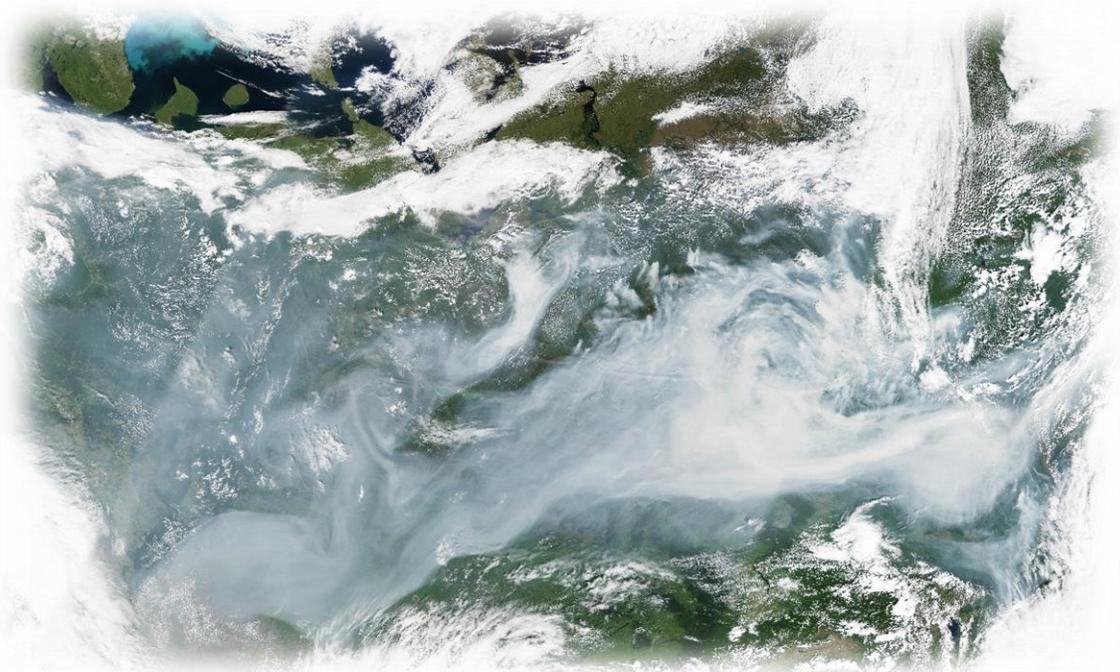


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Estimating wildfire-attributed boreal forest burn in Central and Eastern Siberia during summer of 2016



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2017

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Disclaimer

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Estimating wildfire attributed boreal forest burn in Central and Eastern Siberia during summer of 2016

Martynas Cerniauskas

2017

Bachelor's thesis

in Physical Geography and Ecosystem Analysis, 15 credits

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Cover picture: Wildfire smoke covering central Siberia in July of 2016. NASA Earth Observatory image by Jesse Allen and Joshua Stevens, using data from the Land Atmosphere Near Real-time Capability for EOS (LANCE) instrument

Popular Summary

Estimating wildfire extent in Siberia during the early summer of 2016

Wildfire extent is known to increase with higher air temperatures. This thesis investigates whether widespread 2016 fires can be attributed to highest global temperature anomaly ever recorded.

In the context of 2016 being the warmest year in observational history, this thesis attempted to investigate changes in wildfire extent within the central and south-eastern Siberian taiga. Using satellite based data, total burned area throughout May, June and July of 2016 in parts of the Siberian taiga has been estimated at just over 39400 km², nearly the size of Switzerland. It was clear that most intensive wildfires raged throughout July. Burn extents for this month were over 7 times higher than those in June. This strong increase is believed to be caused by anomalously dry and warm local weather conditions, however confidence is partially lacking and further investigations are needed to pinpoint exact reasons behind the intensive July burns. Comparing 2016 wildfires with historical data from 2001 and 2002 revealed that general extent of burned area has been increasing since the start of the century and fires in 2016 damaged an area that was over 2.6 times higher than in 2001 and 2002. However, this increase was most likely overestimated because the chosen study area did not cover all wildfires in 2001 and 2002. As a result, the increases in burned area cannot be fully attributed to increasing global temperature anomalies between the two study periods. Reviews of climate projections revealed that wildfires will have strong impacts on the future shape of the boreal forest ecosystem, as climate change alters wildfire seasons and intensities. Additionally, these alterations are predicted to change how boreal forests contribute to the global carbon balance.

Abstract

Changing climate affects various ecosystem processes within the boreal forest, wildfire among them. Meanwhile temperature is commonly accepted as one of the most important regulating factors. In the context of 2016 being the warmest year in observational history, this review attempts to identify changes in wildfire extent within the central and south-eastern Siberian taiga. Satellite based estimates for late spring and early summer of 2016 quantify total burned area as being just over 39400 km². July is identified as the month contributing most, showing burn extents over 7 times higher than June. The midsummer increase is hypothesized to be governed by mostly local scale weather conditions, temperature among them, but specific processes remain a topic of further investigation. Comparison with historical data from 2001 and 2002 reveals a positive trend in total burned area. The trend is partially attributed to a 65% increase in global surface temperature anomaly between the two study periods. Reviews of climate projections reveal that wildfires will have strong impacts on the future shape of the boreal forest ecosystem. Additionally, wildfire regime alterations are predicted to change how boreal forests contribute to the global carbon balance.

Keywords: Physical Geography, Wildfire, Boreal Forest, Siberia, Taiga, Burned Area, Climate Change, MODIS, Remote Sensing, Carbon Cycle

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Abbreviations and acronyms

MODIS - Moderate Resolution Imaging Spectroradiometer
NASA - National Aeronautics and Space Administration
NASA EOSDIS – NASA’s Earth Observing System Data and Information System
NOAA – National Oceanographic and Atmospheric Administration
ESA – European Space Agency
IPCC – Intergovernmental Panel on Climate Change
Copernicus – European Commission’s and ESA’s Global Monitoring for Environment and Security programme
FTP – File transfer protocol
MCD64A1 – Modis Burned Area Monthly Collection 6 product
GeoTIFF – Georeferenced Tagged Image File Format
HDF – Hierarchical Data Format
AVHRR – Advanced Very High Resolution Radiometer
ESRI - Environmental Systems Research Institute
LPDAAC - Land Processes Distributed Active Archive Centre

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First and foremost, I would like to thank Jonathan Seaquist for his valuable contributions and insights regarding this project. I would also like to thank the lecturers of the Physical Geography and Ecosystem department as well as my opponent Neija. They have provided constructive critique and suggested expanding the scope of this study to include historical observations, land cover and wildfire spreading. Finally, I would like to thank Thomas Holst, Karin Hall and David Tenebaum for being great lecturers and brightening up the world of geography with their positive personalities, as well as Ulrik Martensson for solving countless logistical problems during my 3 years at the department. Thank you all!

1. Introduction and background

2016 was the warmest year on the planet in observational history, according to the National Oceanic and Atmospheric Administration (NOAA 2017a). As one takes a closer look at specific regions on Earth, northern latitudes are predicted to experience the greatest temperature changes under future climate scenarios (IPCC 2007). In fact, observations summed up by NOAA are already conforming to predictions made by the Intergovernmental Panel on Climate Change over 10 years ago. As of 2016, some regions in the high Arctic have experienced annual temperature anomalies over 3 degrees higher than the mean global anomaly of 0.94°C (20th century being the reference period). With the climate continuing on its current trend, circumpolar boreal forests will be among the first of the biomes to experience changes in temperature, precipitation, species distribution and seasonality.

The boreal forest covers approximately 17 percent of total land area on the planet (Juday 1999), spanning most of Canada and Russia as well as substantial parts of Alaska, Finland, Sweden and Norway, as seen in *figure 1*. This study will primarily focus on forests in Russia. Namely central and south-eastern parts of Siberia, where the boreal forest is also known as taiga.

In the context of boreal forests, wildfires are natural disturbances, which control forest ecosystem dynamics. The fires themselves are strongly influenced by weather conditions and increased air temperatures are linked with larger burn areas (Flannigan et al. 2009). Flora in a biome of this nature is usually adapted to the disturbance allowing plants to finish a life cycle before they are killed in a fire.

According to a 2013 study by de Groot, Larix (common name - larch) and Pinus (common name - pine) species dominate Eurasian boreal forests, corresponding to 32 percent and 29 percent of cover, respectively. Most wildfires in the taiga are low intensity surface fires and the dominant tree species in this case employ fire suppressant strategies, ensuring that their trunks survive and canopy sustains non-fatal damage during the burn (Rogers et al. 2015).

Even though wildfires are part of a natural regeneration cycle in the boreal forest, changing climatic conditions are altering the return interval of wildfires and in turn, how these events contribute to the global carbon balance. It is estimated that the entire Russian boreal zone contains over 58.3 gigatons of Carbon (Alexeyev and Birdsey 1998) and previous studies have indicated that nearly 40% of total storage is in the form of plant detritus (Krankina et al. 1996). With the climate exhibiting substantial temperature anomalies, a surface fire regime-dominated forest, like the Siberian taiga will very likely undergo changes in fire intensity and extent.

The understanding of these changes is currently lacking, especially in terms of how wildfire emissions will affect the global carbon cycle and what new feedbacks could form between these systems. An investigation on burned area increase between early 21st century and record warm 2016 could provide first steps towards quantifying said wildfire dynamics changes.

Consequently, the thesis will attempt to measure 2016, 2001 and 2002 early summer/late spring burns within the Russian taiga (study area overview in *figure 2*), link the burned area changes to recent increase in global temperature, provide an overview of research to-date outlining knowledge gaps regarding wildfires and the global carbon balance and finally, investigate possible links to land cover.

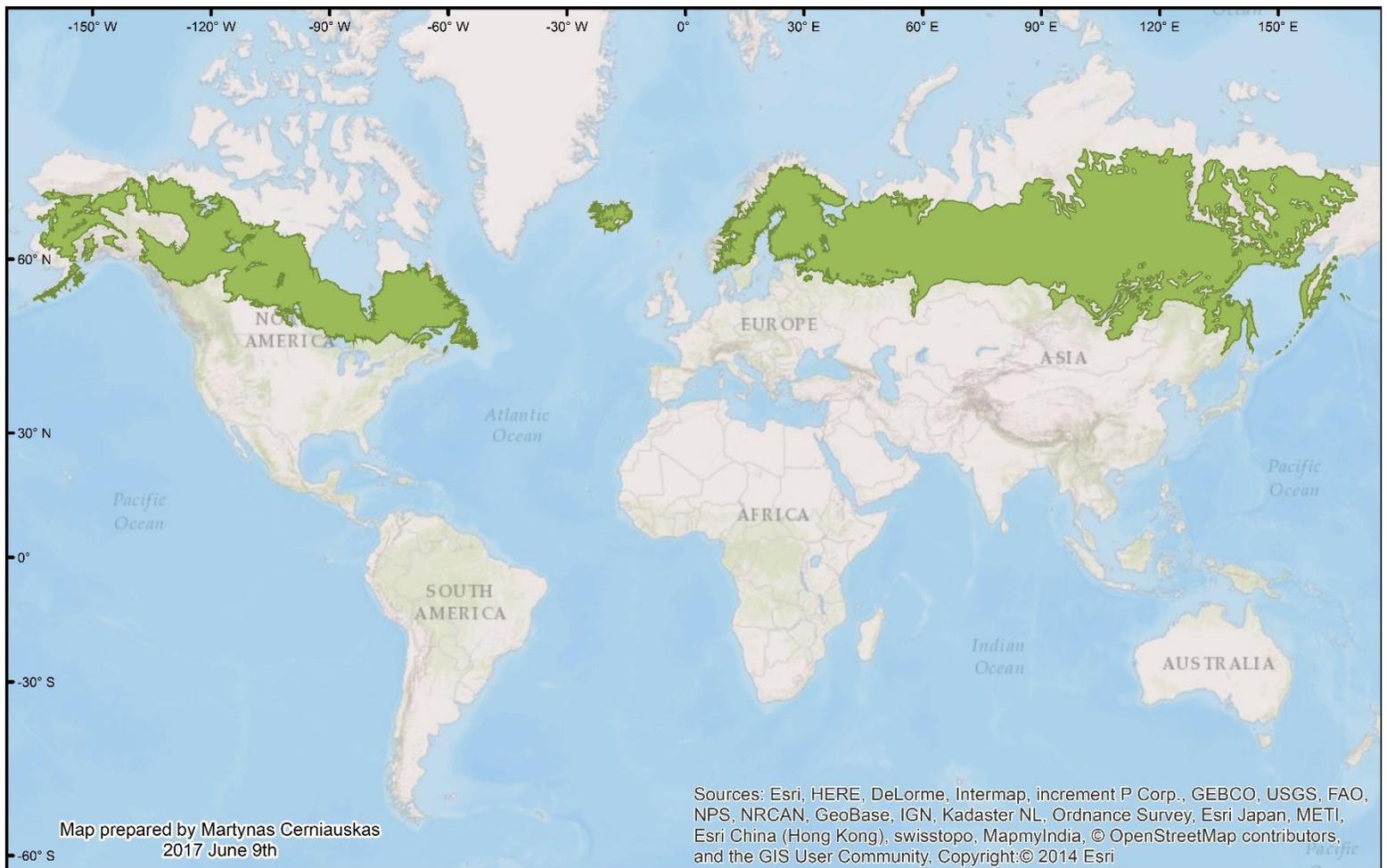


Figure 1 Global extent of the boreal forest biome, covering nearly 17% of the planet’s land surface



