cover change *Science* **342** 850–53) to identify forest extent and disturbance. These data were overlaid with 1 km MODIS active fire (earthdata.nasa.gov/data/near-real-time-data/firms) and 500 m regional burned area data (Loboda *et al* 2007 Regionally adaptable dNBR-based algorithm for burned area mapping from MODIS data *Remote Sens. Environ.* **109** 429–42 and Loboda *et al* 2011 Mapping burned area in Alaska using MODIS data: a data limitations-driven modification to the regional burned area algorithm *Int. J. Wildl. Fire* **20** 487–96) to differentiate stand-replacement disturbances due to fire versus other causes. Total stand replacement forest fire area within the Russian Federation from 2002 to 2011 was estimated to be 17.6 million ha (Mha). The smallest stand-replacement fire loss occurred in 2004 (0.4 Mha) and the largest annual loss in 2003 (3.3 Mha). Of total burned area within forests, 33.6% resulted in stand-replacement. Light conifer stands comprised 65% of all non-stand-replacement and 79% of all stand-replacement fire in Russia. Stand-replacement area for the study period is estimated to be two times higher than the reported logging area. Results of this analysis can be used with historical fire regime estimations to develop effective fire management policy, increase accuracy of carbon calculations, and improve fire behavior and climate change modeling efforts.

Keywords: forest fire, remote sensing, stand-replacement fires, disturbance, fire regime, forest monitoring, Russia

1. Introduction

Wildfire is the dominant stand-level disturbance agent in boreal forests (Shorohova *et al* 2011, de Groot *et al* 2013), shaping forest cover over the majority of Russia. Fires in Russian boreal forests significantly contribute to global carbon emissions and local populations and livelihoods (Shvidenko *et al* 2011, Conard and Ivanova 1997). Consistent fire management in Russia dates back to the beginning of the 20th century. By the 1930s, the system of on-the-ground and aerial forest fire monitoring and suppression was established, and continues to operate following the same basic principles today (Goldammer *et al* 2013). In the 1990s satellite-based forest fire monitoring was prototyped using Advanced Very High Resolution Radiometer to estimate burned areas in unmanaged portions of Siberian forests (Sukhinin *et al* 2004, Loupian *et al* 2006). Satellite-based estimates turned out to be more than 3–5 times greater than official statistics, which employed a ground-based monitoring system. Since the beginning of the 21st century, satellite-based estimates of burned area in Russia's forests have become standard and widely used (Bartalev *et al* 2012, Giglio *et al* 2009, Roy *et al* 2005, Loboda *et al* 2007, Vivchar 2011, Kukavskaya *et al* 2013a). It is also challenging to accurately disaggregate forest and non-forest fires using coarse resolution (500 m–1 km) burned area and land cover maps (Kukavskaya *et al* 2013a). Estimates of burned area without the assessment of fire severity and post-fire tree mortality are insufficient to understand the role of fires in forested ecosystems. For example in Southern Siberia Scots pine forest the fire return interval is 8–21 years (Ivanova and Ivanov 2005), but usually does not lead to significant tree mortality. In dark coniferous forests fires are extremely rare but lead to complete tree canopy mortality (Furyaev 1996). Stand-replacement fire area estimations were previously produced based on approximate crown fire proportions. The proportion of crown fires has been estimated from 16 to 24% by Gromtsev (2002) to 22% by Korovin (1996), while in extreme fire years in Siberia, Kukavskaya *et al* (2013a) estimates proportion of crown fire to be as much as 50%. In this study we distinguish two main types of wildfire: stand-replacement and non-stand-replacement fires. Stand-replacement fire is a fire that kills all or most of the living upper canopy and initiates succession or regrowth (National Wildfire Coordinating Group 2014). While all crown fires are stand-replacement, only a fraction of surface fires lead to significant tree mortality.

