Abstract
Circum-boreal and -tundra systems are crucial carbon pools that are experiencing amplified warming and are at risk of increasing wildfire activity. Changes in wildfire activity have broad implications for vegetation dynamics, underlying permafrost soils, and ultimately, carbon cycling. However, understanding wildfire effects on biophysical processes across eastern Siberian taiga and tundra remains challenging because of the lack of an easily accessible annual fire perimeter database and underestimation of area burned by MODIS satellite imagery. To better understand wildfire dynamics over the last 20 years in this region, we mapped area burned, generated a fire perimeter database, and characterized fire regimes across eight ecozones spanning 7.8 million km² of eastern Siberian taiga and tundra from ∼61–72.5° N and 100° E–176° W using long-term satellite data from Landsat, processed via Google Earth Engine. We generated composite images for the annual growing season (May–September), which allowed mitigation of missing data from snow-cover, cloud-cover, and the Landsat 7 scan line error. We used annual composites to calculate the difference Normalized Burn Ratio (dNBR) for each year. The annual dNBR images were converted to binary burned or unburned imagery that was used to vectorize fire perimeters. We mapped 22,091 fires burning 152 million hectares (Mha) over 20 years. Although 2003 was the largest fire year on record, 2020 was an exceptional fire year for four of the northeastern ecozones resulting in substantial increases in fire activity above the Arctic Circle. Increases in fire extent, severity, and frequency with continued climate warming will impact vegetation and permafrost dynamics with increased likelihood of irreversible permafrost thaw that leads to increased carbon release and/or conversion of forest to shrublands.

1. Introduction
Current-day circum-boreal and -tundra biomes serve as vital carbon sinks that are increasingly vulnerable to climate warming and associated increases in wildfire activity (Gillett 2004, Kasischke and Turetsky 2006, Flannigan et al 2009, Mack et al 2011, McAulchan et al 2020). Fire directly influences carbon cycling through the combustion of organic material (Kasischke et al 2005) and indirectly by altering surface properties such as vegetation cover and composition (Baltzer et al 2021, Mack et al 2021) that influence subsequent permafrost degradation (Gillett 2004, Flannigan et al 2009, Mack et al 2011, Abbott et al 2016, Holloway et al 2020). Understanding the distribution of wildfire activity across northern ecosystems is crucial to identifying feedbacks between vegetation, carbon, albedo, and permafrost that influence climate (Berner et al 2012, Loranty et al 2016, Chen and Loboda 2018, Holloway et al 2020). While North American has an extensive record of wildfire activity (Stocks et al 2002, Kasischke and Turetsky 2006), records from eastern Siberia (and Russia in general) are challenging to acquire from internal agencies or limited to moderate to coarse resolution satellite data products that often underestimate burned area (Shvidenko et al 2011, Berner et al 2012). A more detailed record of fire activity across eastern Siberian taiga (synonymous with boreal) and tundra ecozones is necessary to better
understand spatiotemporal characteristics of fire regimes.

Across Siberian taiga and tundra, fire activity is intricately linked with permafrost degradation through the combustion of vegetation and soils that warm permafrost and increases microbial respiration that releases carbon stores into the atmosphere (Mack et al 2011, Loranty et al 2016, Alexander et al 2018, Holloway et al 2020). Much of the region is underlain by continuous permafrost with regions above the Arctic Circle containing Yedoma—thick, carbon- and ice-rich permafrost deposits (Grosse et al 2013, Strauss et al 2017). The interactive mechanisms of fire and permafrost also influence post-fire vegetation recovery, particularly for larch (Larix spp.) forests that cover much of Siberia and grow atop continuous permafrost (Sofronov and Volokitina 2010, Alexander et al 2018). Understanding the impacts of changing fire regimes on permafrost stability and related climate feedbacks requires an improved understanding of Siberia taiga and tundra fire regimes.