Figure 2 Study area within the Russian taiga. Confining rectangle covers Central Siberia between 69.08 East to 126.6 East and 55.9 North to 69.5 North. *Satellite Image courtesy of Google and the following data providers: Landsat, Copernicus, IBCAO, DataSIO, NOAA, United States Navy, NGA, GEBCO, LDEO-Columbia, NSF*

2. Data and Methods

The study was based on satellite derived data. Fire products produced by NASA come primarily from MODIS instruments aboard both Terra and Aqua satellites and provide data coverage from the year 2000 up to current date. Both satellites are in circular sun-synchronous near-polar orbits around the Earth and have orbital periods of approximately 99 minutes. They operate in low earth orbit, at an altitude of 705 kilometres. Terra and Aqua satellites are part of NASA's Earth Observing System and were designed, as the names suggest, to monitor terrestrial and aquatic environments on a global, long-term scale (NASA 2017a, b). Meanwhile the MODIS sensor aboard both platforms utilizes 36 spectral bands to monitor the Earth's surface every 1 to 2 days and provides information about land and ocean properties, clouds, aerosols and surface temperatures. Complete technical specifications are provided by NASA and can be found by visiting the reference page (MODIS 2017).

The wide spectral coverage of MODIS instrument makes it useful for a plethora of satellite products, fire observations among them. MODIS based MCD64A1 burned area product is derived from a burn sensitive vegetation index and satellite based active fire observations. This is done by applying a dynamic threshold algorithm to vegetation images and using active fire maps for training. The team behind the product deem an accuracy of approximately 90%. Complete accuracy assessment and product derivation can be found in the published product specifications and review paper (Giglio et al. 2009).

Burned Area Monthly Level-3 Global 500-meter products contain per pixel burning information and are parts of both Collection 5.1 and Collection 6. The Collection 6 product has substantially better small burn detection, lower temporal uncertainty and increased spatial coverage, among other improvements over Collection 5.1 (Giglio et al. 2016). These reasons contributed to me basing the project on the MCD64A1 product.

Data comes in 463 meter cells with 16-bit signed integer data, in Plate-Carree projection. Cell values contain burn date, indicating the Julian day on which the burn was observed. Additionally, a quality assurance layer can be obtained, allowing to identify cells with shorter than normal mapping periods, insufficient reflectance time series and other shortcomings, that could lead to faulty data. One can acquire the product via NASA's EOSDIS portal or by accessing same data in GeoTIFF format, prepared by the University of Maryland. MCD65A1 GeoTIFF's are accessed by connecting to a file transfer protocol server as described in the reference list. Metadata for Collection 6 can be found in a PDF distributed by the University of Maryland (Giglio et al. 2016)

To the extent of analysing potential correlation between wildfire and forest type, I have used MODIS derived land cover satellite data, MCD12Q1. This product is based on MODIS land surface temperature and reflectance adjusted with the bidirectional distribution function. The input data undergoes supervised classification, which, in turn, is trained using a live, high quality training site database (LPDAAC 2013). Assessments indicate overall product accuracy of approximately 75%. None, except for two classes relevant to this report fall below the 75% threshold in terms of user accuracy. Those classes are mixed forest and woody savannah (Friedl et al. 2010).

Using this product ensured maximum compatibility and minimal data harmonization issues between the two data series. The land cover product contains 16 discrete land classes, Evergreen Needleleaf and Deciduous Needleleaf among them. Metadata for this product and the data itself can once again be acquired from a file transfer protocol server maintained by the University of Maryland. One should note that Collection 5 only spans a time period between year 2001 and 2012 and more recent Global Land Cover data seems to be unavailable, despite NASA stating that “collection 6 product is expected to reach operational status by end of 2016” (NASA and LAADS 2010).

Since 2016 land cover data was unavailable, I have decided to use MODIS derived Global Land Cover data from the year 2012. To this extent, I have made an assumption that land cover in my study area did not change significantly between year 2012 and 2016. A more detailed argument backing this hypothesis of temporal uniformity is presented in later parts of the discussion section.

Post data acquisition, processing was carried out using ESRI’s ArcMap software. Primary work included combining multiple satellite images into one and making sure it conforms to the chosen study area. Historical burn data and land cover underwent same treatment. With data processing completed, maps were produced using the same software suite.

Tabular data processing and graphing was done using Microsoft Excel software. Burned area was calculated using this software, simply by consolidating monthly burned cell counts and multiplying them with cell area. The cell area in turn was calculated based on grid cell dimensions described in the MCD65A1 product metadata documents. Figures and tables were also produced using Microsoft Excel.

For readability purposes all produced maps have been uploaded to an image hosting server in high resolution and can be accessed by visiting links provided in description boxes below each map. Readers are strongly encouraged to make use of this, as formatting issues do not allow displaying maps in full resolution within this report.

3. Results and Discussion

3.1 Wildfire extent in May, June and July of 2016

Burn extents for May and June varied between 682 km² and 4,626 km², respectively. *Figures 3 and 4* present the spatial burn distribution for the two months.

Unlike in the month of May, wildfire affected areas throughout June can be identified visually, as seen by comparing *figures 3, 4 and 6* suggesting a larger burn extent. Despite that, June wildfire is still quite localised, with the largest hotspot located north of Kodinsk town, as seen in zoomed in *figure 6*. Smaller hotspots are also scattered around southcentral part of the study area. Further visual analysis shows reasonably large areas of missing data in the May dataset. However, this did not seem to affect the quality of burned area product significantly, since the count of wildfire affected pixels for that month was relatively low, as illustrated by *table 1*.

Moving on to July, one can observe that as the summer progresses and air temperatures in southcentral Siberia approach 17 degrees Celsius (Climatedata 2017; NOAA 2017b) wildfires reach peak extent. Multiple large hotspots can be identified in *figure 5* and zoomed in *figure 7*. In addition, wildfires have migrated both northwards and westwards, reaching 69°N latitudes as well as the gulf of Ob in the far west. Initial results of visual comparison are supported by data extracted from the raster image and presented in *figure 8* and *table 1*. July wildfires damaged an area over 7 times larger than wildfires that burned throughout June of 2016.

3.1.1 Combined estimates

Combining burned cell counts for individual months of May, June and July in 2016 yields a total burned area estimate of 39,421 km². This is a significant number in terms of historical estimates. It is nearly 3 times higher than respective burned area extent for 2001 and 2002. A more detailed comparison between these time periods will be presented later. Meanwhile in relation to the entire boreal forest biome within the Russian Federation, observed burn accounts to only 0.33 percent of the total area (World Wildlife Fund 2013).

For clarity, it is worth noting that burned pixel counts vary linearly with estimates for burned area, since the latter is computed simply by multiplying constant pixel area with the burned pixel count for each respective month. Any relative changes discussed in the previous and upcoming section apply to both burned pixel counts and burned area estimates, regardless of which one is mentioned.

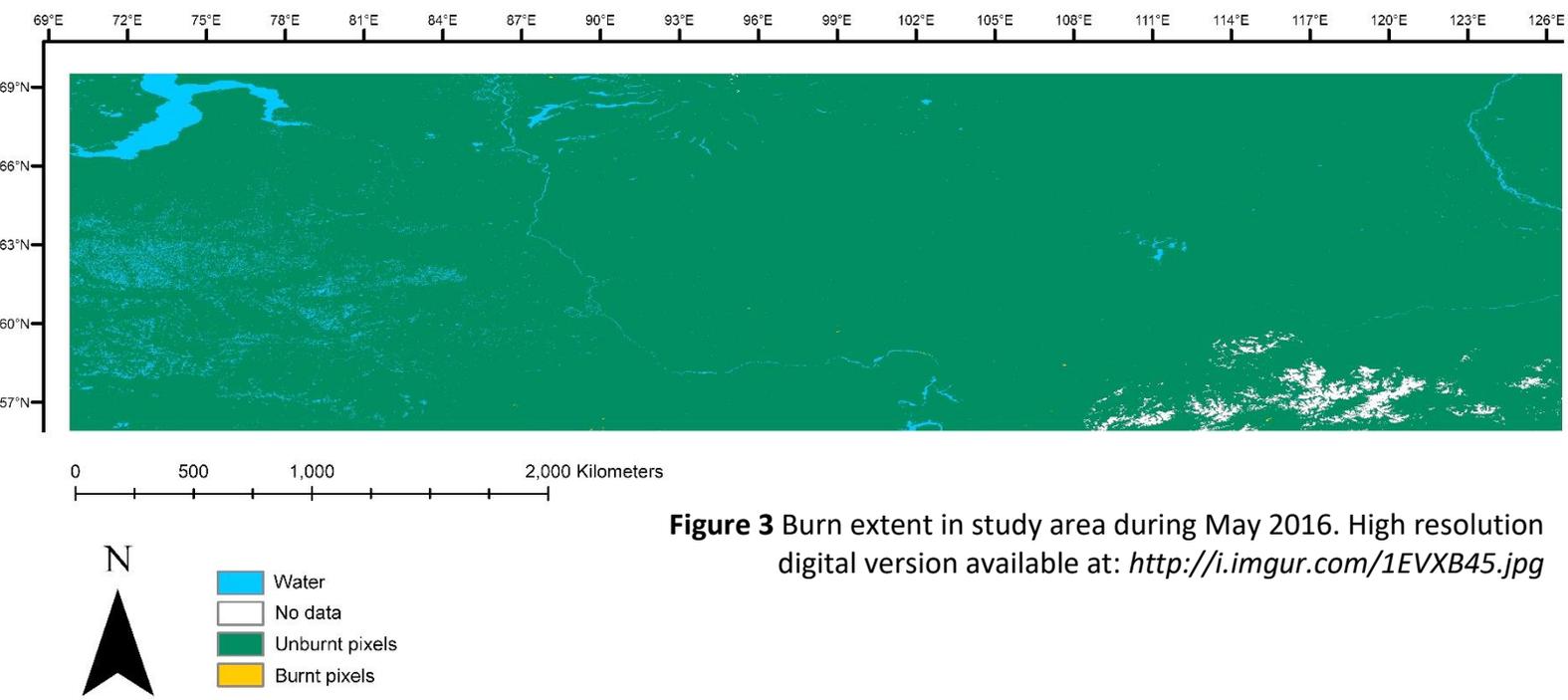


Figure 3 Burn extent in study area during May 2016. High resolution digital version available at: <http://i.imgur.com/1EVXB45.jpg>