According to official inventory data submitted to the Intergovernmental Panel on Climate Change (IPCC), carbon flux from stand-replacement fires in Russia is more than five times the flux from non-stand-replacement fires (Federal Service for Hydrometeorology and Environmental Monitoring 2013). Conard *et al* (2002) estimated that annual variations of stand-replacement fire proportion can lead to variations in carbon emissions by 40%. Shvidenko *et al* (2011) implemented a stand-replacement fire probability model based on seasonality, ecoregion, and dominant species to improve carbon emissions estimations. Stand-replacement fire estimate used in carbon flux inventory data (National Inventory Report 2013) was derived using a complicated inventory-based burned scar area interpolation. While such approaches are suitable for long-term averages at the national level, the variability of stand-replacement fire rates can lead to errors at annual and regional scales.

This research utilizes a newly developed wall-to-wall Landsat map (released in 2013) and provides for the first time quantified spatially explicit forest mortality at 30 m resolution by fusing data products from various satellite observations. While attempts to develop similar products at a coarser 500 m Moderate Resolution Imaging Spectroradiometer (MODIS) resolution have been previously made (Stytsenko *et al* 2013), those results are not publicly available due to the Russian Federal Forest Agency (www.rosleshoz.gov.ru) and Space Research Institute (www.iki.rssi.ru) data distribution policies and have not been published in the English language literature. The resulting data set and method presented here can be used to improve our understanding of the role of wildfire in ecosystem and land-cover change dynamics, to reduce uncertainties of fire-related carbon emission estimates, and, potentially, to improve forest management in the context of wildland fires and occurrence of stand-replacement fires. Knowing the rates of fire-induced mortality is relevant to science through better understanding the carbon cycle of the largest contiguous forests in the world as well as providing a baseline for developing robust post-fire forest management strategies driven by specific goals of management agencies, such as post-fire rehabilitation of commercially viable or ecologically valuable forests.

2. Data and methods

Stand-replacement fires are defined in this study as fire events that lead to substantial overstory tree mortality due to fire damage, immediately or during subsequent years after the fire. Therefore, the area of stand-replacement fire equals the area of fire-induced forest cover loss. Our stand-replacement forest fire mapping approach is based on the integrated use of medium spatial resolution Landsat-based forest cover loss maps (30 m) and coarse spatial resolution MODIS-based active fire (1 km) and burned area products (500 m). We utilized 30 m resolution tree canopy cover for year 2000 and forest cover loss from 2000 to 2012 derived from Landsat Enhanced Thematic Mapper Plus (Hansen *et al* 2013). MODIS-based products include 1 km MODIS active fire data, obtained from the Fire Information for Resource Management System (earthdata.nasa.gov/data/near-real-time-data/firms), and 500 m MODIS-based regional burned area product for Russia (Loboda *et al* 2007 and 2011). The accuracy of each data product was considered before inclusion in this analysis and deemed appropriate for regional-scale quantification of stand-replacement fires.

Only forest fires were considered in this analysis, excluding fires in agricultural and steppe areas. Forest was defined as areas with tree canopy cover above 25% in 2000 using Landsat tree canopy cover dataset (Hansen *et al* 2013). The canopy cover threshold was selected to match the total Landsat-based estimate of 'forested area' to the official inventory-based forest area for Russia of 797 million ha (Mha) (The State and use of Russian Federation Forests—Report for 2012 2013).

Forest fires were mapped and analyzed for the entire Russian Federation from 2002 to 2011. While the Landsat-based dataset includes forest change between 2001 and 2012, we decided to exclude the first and last years due to known disturbance date attribution uncertainty. The Hansen *et al* (2013) forest cover loss product has a 1 year temporal resolution, with approximately 24.8% pixels containing a ±1 year error and 3.3% of pixels possessing a ±2 year error due to the lack of cloud free images (Hansen *et al* 2013).