The current understanding of Siberian fire regimes is spatially and temporally limited, with existing research predominantly focused on western and central regions and little knowledge of fire activity across eastern Siberian taiga and tundra. Annual fire activity has limited ground-based records that are challenging to access and underestimate area burned since all fires are not mapped, compared to coarse spatial resolution satellite-based studies (Soja et al 2007). However, coarse spatial resolution satellites miscalculate large fires (Advanced Very High Resolution Radiometer, AVHRR, 1.1 km) (Shvidenko et al 2011) and underestimate annual area burned by 40%–50% compared to the finer scale resolution of Landsat (30 m) (Berner et al 2012). These underestimations make it challenging to fully understand wildfire dynamics and the changes that are occurring throughout the region. Extreme fire seasons result in increased carbon emissions from soil organic matter combustion (Soja 2004), and there is a rising trend in extreme fire seasons (Soja et al 2007, Kirillina et al 2020). Extreme fire seasons may also influence vegetation shifts from forest to shrubland or treeline advance (Frost and Epstein 2014, Sizov et al 2021) and/or cause irreversible permafrost degradation that does not support larch recruitment (Frost and Epstein 2014). Across northwestern and central Siberia, a rise in fire activity has been attributed to warmer and drier conditions (Soja et al 2007, Ponomarev et al 2016, Masrur et al 2018, Kirillina et al 2020) as well as human activity (Kirillina et al 2020, Sizov et al 2021).

Eastern Siberian taiga and tundra ecosystems are shaped by wildfire activity that contributes to ecological processes and climate feedbacks, but fire dynamics are not well understood. Unprecedented fire seasons over the past several years (Natali et al 2021) highlight the need for a fire perimeter database capable of contextualizing fire perimeter database changes as a baseline for long-term monitoring and characterizing the influence of climate change on fire activity. While there are limitations due to missing data before 1996 from the blackout period (Berner et al 2012), snow, and clouds, Landsat offers an ecologically meaningful resolution (30 m) that can be readily linked with field data and corresponds with North American fire perimeter and burn severity databases (MTBS 2016). We have three main objectives to understand fire activity across the eight ecozones in the eastern Siberian taiga and tundra. First, we develop a fire perimeter database with the Landsat Archive. Second, we characterize the spatiotemporal components of fire regimes, including annual area burned, fire frequency, fire rotation, fire size classes, and fire season length for each ecozone. Finally, we use statistical models to identify the relationship between annual area burned and key climate drivers—mean summer climate water deficit (hereafter water deficit), mean summer precipitation, mean summer temperature, fire season length, and snowmelt timing.

2. Materials and methods

2.1. Study area

This study focuses on eight ecozones across eastern Siberian taiga and tundra regions where fire is a key ecological disturbance on landscapes that are underlain by continuous permafrost (figure 1). The eight ecozones include Bering tundra, Cherskii-Kolyma Mountain tundra, Chukchi Peninsula tundra, East Siberian taiga, Northeast Siberian coastal tundra, Northeast Siberian taiga, Taimyr-Central Siberian tundra, Trans-Baikal Bald Mountain tundra and span 7.8 million km$^2$ from $\sim$61–72.5$^\circ$ N and 100$^\circ$ E–176$^\circ$ W. Each ecozone delineates an area containing similar flora and fauna related to biogeographic realms (Olson et al 2001), and ecozone boundaries were publicly available and free (www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world).

