Surface forcing of non-stand-replacing fires in Siberian larch forests

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Abstract
Wildfires are the dominant disturbance agent in the Siberian larch forests. Extensive low- to mediate-intensity non-stand-replacing fires are a notable property of fire regime in these forests. Recent large scale studies of these fires have focused mostly on their impacts on carbon budget; however, their potential impacts on energy budget through post-fire albedo changes have not been considered. This study quantifies the post-fire surface forcing for Siberian larch forests that experienced non-stand-replacing fires between 2001 and 2012 using the full record of MODIS MCD43A3 albedo product and a burned area product developed specifically for the Russian forests. Despite a large variability, the mean effect of non-stand-replacing fires imposed through albedo is a negative forcing which lasts for at least 14 years. However, the magnitude of the forcing is much smaller than that imposed by stand-replacing fires, highlighting the importance of differentiating between the two fire types in the studies involving the fire impacts in the region. The results of this study also show that MODIS-based summer differenced normalized burn ratio (dNBR) provides a reliable metric for differentiating non-stand-replacing from stand-replacing fires with an overall accuracy of 88%, which is of considerable importance for future work on modeling post-fire energy budget and carbon budget in the region.

1. Introduction
Boreal forests are a major biome on Earth with strong influences on global climate (Bonan et al 1992, Melillo et al 1993, Chapin et al 2006). Among their influences, it has been shown that the albedo effect, i.e. its relatively lower albedo compared with tundra and other forest types during the snow seasons, is particularly important, as it may render the entire boreal zone to be a net heat sink (Bonan et al 1992, Betts 2000, Bala et al 2007, Bonan 2008). However, the albedo-induced warming effect of the boreal forests is considerably weakened by wildfires, which are a major disturbance agent throughout the global boreal biome (Bourgeau-Chavez et al 2000, Kasischke 2000, Shvidenko and Nilsson 2000). Although wildfires can impose warming effects through carbon-related emissions, it has been suggested that over moderate to long term (20–150 years), their cooling effect may play a more dominant role, resulting in a net negative forcing to the climate (Randerson et al 2006). This is because wildfires can considerably elevate forest albedo through different mechanisms. Over shorter temporal scales, wildfires cause the increase in winter and spring albedo by damaging forest canopy (Amiro et al 2006, Randerson et al 2006, Jin et al 2012). Intact forest canopy effectively shields ground layer; when it is damaged or removed by wildfires, forest floor is exposed. And because snow albedo is very high and there are prolonged snow seasons in the boreal zone each year, the elevated snow season albedo in the burned stands leads to a large increase in annual mean albedo. Over longer time spans, as canopy gradually closes, most burned forests in North America still show elevated albedo which is driven by the dominance of broadleaf deciduous species, such as aspen (Populus spp.) and birch (Betula spp.), in the early successional stage (Amiro et al 2006, Liu and Randerson 2008, Lyons et al 2008, McMillan and Goulden 2008). Forests dominated by the deciduous species usually have higher albedo both in the summer (due to higher leaf reflectance) and winter (due to exposure of snow cover after senescence).
Representing about a fifth of the global boreal forest (Osawa and Zyryanova 2010), the Siberian larch forests are a major component of the high-latitude boreal zone. Compared with other boreal forests, these forests in Eastern Siberia are unique in many aspects. For instance, they are dominated by larch species (Larix spp.) (Abaimov 2010, Osawa and Zyryanova 2010). Being deciduous needleleaf species, larch are different from many dominant tree species in other boreal zones, including pine (Pinus spp.) and spruce (Picea spp.), in that they shed their leaves during the snow seasons, leading to higher canopy openness during those time periods. Moreover, unlike the other major boreal zones, where a few tree species rotate dominance during succession, larch generally dominate the entire succession cycle (Zyryanova et al 2010a). In addition, unlike many species in the North American boreal zone which are susceptible to fire, larch are generally adapted to wildfires (Wirth 2005). Their thick bark can effectively prevent larch trees from being damaged by low-severity fires (Wirth 2005, Schulze et al 2012). They also drop low hanging branches, limiting the development of fuel ladders that facilitate the spread of fire into the forest canopy (Wirth 2005). In addition, larch forests are less prone to high-severity fires because their canopy closure is relatively low (Babintseva and Titova 1996, Kharuk et al 2010, Sofronov and Volokitina 2010, Kharuk et al 2011). These factors together effectively lower the likelihood of the occurrence of crown fires and result in extensive occurrence of surface fires which are generally much lower in severity (Wirth 2005). According to Korovin (1996), about 80% of fires in the protected territory of the Russian Forest Fund, which covers the majority of the Russian forests, are surface fires. Kukavskaya et al (2013) stated that the proportion of surface fires is higher than 50% in Siberia in most years. De Groot et al (2013) suggested that surface fires account for more than 90% of total fires in the forests in Siberia, while Krylov et al (2014) estimated that surface fires consist of more than 70% of fires in Russia. Due to the fact that most of the these estimates were not for larch forests specifically, as there are a considerable amount of Scots pine (Pinus sylvestris) forests in Siberia in which surface fires are also common (Conard and Ivanova 1997, Kharuk et al 2010, Kukavskaya et al 2013), there has not been a quantitative estimate regarding the surface fire extent within the Siberian larch forests. The uncertainty involving the areal estimates of surface fires is also a consequence of several other factors including the remoteness of the region, unreliable official statistics, and the mapping challenges from remotely-sensed data as many surface fires occur under the forest canopy and do not emit a thermal signal comparable in magnitude to crown fires (Conard and Ivanova 1997, Sukhinin et al 2004, Kukavskaya et al 2013).