Our mapping algorithm includes two main steps (figure 1). First, total Landsat-based forest loss area was disaggregated into fire- and non-fire related categories. Forest loss patches intersected with MODIS active fire hotspots were

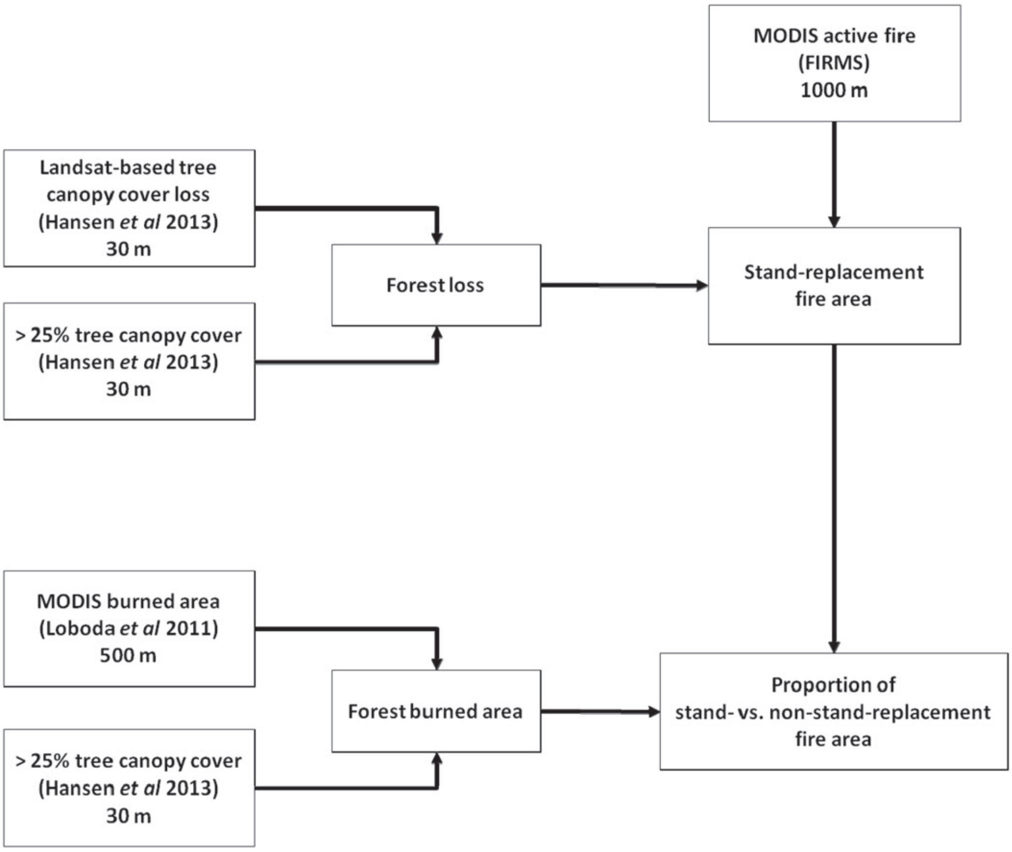

Figure 1. Method used to determine stand-replacement burned area and proportion of stand- versus non-stand-replacement burned area.