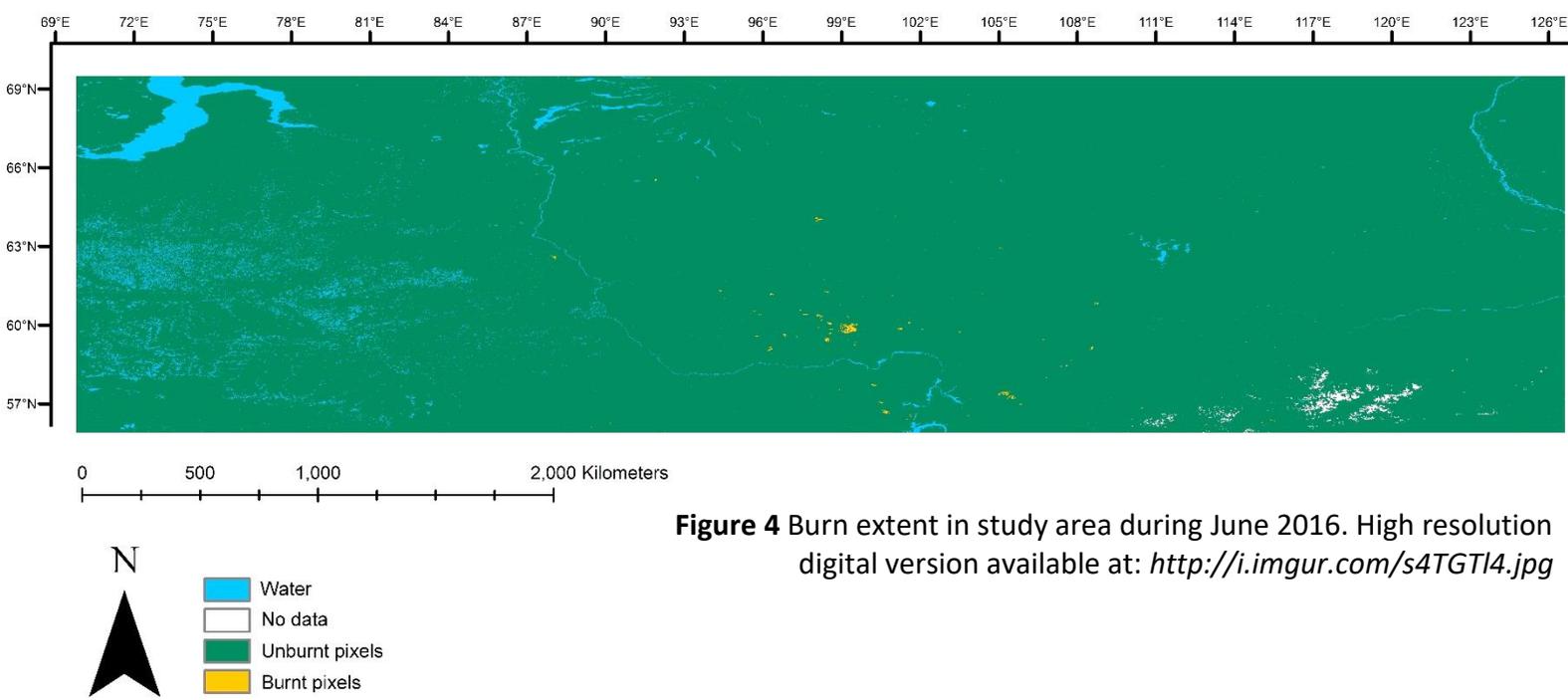


Figure 4 Burn extent in study area during June 2016. High resolution digital version available at: <http://i.imgur.com/s4TGT14.jpg>

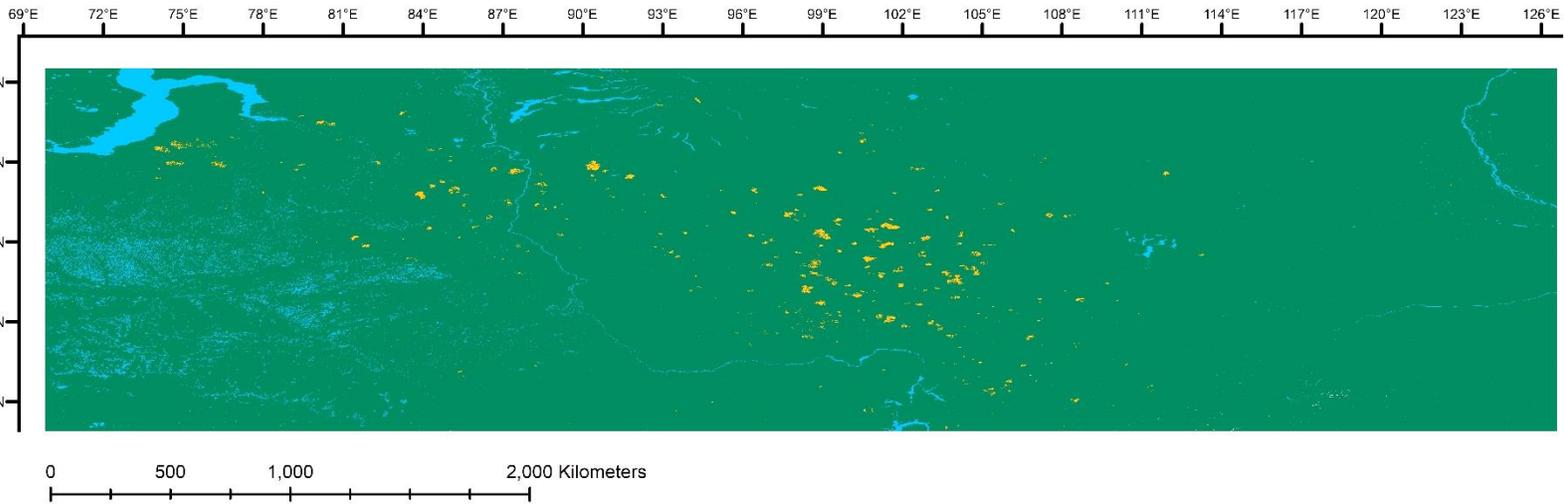


Figure 5 Burn extent in study area during July 2016. High resolution digital version available at: <http://i.imgur.com/1nFdXQc.jpg>

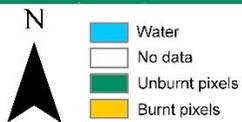
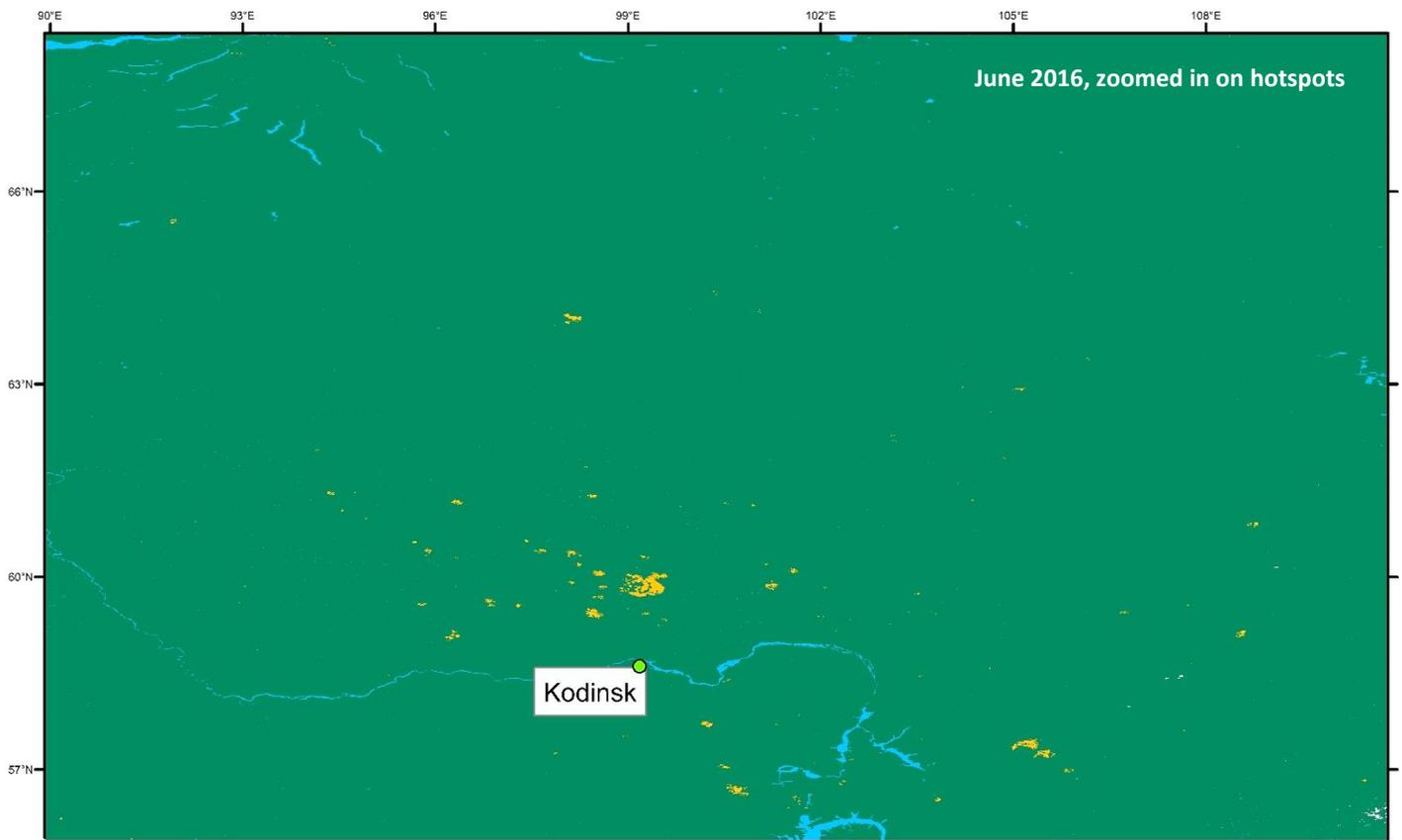
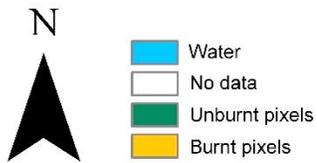


Figure 6 Zoomed in burn extent in study area during June 2016.