It is worth noting that although the severity of surface fires in Siberian larch forests are generally lower than crown fires, sometimes they can also reach high severity and lead to significant tree mortality (Conard and Ivanova 1997, Kharuk et al 2010). This is mainly attributed to a combination of the shallow root system of larch (underlain by continuous permafrost) and dense lichen/moss cover (Tzvetkov 1996, Kharuk et al 2010). Similar to the large uncertainty associated with the proportion of surface fires in the fire regime of Russian boreal forests, there has not been a general consensus regarding what percentage stand-replacing (SR) fires is in all surface fires; however, it is commonly accepted that a considerable portion of surface fires do not lead to tree mortality (Sofronov and Volokitina 2010, de Groot et al 2013). In addition, the mortality rate of wildfires in the Siberian larch forests is generally higher in the north and lower in the south. This is due to the gradual loss of the influences of continuous permafrost following a north-south gradient, as confirmed by studies based on both field observations (Matveev and Usoiltzev 1996) and remote sensing (Krylov et al 2014).

A recent study (Chen et al 2018) showed that SR fires in the Siberian larch forests impose a strong cooling effect through the post-fire albedo change with magnitudes similar to those of the North American boreal fires. Since non-stand-replacing (NSR) surface fires are common throughout the region, it is likely that they also exert significant climatic impacts through the albedo effect. However, most past research on surface fires in the region focused on their implications on the carbon budget (e.g. Soja et al 2004, Schulze et al 2012, Berner et al 2012), while their potential climatic impacts through albedo have generally been overlooked. To the best of our knowledge, the direction and magnitude of the albedo-induced impacts by NSR fires have not yet been assessed independently of SR fires.

In this study we also aim to identify a method that can be reliably used to differentiate such fire types as soon as possible after fire occurrence to enable projection of likely impacts of specific fire events on surface forcing (SF). Since one of the major differences between NSR fires and SR fires lies in burn severity (Conard and Ivanova 1997, de Groot et al 2013), this study examines several remotely sensed indices which may be used to differentiate SR and NSR fires. There is an abundance of remote sensing-based indices which have been used as proxies for burn severity, among which the differenced normalized burn ratio (dNBR; Key and Benson 2006) is a prominent example. Calculated as the difference in normalized burn ratio (NBR; Garcia and Caselles 1991) which captures the fire-induced changes in near- and shortwave-infrared wavelengths, dNBR is a widely-used index in remote sensing-based research involving burn severity. In addition to dNBR, difference in snow season albedo and the differenced normalized difference vegetation index (dNDVI) were also used in this project because they
have been shown to represent burn severity in boreal forests and it has been suggested that the performance of remotely sensed burn severity indices is usually inconsistent over different ecosystems (Murphy et al 2008, Jin et al 2012, Rogers et al 2015).