considered fire-related loss. The post-fire tree mortality process can continue up to 5 years; however, the majority of tree morality in pine and larch forest occurs within 2 years after a fire (Vorontsov 1978, Isaev 1962) and 1–3 years after fire in spruce forest (Maslov 2011). Therefore, forest loss patches occurring within 3 years after MODIS-detected fire events were considered as stand-replacement burned areas. For large loss patches, only loss pixels within a 4 km distance from hotspots were considered fire-related loss. A 4 km buffer was utilized after manual interpretation. This 4 km distance provided a balance between commission errors (falsely including logging) and omission errors (falsely excluding real fire-related forest loss) compared to the buffers of different widths, which tended to inflate commission errors (buffers greater than 4 km) or omission errors (buffers smaller than 4 km). The approximate month of fire occurrence was derived from the MODIS active fire product for each forest loss patch. De Groot *et al* (2013) shows that 34% of all fires in Siberia had no active fire points detected due to the fire being obscured by clouds and smoke, or not burning actively at the time of satellite overpass. This could lead to potential omission errors in our stand-replacement fire product, though the likelihood of fires being too small to be detected by MODIS active fire product and also being stand-replacement fires was low as Giglio *et al* (2006) showed that active fire counts in boreal forests were representative of burned area. We performed visual assessment of loss patches more than 1000 ha mapped as fire- and non-fire-related loss. We manually added 0.19 Mha of stand-replacement fire with missing hot-spot data (1.1% of all stand-replacement fire area), and removed 0.04 Mha of falsely attributed fire-related loss. This is considered potential error margin for a single MODIS active fire detection as these results were not verified with Loboda *et al* (2011) burned area product.

In the second step we used a regional MODIS-based burned area product for Russia (Loboda *et al* 2011) to map stand- versus non-stand-replacement fire dynamics. The regional burned area algorithm was originally created in 2007. The Landsat-based global forest cover loss dataset (Hansen *et al* 2013) allowed us to differentiate forest and non-forest fires. Following a conservative approach, only the fires that penetrate more than 500 m inside forest patches (the approximate burned area product pixel size) are considered burned forest areas. MODIS-detected forest burned areas outside Landsat-detected forest loss patches were classified as non-stand-replacement fires. Fires outside of the Landsat forest mask were considered non-forest burns and not included in this analysis.

3. Results and discussion

Total stand-replacement forest fire area within the Russian Federation for 2002–2011 was estimated at 17.7 Mha. The smallest stand-replacement fire loss occurred in 2004 (0.4 Mha) and the largest annual loss occurred in 2003

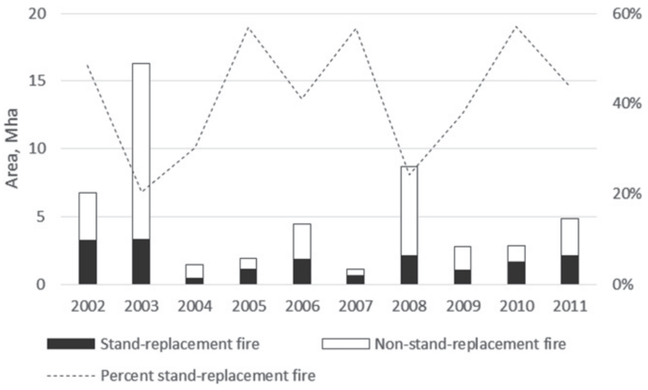

Figure 2. Forest stand- and non-stand-replacement fire by year.

(3.3 Mha). The average stand-replacement fire proportion for all forest fires calculated in this analysis was 33.6%. The annual burned area of stand-replacement fire was less variable than the annual burned area of non-stand-replacement fires in Russia (figure 2) with the coefficients of variation 56% and 121%, respectively.

Figure 3 shows the proportion of stand- and non-stand-replacement fire from 2002 to 2011 across the Russian Federation. The larger circles indicate larger burned areas within forests. Non-stand-replacement fires are most common in Southern Siberia, though this region experiences larger fires. Most of the stand-replacement fires occur in Northeast Siberia. We found a distinct correlation (correlation coefficient of 0.91) between the proportion of stand-replacement fire and latitude (figure 4). The percentage of stand-replacement fires decrease along the North to South gradient from 50–60% to 10–20%. The largest area of stand-replacement fires in the last decade occurred in Yakutia (Northeast Siberia) with 0.58 Mha, or 0.35% of total forest area burned annually.