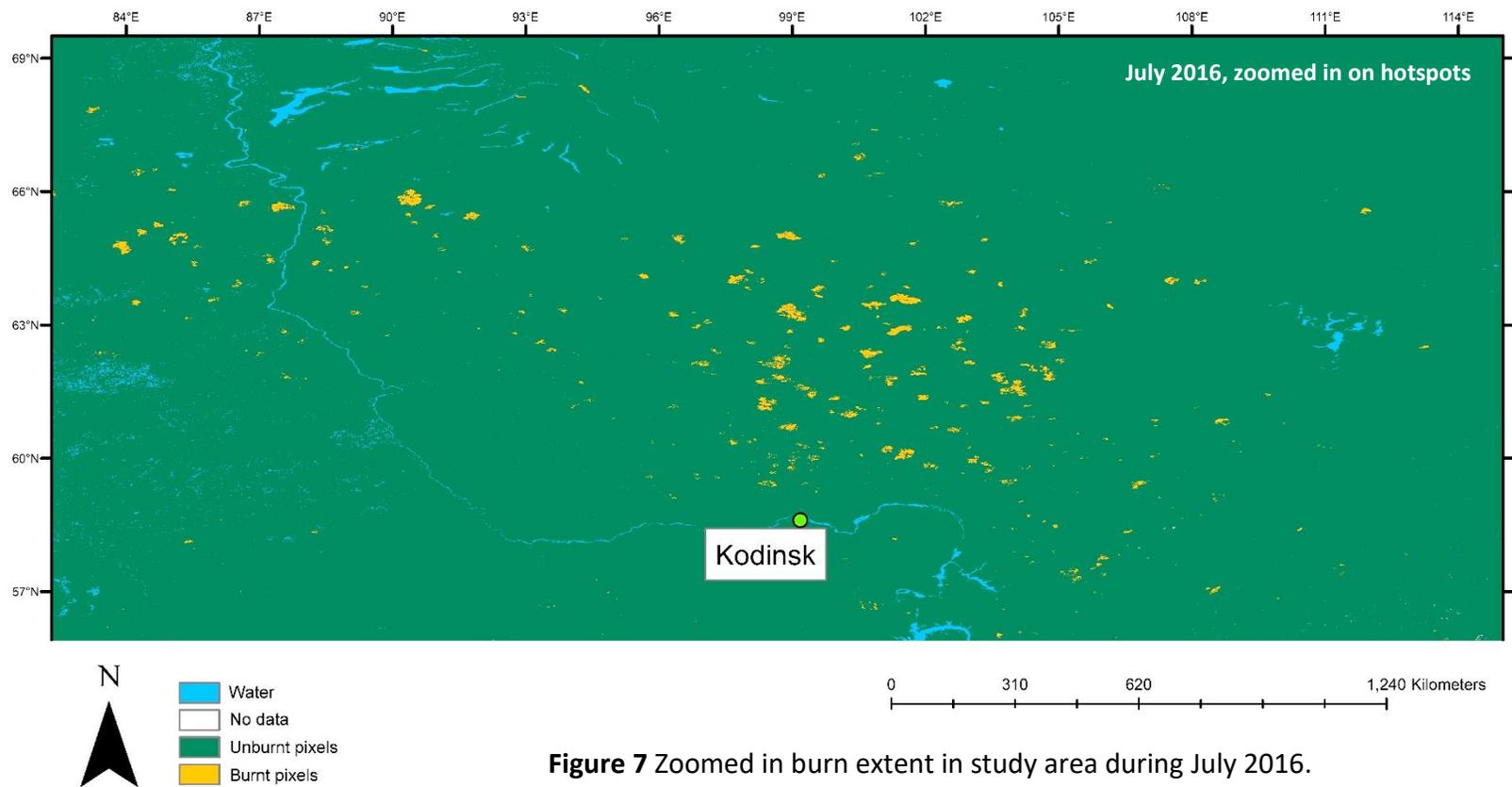


Figure 7 Zoomed in burn extent in study area during July 2016.

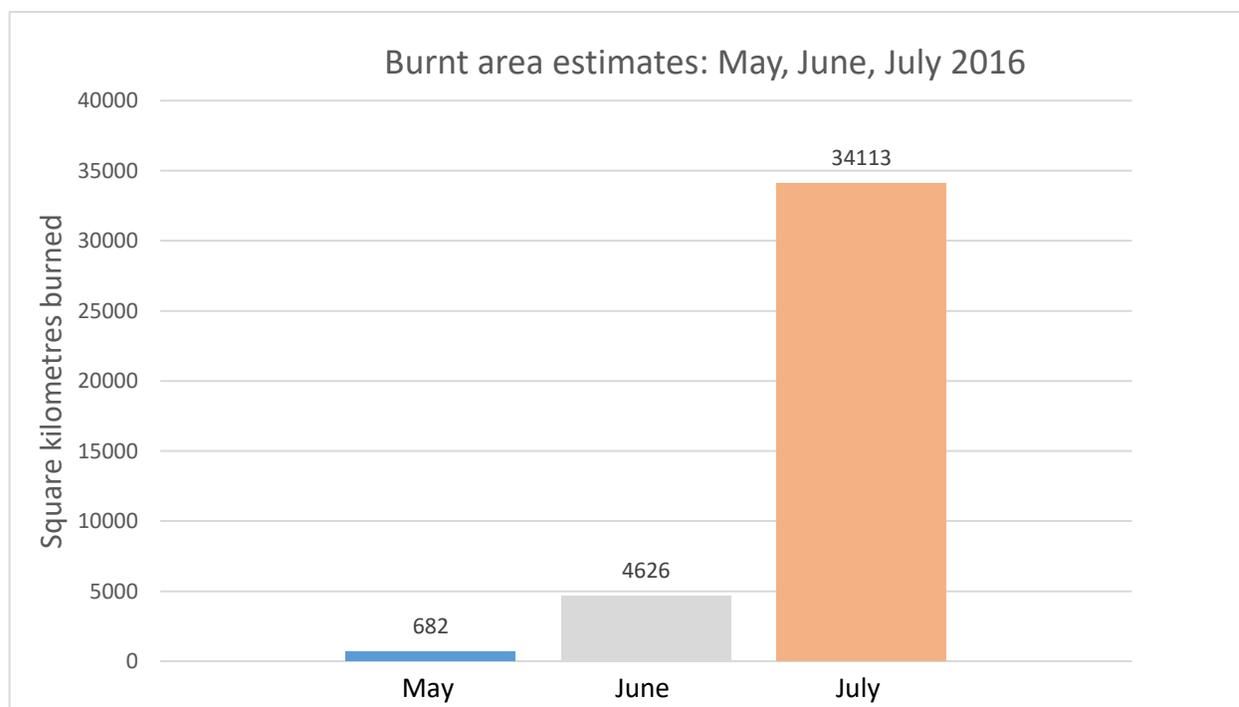


Figure 8 Burnt area estimates for the study area, during May, June and July of 2016

Table 1 Summary of burned pixel counts and consequent areal extent of the burn in May, June and July of 2016

	2016			
	May	June	July	Total
Pixels Burned	3,175	21,552	158,917	183,644
Area Burned, km ²	682	4,626	34,113	39,421

3.1.2 Temporal distribution of 2016 July wildfire

As one investigates the rapid increase in wildfire affected areas throughout July of 2016, a specific trend can be identified. Almost 35% of the 34,113 km² burned in 5 consecutive days, starting with 17th of July and ending with the 21st, as indicated by *figure 9*. Otherwise the wildfire damage had a relatively even temporal distribution and the remaining 65 percent of the burn can be attributed to days between July 1st and July 17th as well as days starting from July 21st and ending with July 31st.

3.1.3 Multiple burn areas

In addition to the temporal analysis, I have investigated cells that burned multiple times in 2016. The result amounted to 168 cells, which in turn correspond to 36 km² of burnt forest - only 0.09 percent of the total early summer/late spring burn in 2016. A more detailed look revealed that most multi-burn cells initially burned in June and had rekindled during the second half of July. This can likely be attributed to high intensity July fires spreading and reigniting small forest stands, which were not completely destroyed in the moderate June wildfires.

3.1.4 Comparison to historical wildfire distribution patterns

The overall temporal distribution of wildfire damage seems to be quite different from other studies. One of them, conducted by Ivanova (1996) suggests that wildfires in similar regions normally reach peak extent in the second half of June. Another group of researchers lead by Kajii et al. (2002) used data derived from NOAA's Advanced Very High Resolution radiometer to analyse wildfires that raged during extreme summer and spring droughts of 1998. They found that regions overlapping with my study area exhibited most intense burns through April and May. Meanwhile the months of June and July showed little to almost no wildfire activity.

This evidence possibly suggests that wildfires in the taiga of central and south-eastern Siberia do not follow distinct and repetitive burn patterns on an annual basis. Instead they most likely depend on weather conditions present during fire season months of that specific year. This hypothesis is partially supported by the fact that succession after a wildfire event takes many decades. During that time, fuel available for fire is significantly lower than in the case of a mature forest and areas that burned in previous years are less likely to burn for two or more consecutive years (Kelly et al. 2013).

Reasons behind the substantial surge in wildfire activity in July are difficult to identify with certainty. One hypothesis includes persistent anomalous local weather conditions drying out large volumes of fuel, which are then readily ignited by smaller fire events. Drought conditions in this region are brought upon by dry, warm anticyclonic air masses as well as circumpolar high pressure centres. Under scenarios of severe drought, even fire-hampering, wet forest and bog sites become wildfire prone. As a result, both deep and surface layers turn into fuel sources for wildfire (Goldammer and Furiaev 1996). However, it is difficult to test this without obtaining large datasets, containing high resolution daily weather data. Additionally, it should be noted that July of 2016 exhibited the lowest monthly temperature departure from average since August 2015 (NOAA 2017a). This observation provides moderate counter-evidence and suggests that general weather conditions during July of 2016 were not more anomalous than usual, despite annual temperature anomaly exceeding every other year since 1880.

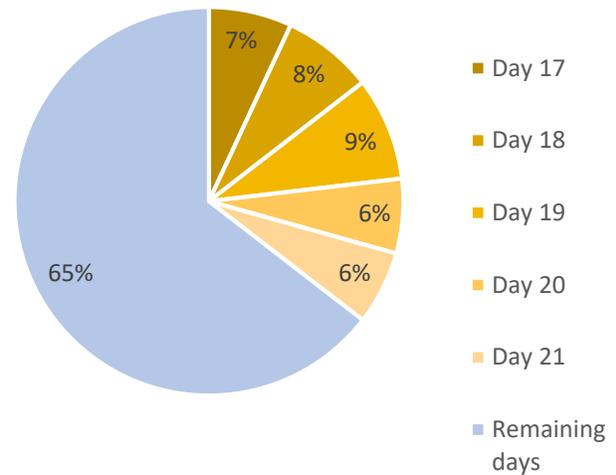


Figure 9 Temporal distribution of wildfire attributed burn in July of 2016. Nearly 35% of monthly burn occurred in 5 consecutive days

3.1.5 Past studies and suggestions for additional analysis

Due to the recent nature of the event in question, few investigations that could help explain fires of 2016 July have been conducted. Additionally, many taiga wildfire studies primarily focus on investigating forest stand dynamics and occasionally, forest development under climate change scenarios. As a result, local scale fire processes that are of interest here can be overlooked. Instead, the research focuses on modelling and quantifying variables that indicate the state of the entire ecosystem or sizeable portions of it. An example of such variable would be cumulative CO₂ emissions during a certain event. Another complicating factor is the extent and remoteness of the study area. The Siberian federal district is one of the least populated areas on the planet, with an average population density of 3.8 inhabitants per km² (Russian Federal State Statistics Service 2011). This translates into poor ground coverage of weather data (Grippa et al. 2004), with 1 weather station covering 1 million km² on average (Running et al. 1999). Fortunately, utilising satellite derived surface temperature observations and extrapolating them to near-surface air temperatures might help solve this particular problem. A future study making use of hourly or daily weather observations would allow researchers to identify local-scale weather variations and consequently shed some light on the processes behind extensive wildfire spread in July of 2016.

3.2 Land cover and fire spread patterns in 2016

Additional analysis covered by this project includes investigating the distribution of burned area land cover classes and the spreading of 2016 early summer / late spring wildfires. *Figures 10 and 11* present visual and numerical information on land classes that burned within the study area throughout May, June and July of 2016. Meanwhile *figures 12 and 12.1* present fire spread throughout May, June and July of 2016. I kindly remind the reader to make use of full resolution digital versions of provided maps.