2. Materials and methods

This project focuses on a forested region in Siberia that is dominated by larch. Located within 50°–66° N and 94°–140° E, the study area (shown in figure 2) encompasses a vast expanse with the total area of 1.93 × 10^6 ha. The larch dominance was determined based on the deciduous needleleaf forest class in the MODIS MCD12Q1 Land Cover Type Product (Friedl et al 2002, Friedl et al 2010) (for detailed procedure for the study area delineation, please refer to Chen et al 2016). There are two major larch species within the region and each of them dominates a sub-region within the study area (Larix gmelinii in the west and Larix cajanderi in the east) (Nikolov and Helmisari 1992, Abaimov 2010). Following larch, Scots pine is usually considered as the second most dominant species in the region (Shorohova et al 2009, Zyryanova et al 2010b). Wildfires are the primary disturbance agent in the region (Goldammer and Furyaev 1996, Zyryanova et al 2010a). In the northern part of the region because there are very little human activities within the region, wildfires are mostly naturally caused (Goldammer and Furyaev 1996, Kharuk et al 2010, Sofronov and Volkovitina 2010). In contrast, in the south, wildfires are mostly of anthropogenic origin (Korovin 1996).

Two datasets were used as data inputs to map NSR fires in the region. The first dataset is the MODIS-based burned area mapping product (Loboda et al 2007) developed for Russian forests. At 500 m resolution, it was produced based on the combined information derived from the MODIS active fire product (Giglio et al 2003) and surface reflectance data (Vermote et al 2002). The second dataset is the 30 m stand-replacing fire mapping product (SRFM; Krylov et al 2014) which identifies SR fires that occurred between 2001 and 2012 in the Russian boreal forests. NSR fires in this study were identified by differencing the two datasets based on the assumption that fires that were mapped by the MODIS product but excluded by the SRFM product in the same year are likely to be NSR fires. The SRFM data was first resampled to 500 m to match the spatial resolution of the MODIS burned area product. Because the resampling procedure is particularly likely to impact the edges of SR events adjacent to NSR fires, to account for this potential misidentification, the resampled SRFM product was buffered outwards by 500 m to limit the inclusion of SR fires. The resultant NSR fire maps were compared with the burned areas mapped in the MODIS-based burned area product for each year between 2001 and 2012. In some cases the uncertainty in timing of mapped forest loss in the SRFM resulted in attributing forest loss to the fire events which occurred one year earlier or later (Krylov et al 2014). To account for this uncertainty, we re-evaluated the timing of all SR fires so that the fire polygons of year x from the MODIS-based burned area product were compared with those from three consecutive years (i.e. years x−1, x and x+1) in the processed SRFM product, and the burned areas mapped in the former but not in the latter were considered NSR fires.

Annual mean SF was computed for all mapped NSR fires following:

\[ SF = (A_{t1} - A_{t2}) \times S_1 \]

where \( A_{t1} \) and \( A_{t2} \) represent annual mean blue-sky albedo for years \( t1 \) and \( t2 \) (\( t1 < t2 \)), and \( S_1 \) represents mean downward shortwave surface flux between years \( t1 \) and \( t2 \) calculated based on data from the Clouds and the Earth’s Radiant Energy System project (Kato et al 2013). Blue-sky albedo was, in turn, calculated by taking the mean value of black-sky and white-sky albedo from the MODIS MCD43A3 albedo product (Collection 6; Schaaf et al 2002). The SF trajectory calculated based on surface fires was compared with that for SR events (Chen et al 2018) to provide an intercomparison of SF magnitude and longevity for the two fire types. In addition, to analyze the seasonal contribution of albedo changes to total SF, MODIS black-sky albedo for forests that experienced NSR fires was extracted and the annual, snow-off (June, July and August) and snow-on (October and March) mean albedo trajectories were constructed (other months were excluded in this analysis because they are either shoulder months when snow is actively accumulating/melting or in shortage of sufficient valid observations). For reference, forest albedo over two years before the fire events was tracked and used to represent the pre-fire condition.