There is a strong relationship between the proportion of stand-replacement fire and season. The majority of stand-replacement fires occur in late summer—July and August (figure 5). Late summer fires are common for the Northern and Central taiga areas. In Southern Siberia, where most of the fires are non-stand-replacement, fires usually occur in spring—April and May. For example, in the Transbaikal region (49°N–59°N, 108°E–122°E), 75% of all annual fire area burned in spring with only 9% of this fire-affected area resulting in stand-replacement. For summer fires in this region, 48% of burned area is stand-replacement, a proportion similar to Northern Russia. The average annual proportion of stand-replacement fire for the Transbaikal region is 19%. In Yakutia (Northeast Siberia 55°N–74°N, 105°E–163°E), the average proportion of stand-replacement fire is 57%, with 77% of fires occurring between July and August.

Previous Russian studies based on statistical data (Melekhov 1947, Furyaev 1996) argue that forest type and structure can determine fire type. Scots pine and larch forests are believed to be more resistant to fire and to have elevated fire frequency, like in Southeast Siberia every 8–21 years (Ivanova and Ivanov 2005). Pine and larch usually have rapid regeneration on burned areas (Melekhov 1947). Pine and larch are often classified as 'resister' strategy species (Wirth 2005). Spruce and fir forest have low resistance to fire, fire return interval more than several hundred years and are classified as 'avoider' species (Furyaev 1996, Wirth 2005). Birch can survive forest fires and aspen is fire intolerant (Nikolov and Helmisaari 1992). Birch and aspen have extremely fast after fire regeneration and are classified as 'invader' species (Wirth 2005).

We used our data combined with a forest type map (Bartalev et al 2004) to analyze fire frequency within different forest types (figure 6). Dark conifer (spruce, fir, Siberian pine) forests have the longest fire return interval (640 years) and the largest proportion of stand-replacement fire (72%), which corresponds to the classic 'avoider' species definition. The proportion of stand-replacement fires in light conifer (larch and Scots pine) forests was 42%. Light conifer stands comprise 65% of all non-stand-replacement and 79% of all stand-replacement fire in Russia. Siberian light conifer forests have stand-replacement fire regime in North taiga and non-stand-replacement regime in South taiga. In European Russia, Scots pine forests have stand-replacement fire regimes both in the Southern and in the Northern parts of the region.

We found that the most fire-resistant forest type is temperate oak-dominant broadleaf forest in the Far East of Russia (less than 3% stand-replacement fires). Similarly, mixed secondary forest stands (typically birch-dominant) are also less likely to experience stand-replacement fires.

We compared our product with a MODIS-based post-fire tree mortality assessment for 2006–2012 from the Space Research Institute of the Russian Academy of Sciences (Stytsenko et al 2013). In this study, post-fire tree mortality data was presented in four classes: 1—low, 2—medium, 3—high, and 4—very high tree mortality. Classes 1–2 are non-stand-replacement fire, classes 3–4 are stand-replacement fire. The Stytsenko product estimated 1.69 Mha of annual stand-replacement fire area for the period of 2006–2011. For the same period, we estimate stand-replacement fire to be 1.54 Mha, a value 7% lower than the Stytsenko estimate with relative agreement in terms of interannual variation (figure 7). Finally, we compared our stand-replacement burned area estimates with the estimates for 2002–2011 used in Russia's national greenhouse gas emissions inventory report submitted to the IPCC (Federal Service for Hydrometeorology and Environmental Monitoring 2013). The national estimate based on the interpolation of forest inventory data is 13% lower than this analysis.

Our estimate of the average stand-replacement fire proportion (33.6%) is slightly above the range of previously published estimates of crown fire proportion derived using statistical data (16–24%; Korovin 1996, Gromtsev 2002) and remote sensing data (6.5%, De Groot et al 2013). The results of this analysis show that a significant proportion of fire-related tree mortality was due to high intensity surface fires.

The proportion of stand-replacement fire has high annual variation. This variation comes from regional differences in forest type and fire regime. Fire regimes at the regional scale were described in several papers (Rubtsov et al 2010, Furyaev 1996, Sofonov and Volokitina 1990). Burned area and

Figure 3. Proportion of stand- and non-stand-replacement fire from 2001 to 2012; size of circle also proportional to total forest burned area within 4° × 8° grid.