3.2.1 Land cover classes affected by wildfire

Areas affected by wildfire in May and June were predominantly covered by deciduous needleleaf and occasionally mixed forest, as seen by analysing *figure 11* and cross-comparing with *figures 3, 4 and 5*. Relating this result to an analysis conducted by Chen et al. (2016) confirms that Siberian larch is the dominant species within the study area and consequently was damaged most in May and June. Assuming that majority of May and June hotspots exhibited surface fires is reasonable, considering that Larix species employ fire suppressant strategies and canopies do not burn during events of moderate intensity (de Groot et al. 2013). Moving on to July, observations conform to the prior 2016 analysis, which showed hotspots shifting northwards and westwards. With increasing latitude, dark taiga gradually gives way to sparser, woody savannah and shrubland-like vegetation, which did not burn during the two previous months. A look at *figure 10* reveals that nearly 43 percent of total 2016 early summer burn can be attributed to these two land classes. With the absolute majority of savannah and shrubland burn occurring throughout July.

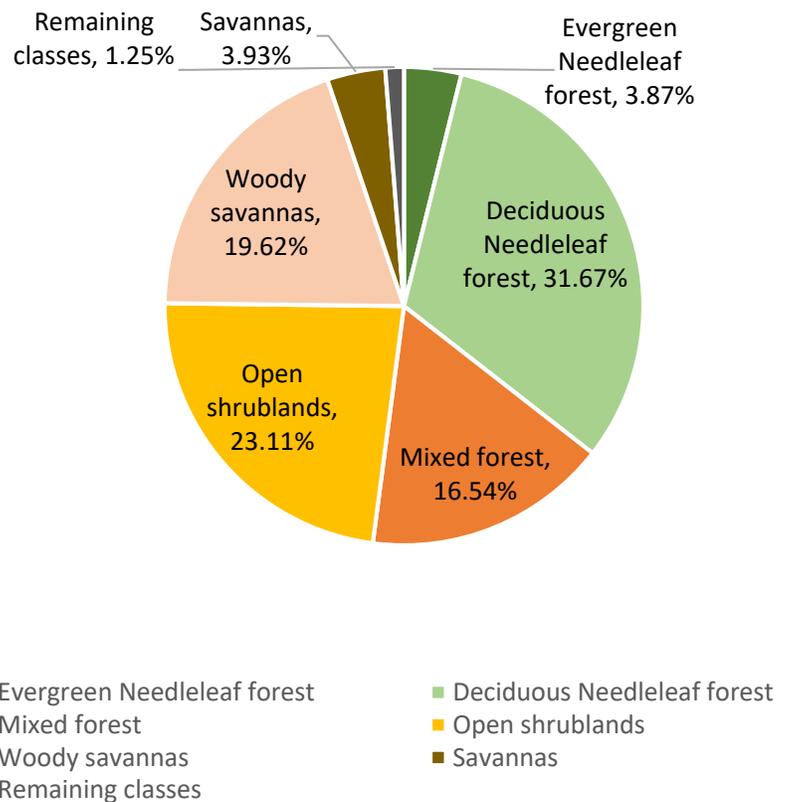


Figure 10 Land cover distribution of the combined areas that burned through May, June and July of 2016

Other prominent land classes include evergreen needleleaf forest and mixed forest. The latter gradually replaces larch forests with more southern latitudes, namely between 60 and 56 degrees north. Despite parts of mixed forest burning in May and June, the sheer extent of July wildfires meant that majority of this land- cover class was consumed throughout July as well.

Reflecting on the major land cover class, larch is accepted as fire resistant and stands of this species are much less likely to burn compared to pine forests (Goldammer and Furiaev 1996). Despite that, the dominance of Larch in the Siberian boreal forest as well as low crown closure properties result in majority of the wildfires occurring within Larch communities (Ponomarev et al. 2016). As mentioned before, fire suppressant strategies employed by this species prevent crown fires during most events and instead surface fires are more common (de Groot et al. 2013), with ground covering mosses and lichen providing fuel. Unfortunately, shallow Larix root systems, owing to presence of permafrost, can often be damaged in surface fire events. A common result of such damage is complete stand replacement.

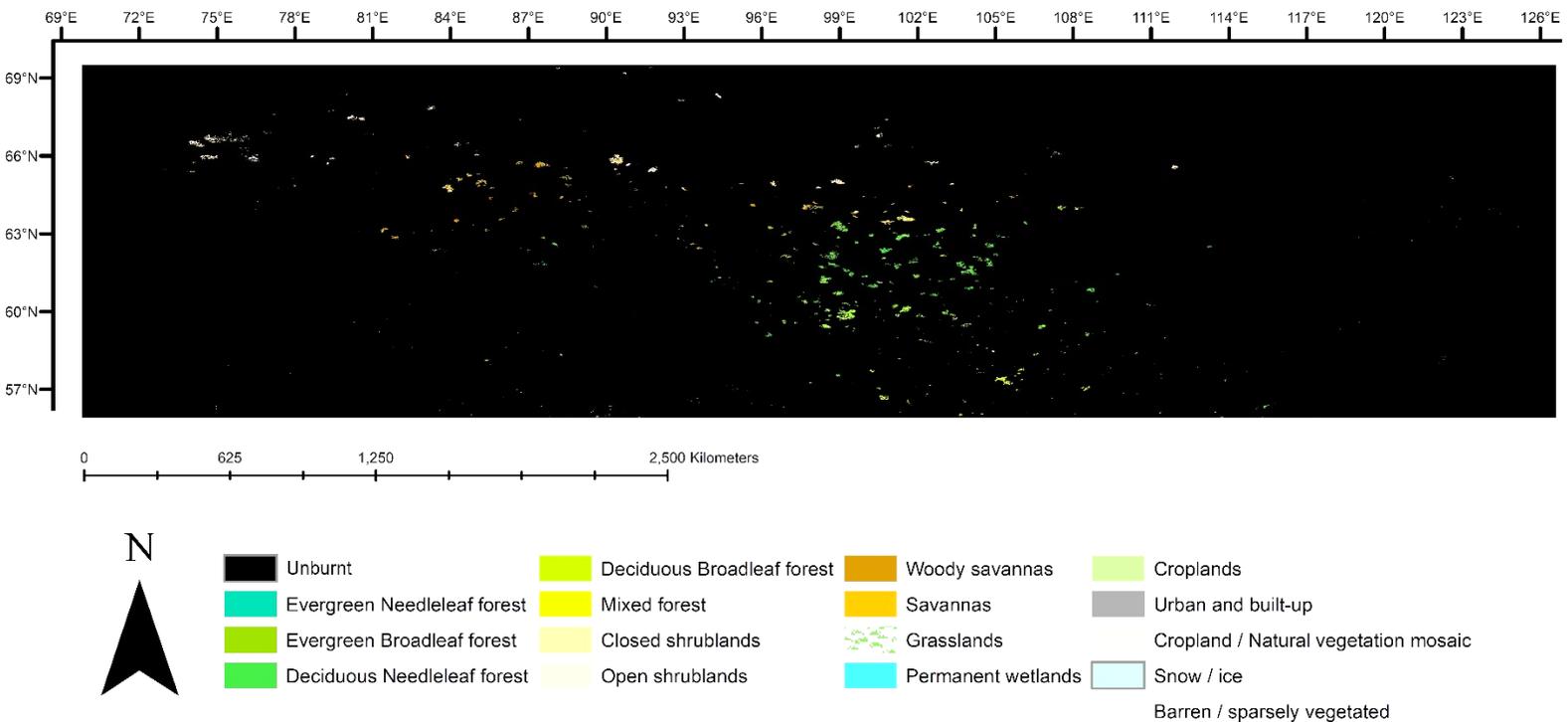


Figure 11 Land classes of 2016 combined May, June and July burn pixels
 High resolution digital version available at: <http://i.imgur.com/I344qiG.jpg>

3.2.2 Regeneration rates and mean disturbance cycles

Regarding post-fire regeneration, multiple research efforts have shown that forest stands in the Siberian taiga exhibit substantially slower regeneration and growth rates compared to their Western European counterparts. The primary reason behind these differences is the shorter growing season (Lindgren 2011). Meanwhile fire return intervals presented in literature can vary quite dramatically. A study by de Groot et al. (2013) suggests a mean fire return interval of 53 years. But an independent analysis conducted by Schulze et al. (2005) suggests even longer disturbance return intervals, with mean wind or insect disturbance cycle averaging 150 years and mean wildfire cycle averaging 425 years. Despite the disagreement between presented estimates, it is quite clear that succession and regeneration in the taiga is slow, with land cover remaining the same for multiple decades. This, in the light of no recent data being available, allowed me to assume that MODIS land cover dataset from year 2012 will be suitable for identifying relationships between wildfire and distinct forest types.

3.2.3 Spread of wildfire in 2016

Figure 12 presents a colour ramp map depicting wildfire spread throughout the 2016 study period. Bright colours indicate earlier burn days and dark colours indicate later burn. Julian day 122 corresponds to May 1st and day 213 corresponds to July 31st, seeing as 2016 was a leap year. The colour ramp reaches midpoint at around June 15th, as indicated by light pink hues. Finally, red cells indicate pixels which have been found to burn on multiple occasions throughout the study period. The total count of said pixels was 168. Considering that each map comprises over 4 million pixels, the reader might have difficulty spotting multi-burn sites. The map generally helps putting July wildfires into perspective, showing that most of the burn did not occur until very late into the study period, dominant colours being dark purples and blues. This information is confirmed by *figure 12.1*, which presents burned area estimates for each day throughout the study period. It is once again, quite clear that wildfires in the study area reached peak intensity mid-July, as was indicated when discussing temporal distribution on page 10.

An in-depth look allows observing wildfire evolution and spread. For example, a massive hotspot at 99°E and 60°N shows clear evolutionary track. In this case the fire seems to have started in the centre of the hotspot on June 13th and consequently spread in a circular pattern, with the last border fires dying out on the 6th of July. This hotspot alone corresponds to over 1550 km² of burned forest and was the largest portion of connected forest to burn throughout June. Remaining larger hotspots exhibit either late June to early July burns, as indicated by the pink tones. Mid-to-late July burns are present as well, corresponding to a peak intensity period that was discussed on page 10. The latter type of fire can be identified from the purple/blue hues. Finally, the medium-to-small sized fires seem to exhibit little temporal variation, as all pixels in connected areas of this size burned within 10 days of each other. Finally, an overwhelming majority of investigated wildfires appear to spread outwards from the centre.