East Siberian taiga and Northeast Siberian taiga are composed predominantly of larch, a deciduous needle-leaf conifer that requires periodic fire to persist on the landscape (Kharuk et al 2011). Fire typically spreads across the surface resulting in tree mortality primarily from root damage and consumption of shrubs and the soil organic layer, exposing mineral soils and removing competition, thereby facilitating larch seedling establishment (Sofronov and Volokitina 2010, Alexander et al 2018, Kharuk et al 2021). The southwestern portion of the study area gives way to forests of Scots pine (Pinus sylvestris), a fire-adapted species that require periodic fires that burn as surface and crown fires resulting in tree mortality
Figure 1. The study area spanned eight ecozones across the boreal forest and tundra biomes of Eastern Siberia: East Siberian taiga (B1), Northeast Siberian taiga (B2), Bering tundra (T1), Cherskii-Kolyma Mountain tundra, (T2), Chukchi Peninsula tundra (T3), Northeast Siberian coastal tundra (T4), Taimyr-Central Siberian tundra (T5), and Trans-Baikal Bald Mountain tundra (T6). The ecozone shapefile was developed by Olson et al. (2001) and is freely available through the World Wildlife Fund (www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world). The white dashed line indicates the Arctic Circle. Also shown are the city of Yakutsk and the urban locality of Cherskiy.

(Kharuk et al. 2011, 2021). Northern latitudes transition to forest-tundra and then tundra zones composed of graminoids, prostrate shrubs, erect shrubs, and wetlands (Walker et al. 2010).

2.2. Fire perimeter product
We generated an annual fire perimeter database from 2001 to 2020 using the Landsat archive (30 m resolution) (Wulder et al. 2016) for the study area using Google Earth Engine (hereafter Earth Engine) (Gorelick et al. 2017) and the R Statistical Computing Software (R Core Team 2018). The time frame was selected due to the overlap with MODIS Collection 6 (i.e. hotspots) that detect thermal anomalies and the best available Landsat imagery due to a lack of imagery prior to 1996 from the blackout period (Berner et al. 2012). Landsat was chosen because of the spatial-temporal coverage, specifically, the finer spatial resolution (30 m) compared to MODIS (500 m) that would align with burn severity mapping in North America (Key and Benson 2006, Eidenshink et al. 2007, Wulder et al. 2016) that relies on the long temporal record 1984–present. The spatial scale of Landsat would allow for future research addressing pertinent ecological questions about post-fire landscapes that depend on ecologically meaningful scales. The 30 m resolution of Landsat maintains finer-scale features that are lost at coarser resolutions like MODIS (Turner et al. 1989, Benson and MacKenzie 1995). The methods to delineate fire perimeters around burned areas were assessed with an existing fire perimeter dataset from the 2004 Alaskan fire season (see supplementary material (available online at stacks.iop.org/ERL/17/025001/mmedia)). Due to computational limits in Earth Engine, the study area was split into three regions of interest (ROIs) to process imagery and apply the vectorization function for each fire season.

We used the Landsat 5, 7, and 8 Surface Reflectance Tier 1 products that were harmonized for corresponding bands (Roy et al. 2016). We selected growing season months (May–October), masked pixels covered by snow and clouds, and then generated annual composite images using the best pixel approach (Hermosilla et al. 2015). Composite images allowed us to mitigate missing data from snow-cover, cloud-cover, and the Landsat 7 scan line error. We used one-year prefire and one-year post-fire annual composites to calculate the difference Normalized Burn Ratio (dNBR) (Eidenshink et al. 2007) for each fire year using the extended assessment outlined by Key and Benson (2006). Each annual dNBR image was converted to a binary burned/unburned image.

Delineating fire perimeters relied on the binary image. We created polygons from MODIS hotspot data to constrain the extent of computational
processing. We buffered the hotspot point data by 3 km and converted them into polygons with the ‘sf’ (Pebersa 2018) package in R. The purpose of transforming points to polygons and buffering by 3 km was to limit the spatial extent of the vector algorithm so we would remain within computational limits of Earth Engine. We visually compared the 3 km with both smaller and larger buffers. However, the 3 km buffers allowed us to stay within the computational limits and capture the extent of the wildfire. The fire perimeters were delineated around Landsat pixels with the vectorize function in Earth Engine and exported as shapefiles. The shapefiles were cleaned in R with the ‘sf’ (Pebersa 2018) and ‘spatialeco’ (Evans 2021) packages. The three ROIs were combined, and polygons were buffered at 1000 m to combine any adjacent polygons. We then removed any holes within the polygons and converted them from multi-polygon to individual polygons. We applied a ~1000 m buffer once holes were removed to counteract the first 1000 m buffer. Finally, we used a smoothing and simplification function with the ‘smoothr’ (Strimasc- Mackey 2021) and ‘rmapshaper’ (Teucher et al 2021) package respectively, to reduce the pixelated appearance and number of vertices.