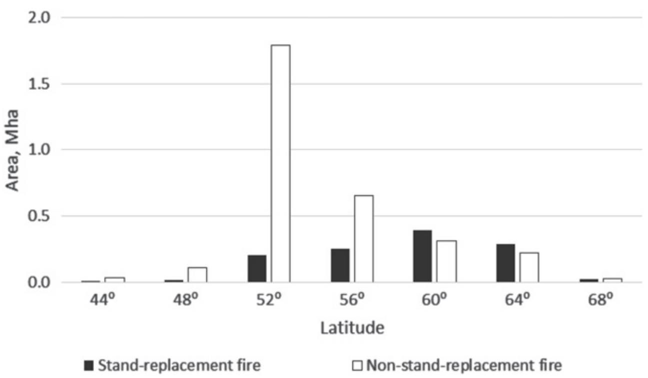

Figure 4. Relation between stand-replacement fire proportion and latitude.

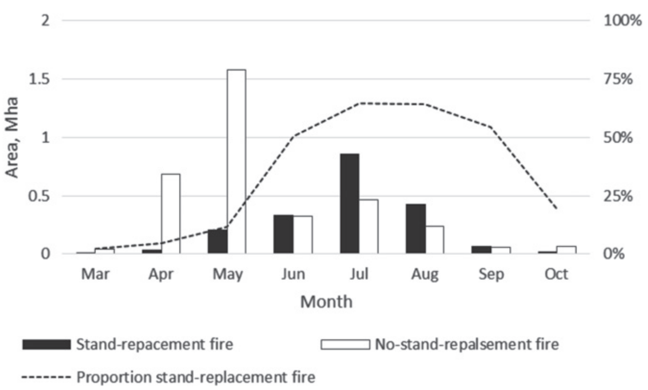

Figure 5. Seasonal dynamic stand- and non-stand-replacement fire.

proportion of low intensity surface fires increase across Russia from West to East along temperature and precipitation gradients (Furyaev 1996). Korovin (1996) showed differences in the fire season from North to South based on official fire statistics. A study along the Yenisei meridian (central Siberia) showed the increase in burned area and decrease in fire severity from North to South (Furyaev *et al* 2004, Tsvetkov 2006). Rubtsov *et al* (2010) performed regional analysis of fire regime based on active fire data, but ignored regional differences in fire severity. Our results suggest that the regional distribution of severe fire weather is also important. During the years when fire weather affects Northern regions, the proportion of stand-replacement fires in the entire country is high. However, when warm weather is concentrated in Southern regions, the fraction of national stand-replacement fires is lower. Years with high burned area totals, 2003 and 2008, had the lowest stand-replacement fire proportions (20% and 24%, respectively) due to the fact that most of the fires during these years occurred in Southeast Siberia.

Several factors can be responsible for the latitudinal differences in stand-replacement fire fraction. Kharuk *et al* (2005) and Furaev *et al* (2004) showed that forest floor fuel loads decrease from North to South due to slow organic material decomposition in colder climates (Tsvetkov 2006). Fire return intervals also decrease from North to South due to increased fire season length and population density (Furaev *et al* 2004, Korovin 1996). It has been shown that Northern Larch forests on permafrost soils have less resistance to fire and higher tree mortality following surface fires that damage root systems (Tsvetkov 2006). Southern taiga Larch forests have high resistance to surface fires (Kharuk *et al* 2005). In Central Siberia, McRae *et al* (2006) and Conard and Solomon (2008) describe a mixed fire regime characterized by 25% stand-replacement fire proportions.