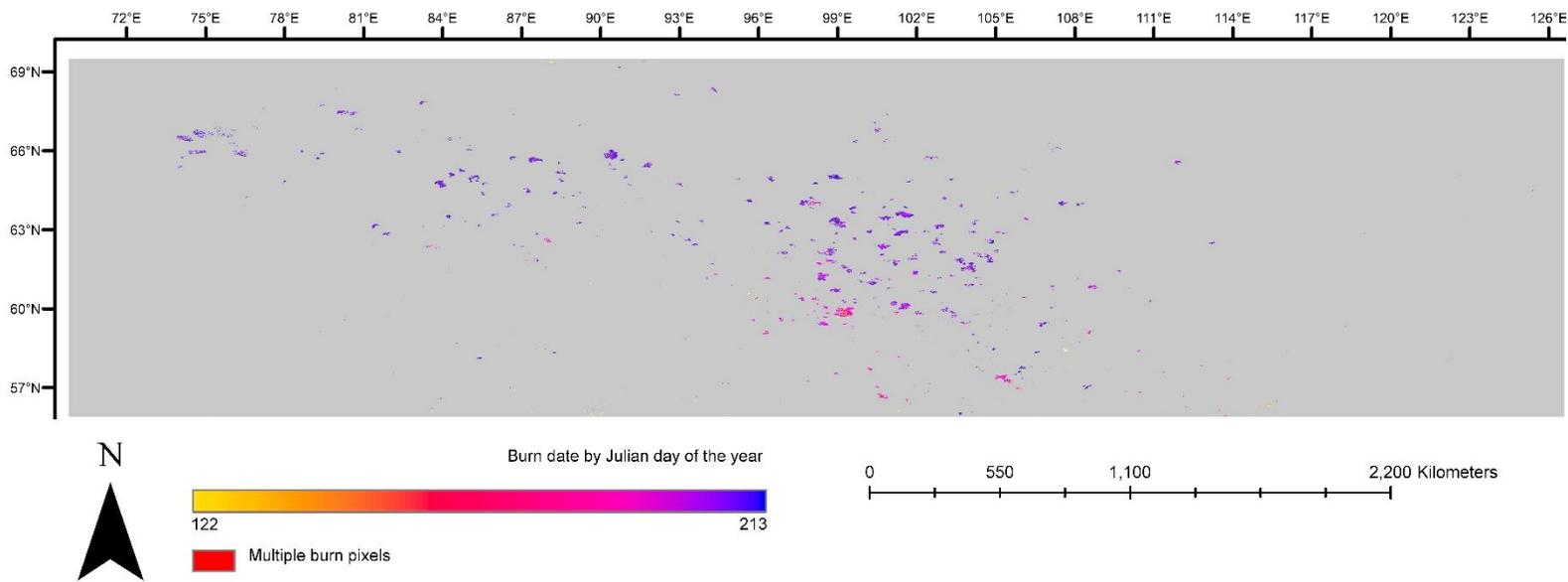


Figure 12 Wildfire spread throughout May, June and July of 2016. High resolution digital version available at: <http://i.imgur.com/ubV32Us.jpg>

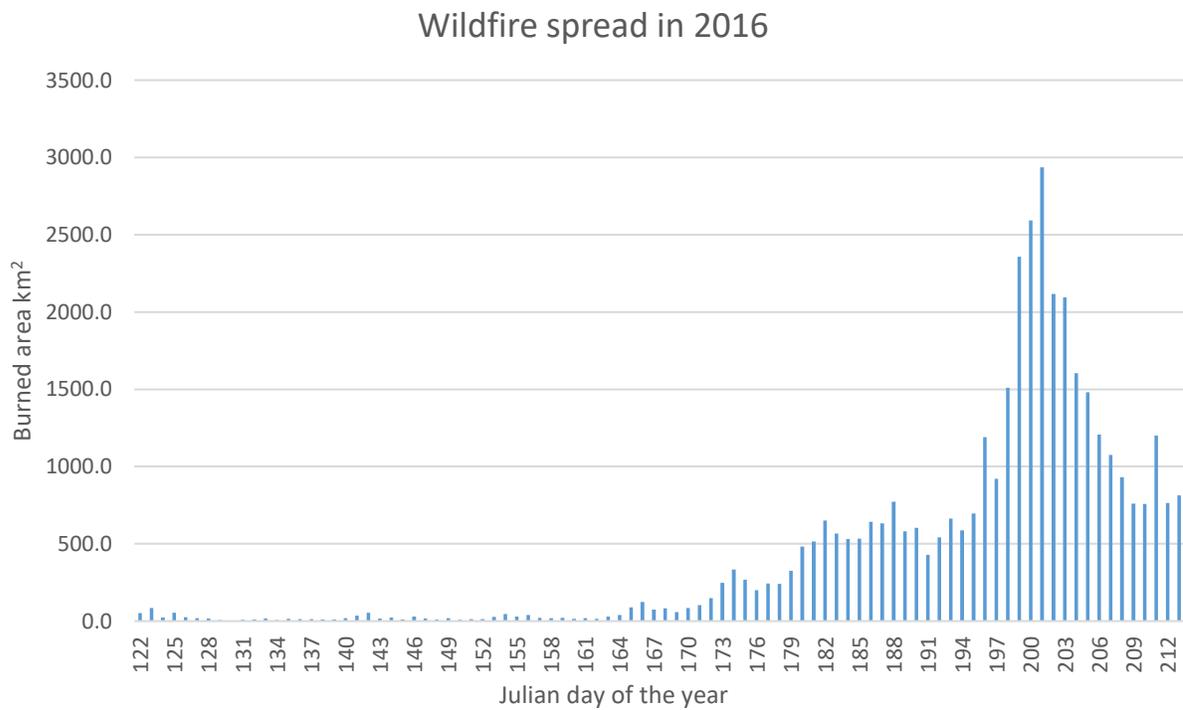


Figure 12.1 Wildfire spread throughout May, June and July of 2016 and corresponding area burned on each Julian day of the year

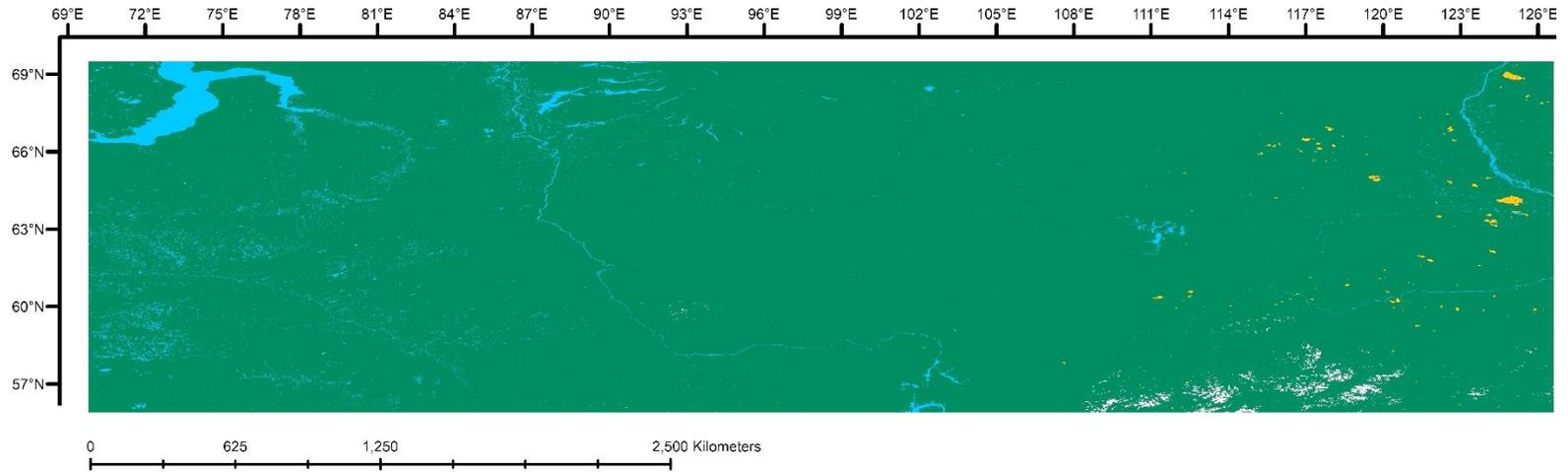
3.3 Historical observations from the year 2001 and 2002

After investigating recent burns in the Siberian taiga I have compared wildfires of early 2016 summer to historical observations in the same target area. As mentioned in the methodology section, I have used a burn product derived from the same instrument, for data harmonization and consistency purposes. This limited the available temporal range of data to years between 2001 and 2016.

After initial visual inspection it becomes evident that fire hotspots were more prominent in the east of the study area at the start of the 21st century. Majority of the burns in 2016 were located in proximity to the 100th east meridian, whereas in 2001 and 2002 the wildfires are mostly present around the 123rd east meridian, as presented in *figures 13 and 14*, respectively, as well as zoomed in *figures 15 and 16*. Reasonably large areas of missing data can also be identified, but as was the case with the 2016 dataset, coverage issues seem to mainly affect the month of May, where burn extent is rather low. Consequently, it has little to no impact on the combined dataset.

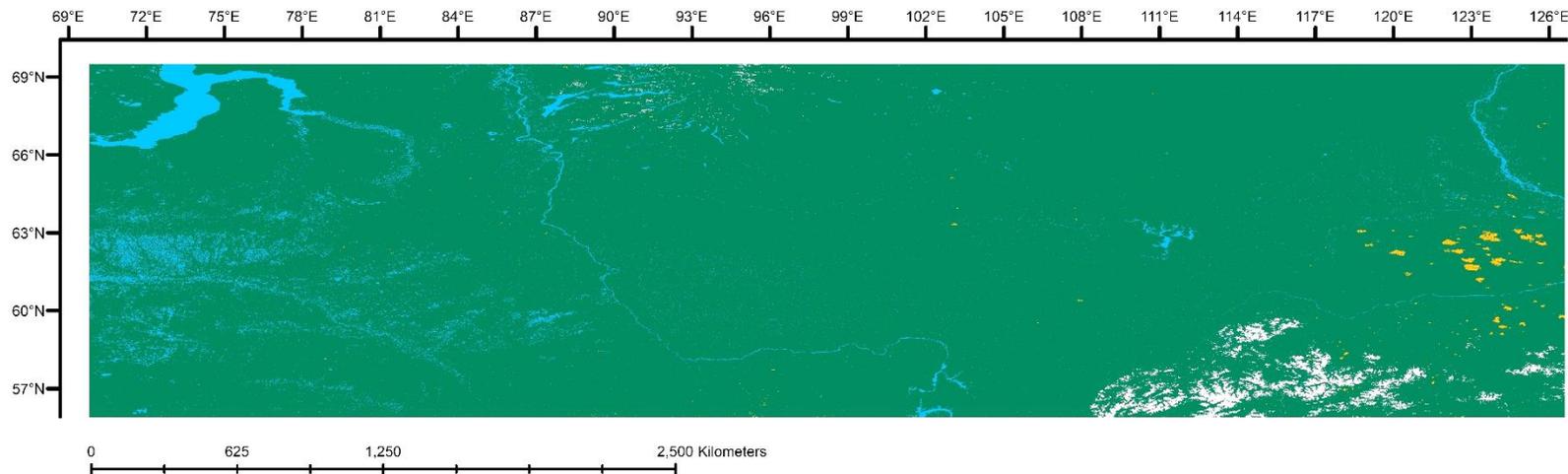
In both cases it is clear, even from visual comparison, that cumulative burn extent through May, June and July is lower than in July of 2016 alone. *Tables 3 and 4* provide numbers on how many burn pixels have been identified and the corresponding burned area estimates. Comparison between the two years reveals that combined area burned in 2002 was nearly 35 percent larger than in 2001. In terms of individual months, May and July showed the largest departures, increasing by 51.7 percent and 35 percent, respectively.

Moving on from changes between year 2001 and 2002, *table 2* presents numbers for all three of the analysed years. A comparison between combined 2016 early summer burn extent and averaged extents for 2001 and 2002 reveals a staggering 268 percent increase in area burned. This change took place over a period of 14 years - a rather short amount of time, as compared to typical temporal scales of climatological and ecosystem processes. Knowing that temperature is one of the most important factors governing wildfire presence and extent (Flannigan et al. 2009), I have attempted to explain the increase by tying the unusually large 2016 wildfires to annual climate anomalies. Results of that analysis will be presented in the next section. Meanwhile I would like to note the fact that the investigated data series was constructed out of observations from three years. With this particular temporal resolution, conclusions about decadal and longer trends in burned area should be drawn with care. For that specific purpose, a detailed investigation on annually burned areas since the start of the century should be carried out.