We created attributes to characterize each fire perimeter with the ‘tidyverse’ package (Wickham et al 2019). We assigned each fire perimeter its major- ity ecozone, a location of either arctic or subarctic, and a permafrost designation of continuous or discontinuous. We summarized the MODIS hotspot data to assign a start and end day and confidence levels as mean, maximum, and minimum to each fire perimeter. We calculated the area for each fire perimeter in hectares (ha) and assigned a unique fire ID. We assigned a fire size class based on the perimeter area following the Canadian large fire data- base (Stocks et al 2002). While there is not globally common language to characterize fire size (Burton et al 2008, Stephens et al 2014, Tedim et al 2018), we describe small fires as <1000 ha, moderate fires as 1000 < 10 000 ha, large fires as 10 000 < 50 000 ha, extremely large fires as 50 000 < 100 000 ha, and mega-fires as ≥ 100 000. We removed any fire perimeters with zero percent confidence per the MODIS hotspot data measures. We chose to retain other low confidence intervals because fires burn less intensely in the Russian taiga compared to the North Amer- ican boreal (Wooster 2004), needle-leaf forests tend to see lower confidence levels than open landscapes (Roy et al 2008), and cloud cover is a persistent issue (Warren et al 1986). Many of the fires with lower confidence were smaller. Fire perimeters less than 200 ha were removed to match similar database criteria in North America (Stocks et al 2002). The fire perimeter database is available through the Arctic Data Center (Talucci et al 2021).

To assess the fire perimeter product, we visually compared the vectors generated in Earth Engine with fire perimeters from the 2004 Alaska fire sea- son. Alaska fire perimeters were downloaded from Monitoring Trends in Burn Severity (MTBS 2016). The MTBS perimeters are generated with various techniques, including aerial surveys, image digitiz- ation, and combinations thereof. We implemented the process described above and then visually inspec- ted the alignment and coverage of our vectors with MTBS vectors (MTBS 2016). Additionally, we com- pared the Landsat scale fire perimeter database to the MODIS burned area product to quantitatively assess differences.

2.3. Analysis of fire regimes and climate controls
To provide a foundational understanding of fire activity from 2001 to 2020, we characterized spati- temporal attributes of fire regimes across ecozones. We summarized each ecozone’s annual area burned, number of fires per year, area burned by fire size class, fire season length and timing, and fire rota- tion. Fire rotation refers to the time it takes to burn the area equivalent to the landscape and is calcu- lated as the time of study period divided by the pro- portion of area burned (Heinselman 1973, Bond and Keeley 2005, Berner et al 2012). For example, in the Northeast Siberian Taiga zone, we divide the 20 year study period by the total proportion of area burned within the ecozone that burned during the study period, 0.159 (i.e. total area burned, 19 295 km², divided by the area of the ecozone 1133 262 km²) resulting in a fire rotation of 126 years.

We examined trends in annual area burned as they related to climate factors—mean summer water deficit, mean summer precipitation, mean summer maximum temperature, fire season length, and snow- melt timing—with linear models. There are few evalua- tions of climate and fire in Siberian taiga and tun- dra (Balzter et al 2005). Precipitation (Balzter et al 2005), temperature (Balzter et al 2005), and water deficit (Stephenson 1998, Abatzoglou and Williams 2016, Abatzoglou et al 2018) are important drivers of fire activity (Gillet et al 2004, Flamigan et al 2009).