Finally, three indices—snow season differenced albedo (dA), summer dNBR, and summer dNDVI—were examined to quantify their success rate at differentiating NSR fires from SR fires in the region. Snow season dA was calculated as the difference in mean October/March blue-sky albedo. Because very few valid observations were acquired from November through February in most of the study area and that October and March are generally still within snow season in the region, dA is measured between the albedo of the first post-fire snow season and the last pre-fire snow season. For example, snow season dA for a fire event that occurred in year \( x \) would be calculated as

\[ dA_x = \frac{A_{October} - A_{March} + 1}{2} - \frac{A_{October} - 1 + A_{March} + 1}{2} \]

Summer dNBR and dNDVI were calculated as the difference in mean summer (i.e. June, July and August) NBR and NDVI. For example, summer dNBR and
dNDVI for a fire event that occurred in year $x$ would be calculated as

$$dNBR_x = \frac{NBR_{June,x-1} + NBR_{July,x-1} + NBR_{August,x-1}}{3} \frac{- NBR_{June,x+1} + NBR_{July,x+1} + NBR_{August,x+1}}{3}$$

$$dNDVI_x = \frac{NDVI_{June,x-1} + NDVI_{July,x-1} + NDVI_{August,x-1}}{3} \frac{- NDVI_{June,x+1} + NDVI_{July,x+1} + NDVI_{August,x+1}}{3}$$

where NBR and NDVI were, in turn, calculated based on different combinations of two bands from the MODIS MCD43A4 reflectance data (Schaaf et al 2002):

$$NBR = \frac{(\text{Band 2} - \text{Band 7})}{(\text{Band 2} + \text{Band 7})}$$

$$NDVI = \frac{(\text{Band 2} - \text{Band 1})}{(\text{Band 2} + \text{Band 1})}$$

All three indices were calculated for all NSR fires identified in this project and SR fires mapped in Chen et al (2017) based on the years immediately before and after the years of fires to develop a consistent method that is not impacted by the specific timing of fire occurrence within a given fire season. Then each of the three indices was examined through a series of binary classifications to differentiate SR and NSR fires. To identify the classification threshold with the most optimal classification accuracy for each index objectively, the entire range of the distribution of each index was divided into 100 equal intervals which were used iteratively to determine the threshold with the best binary classification accuracy.

#### 3. Results

The total area that experienced NSR fires between 2001 and 2012, including repeated burns, is 122,407 km$^2$, which is $\sim$20% greater than the total area of SR fires (103,460 km$^2$) that occurred during the same time period (Chen et al 2016). The amount of area burned in NSR fires in individual year varies very substantially—more than 75% of area burned in NSR fires occurred in 2003 and 2012 combined (figure 1). The spatial distribution of NSR fires in the study area shows strong clustering patterns as NSR fires are clustered in two regions (figure 2): (1) the area (59°N–63°N and 129°E–136°E) along the mid- to down-stream of the Aldan River, a tributary of the Lena River, and (2) the southern edge of the study area (52°N–55°N and 111°E–127°E) along the Chinese border in the east and the temperate grasslands in southern Zabaykalsky Krai in the west.

Mean SF of NSR fires is shown to follow a similar trajectory as that of SR fires but the magnitude of the fire-induced forcing is considerably smaller (figure 3). In the first two years after fire, mean SF from both NSR and SR fires are similar with the difference being smaller than 0.3 W m$^{-2}$. However, by year 3, the magnitude of SF of SR fires increases at a much more rapid rate. Mean NSR fire SF grows at a mean rate of $-0.16$ year$^{-1}$ between years 2 and 6, after that the direction of the trajectory changes as the SF gradually moves towards the pre-fire state at a mean rate of 0.13 year$^{-1}$ between years 6 and 14. The albedo trajectories constructed for NSR fires (figure 4) show that the cause of the cooling effect in the post-NSR fire sites is the increases in albedo, particularly during the snow season. The variability of SF of NSR fires is much larger than the SR fires. After occurrence of a NSR fire, forest stands can exhibit either warming or cooling effects within the 14 year time period after fire.

The difference in post-fire forcing between NSR and SR fires brings out the importance of separating the two fire types in modeling activities that attempt to forecast the post-fire impacts on regional and global
4. Discussion

4.1. Mapping NSR fires in Siberian larch forests
NSR fires are a key element of the Siberian larch forest functioning. They support larch dominance by increasing soil temperature and drainage and eliminating competition (Shorohova et al 2009, Sofronov and Volokitina 2010, Schulze et al 2012, Kharuk et al 2016). Because of the differences in spatial coverage, a direct comparison of the total burned area estimated by this project and those by previous studies is not feasible. However, in terms of the proportion of NSR fires, taken into account the fact that surface fires include not only NSR but also SR fires, our result (54%) is consistent with those yielded by previous studies, which almost uniformly suggested that surface fires cover more areas than SR fires (Korovin 1996, de Groot et al 2013, Kukavskaya et al 2013, Kukavskaya et al 2017).