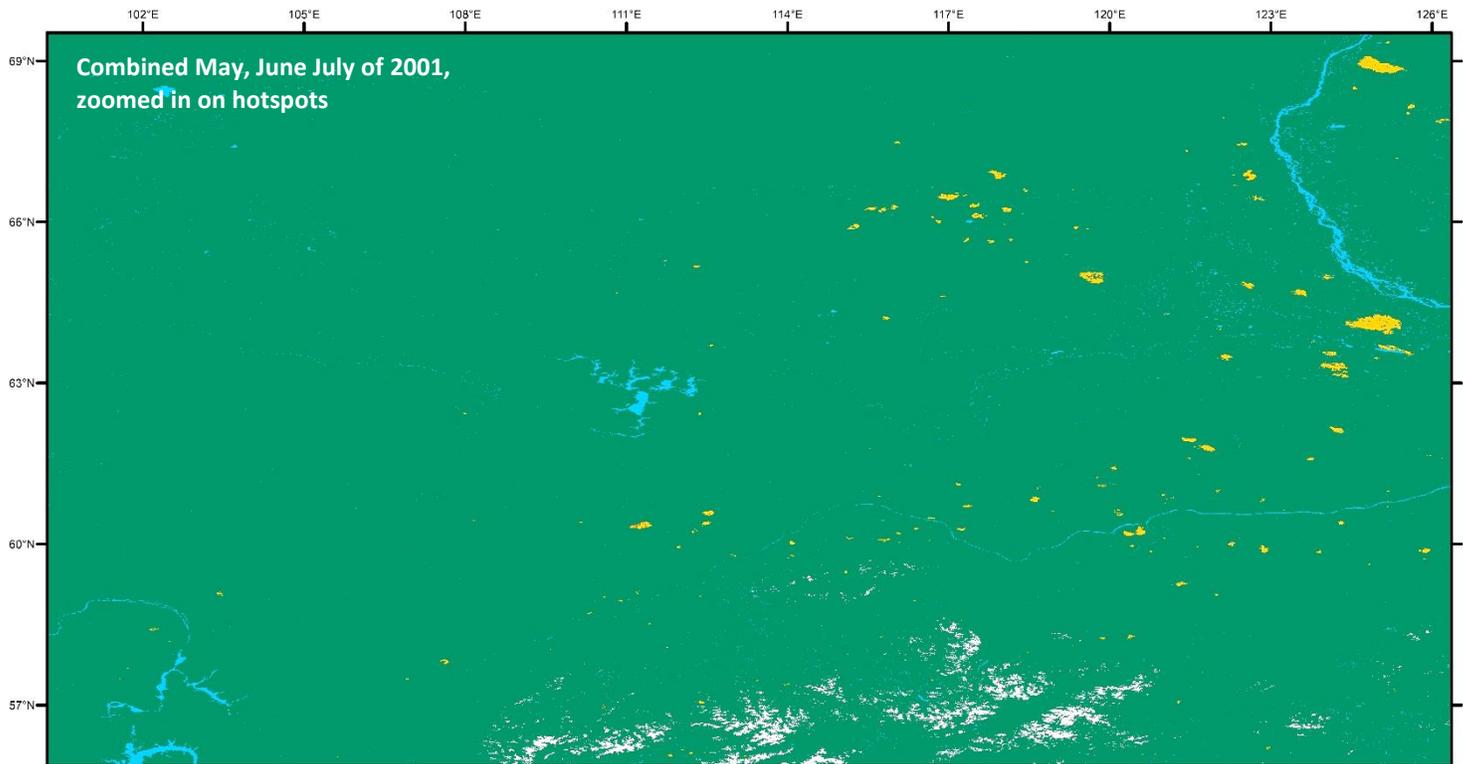
- Water
- No data
- Unburnt pixels
- Burnt pixels

Figure 13 Combined burn extent in study area throughout May, June and July of 2001.
 High resolution digital version available at: <http://i.imgur.com/AEBt5fh.jpg>



- Water
- No data
- Unburnt pixels
- Burnt pixels

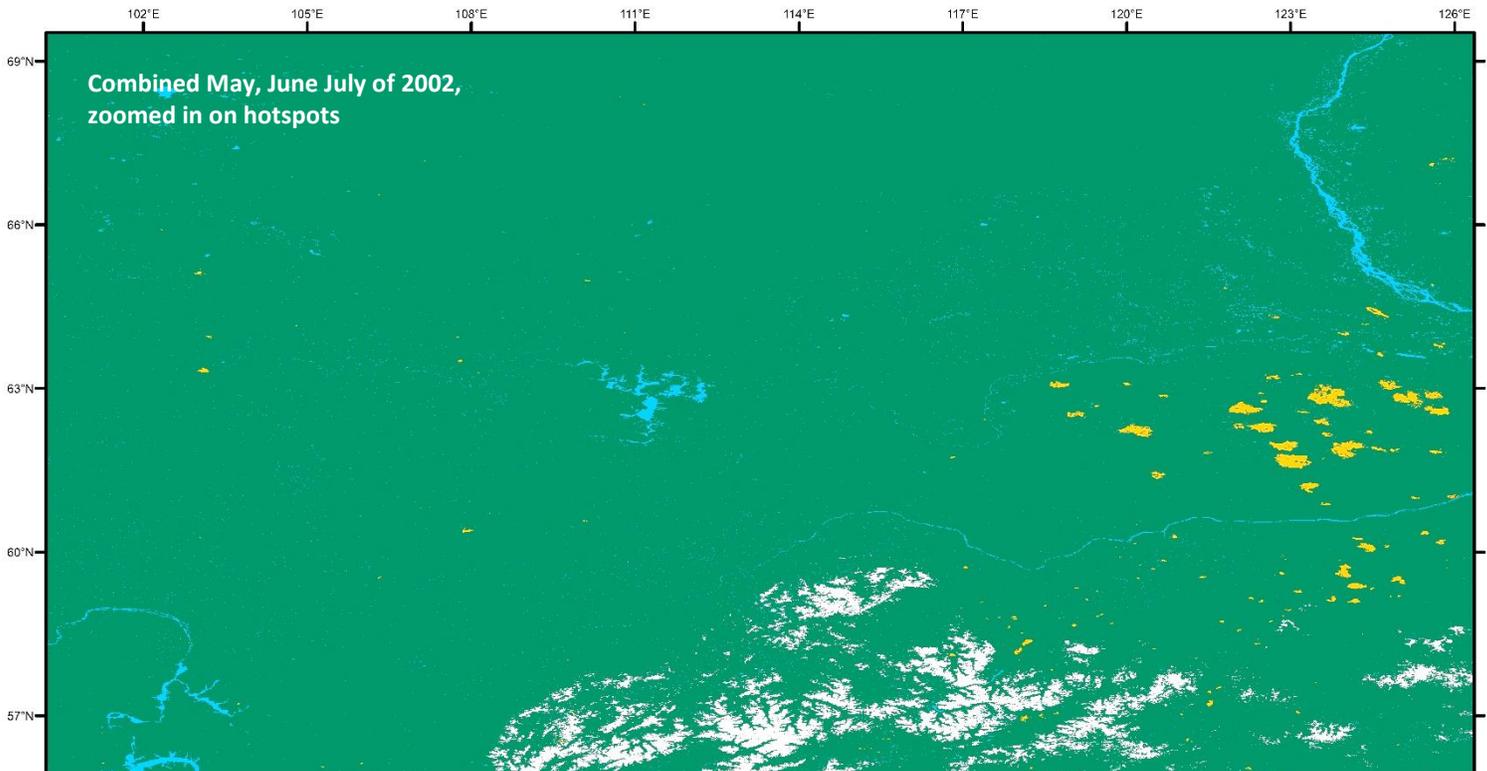
Figure 14 Combined burn extent in study area throughout May, June and July of 2002.
 High resolution digital version available at: <http://i.imgur.com/8vESZBA.jpg>



0 250 500 1,000 Kilometers

- Water
- No data
- Unburnt pixels
- Burnt pixels

Figure 15 Zoomed in burn extent in the study area throughout May, June and July of 2001



0 250 500 1,000 Kilometers

- Water
- No data
- Unburnt pixels
- Burnt pixels

Figure 16 Zoomed in burn extent in the study area throughout May, June and July of 2002

Table 2 Burn extent comparison between early summer months of years 2016, 2001 and 2002

2016 vs 2002 and 2001				
	2016	2002	2001	Increase in 2016 compared to 2001 and 2002 average
Pixels Burned	183,644	78,720	58,437	268%
Area Burned, km ²	39,421	16,898	12,544	

Table 3 Burn extent in the study area through May, June and July of 2001

2001				
	May	June	July	Total
Pixels Burned	2,591	2,664	53,182	58,437
Area Burned, km ²	556	572	11,416	12,544

Table 4 Burn extent in the study area through May, June and July of 2002

2002				
	May	June	July	Total
Pixels Burned	3,931	2,975	71,814	78,720
Area Burned, km ²	844	639	15,415	16,898

3.4 Burn extent in relation to annual climate anomalies

Multiple research efforts have shown that under a warming climate scenario, profound effects on the taiga biome would be observed (Tchebakova et al. 2009). Among the changes in weather and vegetation distribution, fire regimes will be altered as well. Additionally, it has been hypothesized that indirect effects of fire regime alterations might be more important for the ecosystem, than effects that are owed directly to climate change (Weber and Flannigan 1997). As I have indicated before, temperature is one of the most important regulating factors (Weber and Flannigan 1997; Kelly et al. 2013) and global increases in this variable could partially explain the surge in area burned between the start of the 21st century and the year 2016.

The National Oceanic and Atmospheric administration has been keeping track of annual climate anomalies in relation to the 20th century temperature average of 13.9 degrees Celsius (NOAA 2017c) and publishing yearly reports on the state of the climate. A summary of the anomaly records is presented in *table 5*. Meanwhile scatter analysis shown in *figure 17* reveals that despite marginal annual fluctuations, the trend is positive and temperature anomalies have increased by 0.39°C over the last 16 years. The highest shift was observed between 2014 and 2015. Global land and ocean surface temperatures rose by over 0.15°C between the two years. Both 2014 and 2015 have held respective temperature records prior to 2016.

Relating these changes back to the discussed increase in burned area shows that annual temperature anomaly for year 2001 and 2002 combined was 0.575°C. Meanwhile in 2016 the anomaly corresponded to 0.94°C - a near 65% increase. During the same period relative burned area has increased nearly threefold. This suggests that the relationship is not linear - small temperature anomalies likely lead to a significant increase in wildfire damaged area. The observation conforms to academic consensus that burned areas will increase in extent as the climate gets warmer. However, the magnitude of the increase is beyond any observed estimate. It is mostly accepted that the Canadian boreal forest belt will undergo stronger fire regime changes under a future climate scenario, as compared to the Siberian taiga. Flannigan et al. (2009) showed that if current CO₂ concentrations are doubled by mid-21st century, Canadian boreal forests are expected to see a 50% increase in burned area. Considering that taiga has been identified as being less sensitive of the two, a 268% increase in 14 years seems rather extreme. I believe there are a couple of reasons that could explain this anomaly. However before breaking down the surge in area burned, I would like to briefly reflect on burn extent for the investigated years and compare it with results from other datasets.

A study conducted by Kukavskaya et al. (2012), where MODIS thermal anomalies, burn products and NOAA's AVHRR based burn products were used, partially conforms to the identified burn extent during early summer of both 2001 and 2002. However, a more detailed look into annual data from the start of the 21st century shows that taiga wildfire extent and locality can vary substantially on a yearly basis. This hypothesis has been previously outlined when discussing 2016 observations. The variance occurs even in the case of two years having near identical temperature anomalies, indicating that more local scale processes, like daily weather, have higher influence on extent and locality of wildfire. Mapping efforts carried out by the mentioned research team indicate that hotspots between two consecutive years can shift by 20 or more degrees of latitude and 10 degrees of longitude.

Based on this information I would suggest that anomalously high increase in burned area in 2016 is partially owed to an inaccurate estimation. Study area for 2001 and 2002 likely did not cover the entire extent of wildfire for the respective years. For 2002, multiple hotspots below the 50th north parallel can be identified, whereas the study area was limited by the 56th north parallel. It is important to note that the analysis has correctly portrayed changes within the study area. However, due to the dynamic nature of annual wildfire recurrence, the estimate only represents the direction of general wildfire trend within the Siberian taiga, rather than the magnitude of the changes.

These observations also support the hypothesis of the importance of local weather that I outlined in 2016 observations section. Meaning that global climate trends do influence wildfire by dictating average temperatures, but it is ultimately micro and mesoscale weather conditions that govern the spread and intensity. If this is truly the case, accurately modelling future wildfire scenarios would require integration of both general circulation and high resolution climate models. An effort of this scale would allow predicting changes to local weather together with identifying long-term trends.