For a part of South Siberia (80°–100°E, 54°–62°N), we compared our results with reconstructed fire interval data based on species composition and age structure (Furyaev 1996). For the Eastern part of this area, dominated by light

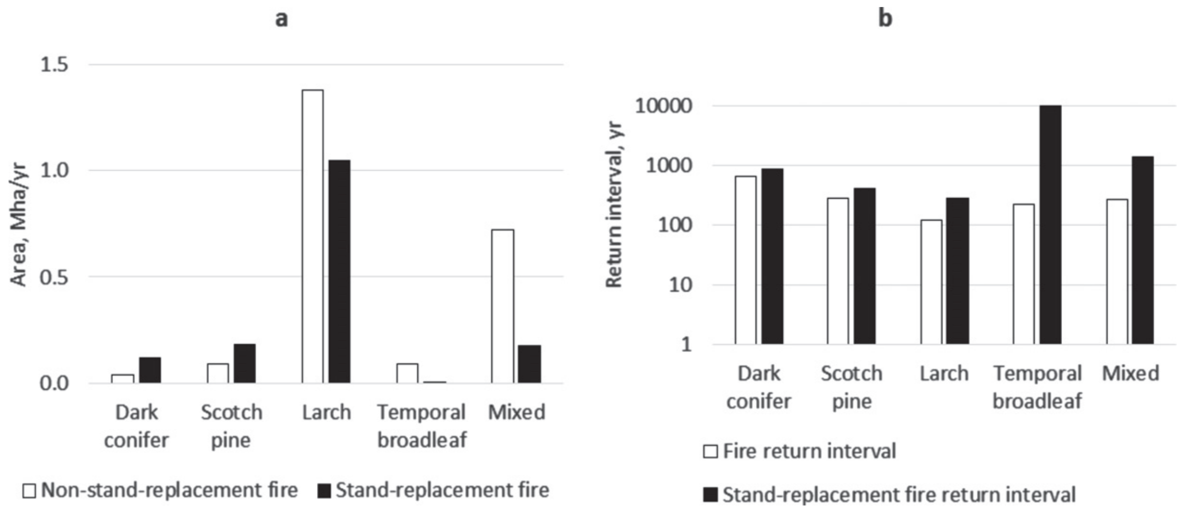

Figure 6. Annually burned area (a) and stand-replacement fire return interval (b) by forest type.

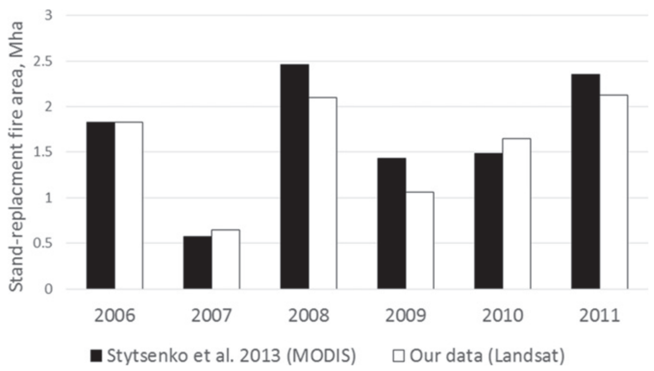

Figure 7. Forest stand-replacement fire area estimation based on Landsat and MODIS data.

conifers, our annual average stand-replacement fire fraction (0.11%) is close to the historic estimate of 0.18% (Furyaev 1996). However, for the Western part of the area consisting of dark conifers, Furyaev (1996) estimated annual stand-replacement fire fraction of 0.33% for the 1700–1970 time period. This is equivalent to a 300 year stand-replacement fire return interval. Our analysis quantified a 0.04% annual stand-replacement fire rate, equivalent to a 2500 year stand-replacement fire return interval.