radiative budget. The results (figure 5) show that dNBR provides the best classification accuracy (88%) achieved at the threshold of 0.175. In contrast, dA and dNDVI performed poorly, with classification accuracy generally below 60%.
Figure 4. Mean albedo trajectories for the forests that experienced NSR fires generated using the MODIS albedo data for 2001–2015. The vertical dashed line represents the year of fire occurrence. The negative ‘year since fire’ range presents pre-fire conditions over two years before fires. The horizontal dashed lines represent the mean pre-fire annual albedo for the corresponding trajectories.

The mapping accuracy of NSR fires is inevitably affected by uncertainties. In addition to those that were introduced during the fusion of datasets with different spatial resolutions, another source of uncertainty involves the accuracies of the remotely sensed datasets that were used. Among these, it is worth noting one source that is specific to mapping NSR fires and it stems from the challenges associated with mapping NSR fires based on existing remotely sensed datasets. Because of their low severity, the thermal signals emitted by NSR fires are generally weak. This, coupled with the relatively large footprints of commonly-used active fire observations (AVHRR- and MODIS-based), makes mapping NSR fires accurately quite difficult. With the development of the Visible Infrared Imaging Radiometer Suite (VIIRS) active fire product (Csiszar et al 2014), it is expected that the accuracy in mapping NSR fires can be increased significantly. With a higher spatial resolution (375 m) and better radiometric quality, the VIIRS active fire product possesses the potential to identify low severity NSR fires much more accurately than its predecessors (Csiszar et al 2014).

4.2. Surface forcing trajectory of NSR fires

According to the established SF trajectory, NSR fires in the region on average impose a cooling effect through the albedo change within 14 years after fire. A further analysis on the post-fire annual and seasonal albedo trajectories shows that the cooling is attributable to the increased albedo in burned forests, especially during snow-on season. This is similar to the mechanism for the albedo-induced cooling observed in the forests that experienced SR fires, which is likely a result of canopy damage and sub-canopy mortality caused by NSR fires. Although NSR fires have been known to be of lower severity than SR fires, they can still lead to a certain level of canopy loss by killing the juvenile trees which are less resistant to fires than the mature trees (Conard and Ivanova 1997, Shorohova et al 2009, Schulze et al 2012, Kharuk et al 2016), which may also cause increases in forest albedo. Another potential reason is that although NSR fires do not cause significant damage to the canopy of mature trees, they consume shrubs in the understory which also create a shading effect similar to the canopy. Post-NSR fire albedo and SF trajectories exhibit higher variability than SR fires as indicated by the uncertainty intervals in figures 3 and 4, respectively. We believe this may be contributed to the inclusion of other tree species, especially pine, in our study area. Pine is known to co-exist with larch in Siberia. Due to their similarity in canopy openness, together they constitute the vast forest region commonly known as the ‘light taiga’ (Tishkov 2003). However, as an evergreen species, pine retains the canopy during the snow season. This inevitably leads to the differences in post-fire albedo dynamics in the burned forests formed by larch and pine, hence introducing higher variability in the post-fire climatic effects. Moreover, the differences in canopy openness in different parts of the Siberian larch forest could also contribute to the variability in observed post-fire albedo and SF.

Associated with the higher variability of albedo and SF trajectories of NSF fires is the fact that a significant
fraction of forests that experienced NSR fires exert a warming effect. This is in great contrast with SR fires, which consistently lead to cooling effects. We believe this is, at least partially, due to the darkening effect of NSR fires. One of the immediate effects of wildfires is usually the darkening of the forest floor and tree boles caused by char deposition (Chambers and Chapin 2002, Randerson et al. 2006), which lowers the albedo of the burned forests and thus leads to a warming effect. Another factor likely contributing to the warming effect is the lengthening of snow-free season in Siberia. A considerable increase in mean annual temperature has been observed in Siberia over the past several decades and it is widely expected to persist in
the region (IPCC 2013). One of the consequences of this warming is an increase in duration of snow-free seasons, which has been evident in spring and fall albedo record within the Siberian larch forests since 2000 (Chen et al. 2018).