Table 5 Yearly land and ocean surface temperature anomalies compared to the 20th century average

Global temperature anomaly by NOAA, compared to 20th century average	
2001	0.55
2002	0.60
2003	0.61
2004	0.58
2005	0.66
2006	0.61
2007	0.61
2008	0.54
2009	0.64
2010	0.70
2011	0.58
2012	0.62
2013	0.66
2014	0.74
2015	0.90
2016	0.94

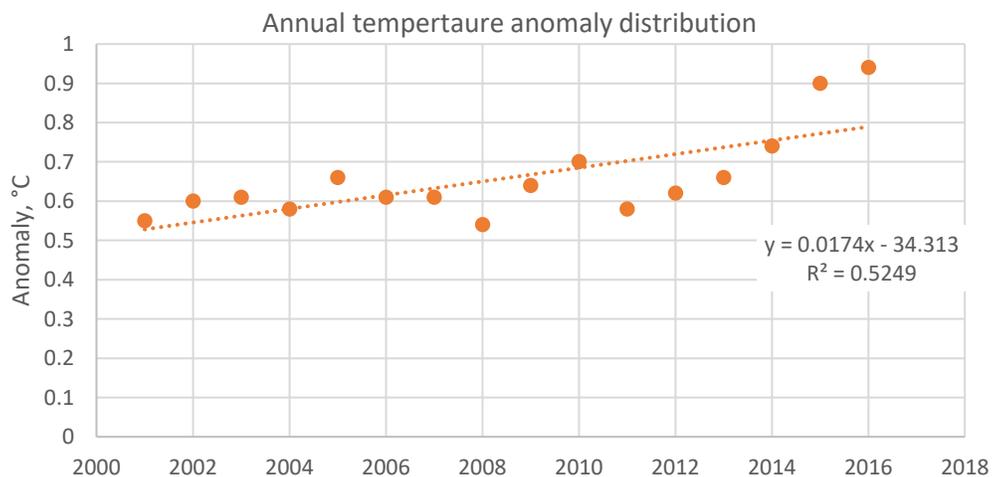


Figure 17 Yearly land and ocean surface temperature anomaly trend

3.5 Global carbon balance and climate change

Modelling efforts to-date and historical investigations suggest multiple changes within the boreal forest ecosystem, wildfire dynamics likely being even more important than direct effects of climatic changes. This is due to fire seasonality, intensity and frequency directly affecting the structure of the boreal forest ecosystem. Weber and Flannigan (1997) and de Groot et al. (2013) predict that among many other variables, species composition, age classes, boundaries, carbon sequestration dynamics, susceptibility to pathogens and insect disturbances will be altered following the changes in wildfire regime. Furthermore, each of these processes can form feedback loops with the climate and the fire dynamic itself.

Other predictions include significant increase in areas under high or extreme fire danger for months of June and July (Flannigan et al. 2009) and wildfire attributed smoke issues. Presence of smoke could alter local or possibly even global radiation budgets and form positive feedback loops with lightning ignitions of forests (Simmonds et al. 2005; Flannigan et al. 2009).

In addition, one must take interactions with the global carbon cycle into account. Wildfires have been shown to have significant impacts on global atmospheric composition and thermal balance. Historically, steady emissions have been sequestered by regrowth of vegetation, but ongoing land use changes will likely reduce storage capabilities (Conard et al. 2002). Currently, boreal forests hold more than 30% of all terrestrial carbon (Kelly et al. 2013). With this information in mind, accurately estimating boreal wildfire emissions seems vital to our understanding of climate development in the future.

Unfortunately, the contribution of wildfire events is rather difficult to evaluate, due to different species having different fuel loading and combustion parameters. While satellite derived global land cover maps are available, the classification criteria are often too coarse and distinction between ecosystems with different fire regimes cannot be made. Consequently, researchers have to resort to using older digitized paper maps or obtaining field data (Kukavskaya 2016). The latter being extremely difficult and expensive in an area spanning nearly 9 million km² (World Wildlife Fund 2013). Further complications include fuel consumption parameters varying greatly based on time of year and present weather conditions. As a result, final gas emission estimates can vary more than twofold (Kukavskaya 2016).

Despite uncertainty, some studies have attempted to estimate CO₂ emissions. Konovalov et al. (2014) utilised a top-down approach to achieve this. Using satellite estimates of emitted CO, aerosols and a chemistry-transport model the scientist and his team have estimated that total CO₂ emissions from 2012 wildfires in Siberia amounted to approximately 392 Teragrams of Carbon. This number is equivalent to nearly 4% of global anthropogenic CO₂ emissions in 2010 (Pachauri et al. 2015). However, the mentioned estimate is nearly two times larger, compared to multiple bottom-up approach estimates. Another study, focusing on the extremely dry summer of 1998 estimated CO₂ emissions to be between 135 to 190 Teragrams of carbon (Conard et al. 2002). Despite the studies not being directly comparable due to different time periods investigated, the estimate varies by over 241%.

Disagreements of this nature confirm a need for accurate carbon contribution assessment of the Siberian taiga wildfires, if they were to be included in the global carbon budget. Considering very few studies on the topic (Ponomarev et al. 2016), research teams as the one led by Kukavskaya (2016) understand the necessity of academic contributions and encourage other researchers in the field: “There is an urgent need to obtain more accurate fire carbon loss estimates in Siberia because of its considerable contribution to the regional and global carbon balance and the atmosphere”.

3.6 Uncertainties

The limitations of the chosen approach mainly lie in uncertainties of satellite data. Despite products undergoing multiple quality assessments, various algorithm attributed drawbacks come with the data. For example, the used burn product has a minimum detectable burn threshold on the order of 120 hectares or 1.2 km². This suggests that small and isolated hotspots go undetected and are consequently not represented in burned area estimates.

Another satellite derived data product used in this project was global land cover. While total accuracy for all land classes has been estimated at approximately 75% as mentioned before, individual uncertainties for each land class varied tremendously, affecting the accuracy of land cover and burned area cross analysis. The chosen land cover product was rather accurate for most forest types, but some classes relevant to this investigation exhibited moderate to low user accuracies. Among them were mixed forests with 53% user’s accuracy and woody savannahs with 34% user’s accuracy.

Finally, the chosen methodology contributed to possible over and under estimations. The most important factor in this regard was likely the extent of the study area. While it was initially chosen based on visual light observations provided by the ESA during 2016 summer, later in the project it became evident that wildfires shift in terms of burn location on an annual basis. Accordingly, while majority of 2016 burns fell within the study area, portions of the 2001 and 2002 burns did not, resulting in the previously discussed overestimation of burned area change between the investigated years.

4. Conclusion

Burn extent in late spring and early summer of 2016 has been successfully quantified using satellite derived data and has shown significant increase as compared to early 21st century. However, the difference between said time periods was most likely overestimated. Relating to annual temperature anomalies since the start of 2000's, it seems that taiga wildfire extent has been increasing as global temperatures keep rising. Unfortunately, since wildfires are quite dynamic in nature, making accurate predictions about future extent is difficult. Despite general trends in global temperature and fires being partially influenced by it, wildfires also strongly depend on local weather conditions for a target year and area.

Cross-analysis with land cover has produced predictable results that conform to other studies on the topic. With majority of boreal forest in the study area covered by larch, this was the land class exhibiting highest burn. Considering that study area covers both southern and northern parts of Eurasia, mixed forests as well as non-forest vegetation like shrublands burned together with Larch stands.

Finally, a review of multiple investigations suggests that current understanding of wildfires in context of the global carbon cycle is incomplete. Climate change is predicted to alter wildfire regimes and these alterations could, in turn, form new feedback loops with the climate system. Considering that boreal forests store almost a third of all terrestrial carbon, a change in ecosystem dynamics could have substantial impacts on this system's contribution to the global carbon cycle.

In review, this study outlines general trends of taiga wildfire in relation to the warming climate. These trends are positive and wildfire damaged areas will most likely expand if global temperature anomalies keep increasing. Adding the apparent lack of research on wildfire in the context of global carbon cycle means that understanding future changes of boreal forest wildfires is important. To this extent, an expanded study investigating annual 21st century Siberian temperature anomalies and their relationship with fire extent, should be conducted.

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5.1 Satellite data

University of Maryland FTP, providing access to GeoTIFF tiles of MCD64A1 burned area product: <ftp://ba1.geog.umd.edu/Collection6/TIFF/>

Metadata information for the MCD12Q1 land cover product: <http://glcf.umd.edu/data/lc/>
 Data access in GeoTIFF tiles from University of Maryland FTP:
ftp://ftp.glcf.umd.edu/glcf/Global_LNDCVR/UMD_TILES/Version_5.1/

Institutionen för naturgeografi och ekosystemvetenskap, Lunds Universitet.

Student examensarbete (Seminarieuppsatser). Uppsatserna finns tillgängliga på institutionens geobibliotek, Sölvegatan 12, 223 62 LUND. Serien startade 1985. Hela listan och själva uppsatserna är även tillgängliga på LUP student papers (<https://lup.lub.lu.se/student-papers/search/>) och via Geobiblioteket (www.geobib.lu.se)

The student thesis reports are available at the Geo-Library, Department of Physical Geography and Ecosystem Science, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden. Report series started 1985. The complete list and electronic versions are also electronic available at the LUP student papers (<https://lup.lub.lu.se/student-papers/search/>) and through the Geo-library (www.geobib.lu.se)

- 400 Sofia Sjögren (2016) Effective methods for prediction and visualization of contaminated soil volumes in 3D with GIS
- 401 Jayan Wijesingha (2016) Geometric quality assessment of multi-rotor unmanned aerial vehicle-borne remote sensing products for precision agriculture
- 402 Jenny Ahlstrand (2016) Effects of altered precipitation regimes on bryophyte carbon dynamics in a Peruvian tropical montane cloud forest
- 403 Peter Markus (2016) Design and development of a prototype mobile geographical information system for real-time collection and storage of traffic accident data
- 404 Christos Bountzouklis (2016) Monitoring of Santorini (Greece) volcano during post-unrest period (2014-2016) with interferometric time series of Sentinel-1A
- 405 Gea Hallen (2016) Porous asphalt as a method for reducing urban storm water runoff in Lund, Sweden
- 406 Marcus Rudolf (2016) Spatiotemporal reconstructions of black carbon, organic matter and heavy metals in coastal records of south-west Sweden
- 407 Sophie Rudbäck (2016) The spatial growth pattern and directional properties of *Dryas octopetala* on Spitsbergen, Svalbard
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- 409 Abdalla Eltayeb A. Mohamed (2016) Mapping tree canopy cover in the semi-arid Sahel using satellite remote sensing and Google Earth imagery
- 410 Ying Zhou (2016) The link between secondary organic aerosol and monoterpenes at a boreal forest site
- 411 Matthew Corney (2016) Preparation and analysis of crowdsourced GPS bicycling data: a study of Skåne, Sweden
- 412 Louise Hannon Bradshaw (2017) Sweden, forests & wind storms: Developing a model to predict storm damage to forests in Kronoberg county
- 413 Joel D. White (2017) Shifts within the carbon cycle in response to the absence of keystone herbivore *Ovibos moschatus* in a high arctic mire

- 414 Kristofer Karlsson (2017) Greenhouse gas flux at a temperate peatland: a comparison of the eddy covariance method and the flux-gradient method
- 415 Md. Monirul Islam (2017) Tracing mangrove forest dynamics of Bangladesh using historical Landsat data
- 416 Bos Brendan Bos (2017) The effects of tropical cyclones on the carbon cycle
- 417 Martynas Cerniauskas (2017) Estimating wildfire-attributed boreal forest burn in Central and Eastern Siberia during summer of 2016