While climate cycles can lead to fire regime change (Kharuk *et al* 2005, Groisman and Soja 2009), other drivers of fire frequency and severity are present in Russian forests. The Siberian moth (*Dendrolimus superans sibiricus*) regularly impacts forests in Siberia and in most cases leads to large and severe fires (Furyaev 1996) due to increased fuel loads. Between 1999 and 2002, Siberian moth infestations occurred in Yakutia, leading to more than 1 Mha damaged. In 2010, Siberian moth damage was detected over an additional area of about 0.1 Mha (Buratia Republic Forest Health Center 2013). We observed stand-replacement fire over much of this same area.

Socio-economic factors like population density and infrastructure also influence fire regimes. The fire return interval in the Transbaikal region was reduced by half after the construction of the trans-Siberian railroad due to increase rate of anthropogenic fire ignition (Swetnam 1996). In North Siberia in the mid 20th century, a geologic survey led to increased burned area (Kharuk *et al* 2005). In Southern Siberia, clear cuts increase fire hazards (Kukavskaya *et al* 2013b). Additionally, 3.8 Mha of peat bogs, mostly in European Russia, have been drained (Paavilainen and Päivänen 1995) and converted to pine plantations with higher fire risk.

Other factors reduce fire risk. Increasing populations can result in fire suppression. Timber harvesting can increase the acreage of secondary broadleaf forest area. Broadleaf and mixed forests have lower stand-replacement fire rates according to our data. The logging area in Russia increased during the last decade from 0.6 to 1 Mha (Zamolodchikov *et al* 2011). Our data does not show a statistically significant trend of annual stand-replacement fire during the same time interval. However, annual variation of burned area is very high (0.4–3.3 Mha) while logging area inter-annual variation is low.

Hansen *et al* (2013) estimate an approximate 2.6 Mha annual forest loss in Russia (in more than 25% canopy cover forests), equivalent to 0.33% of forest area in all of Russia. This analysis found that wildfire is a driver of 65.5% of total forest disturbance and this estimation is nearly equal to Potapov *et al* (2008) estimate of fire-related forest loss (65.2%) for Russian boreal forests for a time period of 2000–2005. Zamolodchikov *et al* (2011) found the average annual logged area for Russia from 2000 to 2010 is 0.8 Mha, or roughly 30% of all forest disturbance. Based on this analysis, the average annual stand-replacement fire area in Russia is roughly twice that of the annual logged area. Other disturbances include large windfalls occurring in 2009–10 (Baumann *et al* 2014), Siberian moth outbreaks in Siberia (Devyatova *et al* 2006), and bark beetle outbreaks in European Russian spruce forests (Maslov 2010). Our results suggest that fire is still the most important stand-replacement disturbance agent in Russian forests. Climate change and variability may lead to an increased role of fire in forest stand-replacement disturbance. However, the time period used in this analysis, 2002 through 2011, and the accurate information on stand-replacement fire conditions in the 20th century is not available from the scientific literature to allow for make suggestions about the relationship between climate change and stand-replacement fire.

4. Conclusions

Through the integrated use of Landsat and MODIS-derived forest cover and fire products, a 30 m resolution stand-replacement fire product for the Russian Federation from 2002 to 2011 was created. Average annual stand-replacement fire area was estimated to be 1.77 Mha, with an annual range of 0.4–3.3 Mha. Our stand-replacement burned area estimation was similar to the MODIS-based post-fire tree mortality estimate of Stytsenko *et al* (2013) and 13% higher than the areal estimation used in Russia's national greenhouse gas emissions inventory report submitted to the IPCC. Of the vast majority of stand-replacement loss due to fire, approximately 79% occurred in light conifer taiga (which account for 51% of all Russian forests according to The State and Use of Russian Federation Forests) while only 8% occurred in dark conifer (which account for 15% of all Russian forests). Despite an increase in logging intensity in the last 10 years, fire is still the most important stand-replacement disturbance agent in Russian forests. Annual average stand-replacement area was estimated to be twice that of logging area. Results improve our understanding of the spatio-temporal variation of the leading land change dynamic in Russia and can be used with historical fire regime data to develop effective current and future fire management policies and improved forest biogeochemical cycle models.

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