In Earth Engine, we extracted monthly means for water deficit, precipitation, and temperature by year for each fire perimeter and ecozone from the TerraC- limate dataset (Abatzoglou et al 2018). In R, climate values were calculated for each year as the mean summer maximum temperature and mean summer pre- cipitation from April to September following Balzter et al (2005), mean accumulated water deficit from April to September for perimeters within each eco- zone. Annual ecozone values were calculated similarly and used for ecozones and years with zero annual area burned. We calculated the first day of snowmelt with MODIS Terra snow cover daily global 500 m
product (MOD10A1 V6) in Earth Engine. Snowmelt was extracted as a mean for each fire perimeter and each ecozone in Earth Engine. In R, an annual mean snowmelt date was calculated for each ecozone based on fire perimeter values, and for years with zero annual area burned, snowmelt days came from ecozone values. Fire season length was calculated from the minimum start day and maximum end day for fire perimeters within the ecozone.

3. Results

3.1. Fire perimeter product
We mapped 22,110 fires burning 150.5 million hectares (Mha) over 20 years (figure 2). We found that vectors from Earth Engine align well with MTBS vectors (figure A1). Where multiple large fire events merged and were delineated with separate perimeters in MTBS, our approach resulted in a single polygon. The estimated area differences between the fire perimeter product and MTBS compared favorably both over and underestimating (figure A1). The MODIS burned area product often underestimated area burned compared to the estimates from the fire perimeter database. Over the 20 year timeframe, MODIS underestimated the area burned by ~48% (~4.9%–78.6%; table 1).

3.2. Fire regimes
Across ecozones, fire activity showed interannual spatiotemporal variability in area burned and the number of fires (figures 2–4). Annual area burned and the number of fires per year exhibited similar patterns for each ecozone, with larger area burned corresponding to more fire events and smaller annual area burned corresponding to fewer fire events (figures 3(a) and (b)). The taiga zones (East Siberian and Northeast Siberian Taiga) were large contributors to annual area burned (figures 3(a), (b), (e) and (f)), with tundra regions accounting for a much smaller portion of annual area burned corresponding with lower fire frequency. The largest fire year based on the total annual area burned for all ecozones was 2003, with East Siberian taiga and Bering tundra being large contributors to the total (table 2). The 2020 season was the largest fire year for Northeast Siberian Taiga, Cherskii-Kolyma mountain tundra, Northeast Siberian coastal tundra, and Chukchi Peninsula tundra, with many large fires burning above the Arctic Circle (figure 2 and table 2). The average annual area burned was highest in the East Siberian taiga, ~6 Mha, followed by Northeast Siberian Taiga with ~0.9 Mha (table 3), with the Bering tundra, Cherskii-Kolyma mountain tundra, Chukchi Peninsula tundra, Northeast Siberian coastal tundra, Taimyr-Central...
Table 1. Comparison between annual area burned of fire perimeter product and MODIS area burned product. We report the annual area burned for Landsat and MODIS, the difference between Landsat and MODIS, the percent difference, and then calculations for the 20 years.