4.3. Differentiating NSR from SR fires using remote sensing-based burn severity indices

NSR and SR fires differ in burn severity and resultant post-fire impacts (Conard and Ivanova 1997, de Groot et al. 2013). Although there have been a host of studies showing the in-situ differences between the two fire types in the impacts on forest properties such as biomass accumulation and successional patterns (Sofronov and Volokitina 2010, Schulze et al. 2012), the effective application of findings from field studies at the regional scale is hindered, at least partially, by the challenge associated with our ability to map NSR and SR fires reliably from satellite observations. As discussed previously, the identification of NSR fires using remotely sensed data has been mostly linked to active fire observations primarily related to very coarse spatial resolution and a comparatively weak thermal signal from creeping NSR fires. Although a fraction of NSR fires are captured by surface reflectance change-based burned area products, none of the burned area products currently routinely differentiate between the two fire types. In part this is a result of the larger discourse in the scientific and management communities on what constitutes burn severity in different ecosystems (French et al. 2008, Hoy et al. 2008). For example, while tree mortality is commonly associated with burn severity, it is not an informative proxy for burn severity in the black spruce forests in Alaska, where in-situ studies show that burn severity is usually indicated by consumption of the surface organic layer (Hoy et al. 2008). Meanwhile, there has been an equally broad debate on how burn severity can be measured using remote sensing (French et al. 2008). Although a number of metrics have been proposed to measure burn severity within boreal biome, their performance is highly influenced by vegetation and terrain conditions and therefore their usage needs to be calibrated for specific applications (French et al. 2008). This study does not address the issue of defining and mapping burn severity in Siberian larch forests. Instead it focuses on a very specific aspect, which can be related to burn severity, and is specific for Siberian larch forests only. This study shows that for the purpose of separating NSR fires from SR fires, dNBR presents the strongest metric among the three that were examined. Not only is dNBR capable of accurately differentiating the two fire types, it is also easily computed. Therefore, it has the potential to be readily adopted in a variety of large-scale fire-based studies, including the work modeling post-fire energy budget and carbon budget, which have been shown to be significantly impacted by fires of different severity.

5. Conclusion

About 20% of global boreal forests are located in Siberia in the form of the Siberian larch forests. Consisting of mostly larch, this is the largest forested region that is dominated by deciduous needleleaf species in the global boreal biome. The sheer size and the uniqueness of these forests, coupled with the fact that the high-northern latitudes have seen and will continue to experience the highest level of warming in the world (IPCC 2013), render a better understanding of the current land-atmosphere interaction in this region a necessity for Earth science community. NSR fires are a key component of fire regime in the Siberian larch forests. In addition to their influence on the carbon budget through carbon emissions, NSR fires also affect the energy budget through the resultant change in surface albedo. This work presents the first regional analysis focusing explicitly on the SF of NSR fires in the Siberian larch forests. The results show that similarly to SR fires, NSR fires also impose an overall cooling effect through SF due to increased snow-on albedo resulting from the partial canopy damage and the removal of shrub understory. The cooling effect of NSR fires, however, is much weaker than that of SR fires, especially over several years after the fire. This carries strong scientific implications because it highlights a potential need to differentiate the two fire types in various studies in which the impacts of wildfires are involved, including those modeling post-fire radiative budget. Based on the rationale that NSR and SR fires differ in burn severity, this study identifies summer dNBR as a remote sensing-based index that can differentiate these two fire types reliably and efficiently. Our results suggest that dNBR-based threshold can be easily incorporated in existing and future coarse resolution burned area mapping products to provide reasonably accurate estimates of the extent of each fire type at least within the Siberian larch forests and can likely be extended to other ecosystems using a similar approach of identifying most appropriate remote sensing indices and thresholds.

Expanding upon the findings of the current study, future research can be conducted in several directions. First, the spatial distribution of NSR fires can be mapped with higher accuracies. This can be achieved by incorporating the VIIRS active fires observations at 375 m resolution, which are more sensitive to low-severity NSR fires than the 1 km MODIS product. Second, factors influencing the post-fire SF of both NSR and SR fires need to be identified. This will help us explain the variability associated with the post-fire SF of both fire types and allow for a better prediction of future wildfire impacts. Third, other impacts that are imposed by wildfires, including those on the carbon budget, in the Siberian larch forests need to be located and quantified. This will likely require a better understanding of the fire-related processes at
the stand level and of the spatial distribution of the forest conditions at the regional scale.

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