| Fire year | Landsat total annual area burned (ha) | MODIS total annual area burned (ha) | Difference in annual area burned (ha; Landsat-MODIS) | Percent difference (%) |
|-----------|-------------------------------------|-------------------------------------|------------------------------------------------------|------------------------|
| 2001      | 5032 601                            | 3109 675                            | 1922 926                                             | 38.2                   |
| 2002      | 14 455 758                          | 5327 506                            | 9128 252                                             | 63.1                   |
| 2003      | 22 207 480                          | 8961 313                            | 13 246 167                                          | 59.6                   |
| 2004      | 813 824                             | 920 693                             | −106 869                                            | −13.1                  |
| 2005      | 2161 571                            | 1784 351                            | 377 220                                              | 17.5                   |
| 2006      | 3789 094                            | 2405 165                            | 1383 929                                            | 36.5                   |
| 2007      | 5582 193                            | 1196 336                            | 4385 857                                            | 78.6                   |
| 2008      | 3990 463                            | 4185 565                            | −195 102                                            | −4.9                   |
| 2009      | 2912 290                            | 2156 204                            | 756 686                                             | 26.0                   |
| 2010      | 3690 995                            | 2694 739                            | 996 256                                             | 27.0                   |
| 2011      | 9227 404                            | 4337 350                            | 4890 054                                            | 53.0                   |
| 2012      | 7744 747                            | 5054 783                            | 2689 964                                            | 34.7                   |
| 2013      | 4800 784                            | 3126 182                            | 1674 602                                            | 34.9                   |
| 2014      | 9207 413                            | 5528 963                            | 3678 450                                            | 40.0                   |
| 2015      | 9111 646                            | 2877 500                            | 6234 146                                            | 68.4                   |
| 2016      | 9067 524                            | 4452 600                            | 4614 924                                            | 50.9                   |
| 2017      | 4536 944                            | 3319 332                            | 1217 612                                            | 26.8                   |
| 2018      | 7178 752                            | 4596 014                            | 2582 738                                            | 36.0                   |
| 2019      | 11 610 258                          | 6106 760                            | 5503 498                                            | 47.4                   |
| 2020      | 13 383 348                          | 6288 662                            | 7094 686                                            | 53.0                   |
| Total     | 150 505 089                          | 78 429 693                          | 72 075 396                                          | 47.9                   |

Siberian tundra, Trans-Baikal Bald Mountain tundra averaging a smaller annual area burned (table 3). We standardized the mean number of fires per 10 000 km², which averaged 2.1 for East Siberian taiga and 1.2 For Northeast Siberian Taiga. At the same time, tundra zones saw a decrease in the mean number of fires per 10 000 km² along the south to north latitudinal gradient (table 3). Area burned in the Arctic increased substantially in 2019 and 2020, with 3.4 Mha burned in 2019 and 5.4 Mha burned in 2020 representing four- and six-fold increases over the 0.9 Mha burned in the previous largest year (2018) (figure 4 and table A2). For the 20 years, the fire rotation varied by ecozone, with East Siberian taiga having the shortest rotation at 65 years, followed by Northeast Siberian Taiga at 126 years. The tundra zones showed fire rotation increases from south to north (table 3).

Across ecozones, the distribution of fire size classes varied with annual area burned and the number of fires (figure 5). For East Siberian taiga and Northeast Siberian Taiga, large annual area burned was predominantly driven by mega-fire events >100 000 ha, and small fires <1000 ha were more frequent. This pattern occurred for the Bering tundra, Northeast Siberian coastal tundra, and Trans-Baikal Bald Mountain tundra. For Cherski-Kolyma mountain tundra, Chukchi Peninsula tundra, and Taimyr-Central Siberian tundra ecozones, annual area burned was driven by moderate to large fire events between 2000 < 20 000 ha, and small fires <1000 ha were more frequent.

Fire season length and timing (e.g. start and end) showed interannual variability across ecozones (figure 6 and table 3). The Bering tundra, Cherskii-Kolyma mountain tundra, Chukchi Peninsula tundra, Northeast Siberian coastal tundra, and Taimyr-Central Siberian tundra had the shortest mean fire season length, where some years had zero days of burning. The Trans-Baikal Bald Mountain tundra had the most extended season of the tundra zones. The Northeast Siberian Taiga fire season averaged 138 days while the East Siberian taiga fire season was the longest averaging 224 days.

3.3. Climate factors and annual area burned
Climate factors—water deficit, precipitation, temperature, season length, and snowmelt timing—influenced annual area burned to varying degrees across ecozones (figure 7 and table 4). As water deficit increased, conditions became drier, resulting in an increased annual area burned across all ecozones with variability in model fit (R² 0.03–0.67). As precipitation decreased, annual area burned increased across all ecozones with variability in model fit (R² 0.05–0.48). As the temperature increased, annual area burned increased across all ecozones, with variability in model fit (R² 0.04–0.87), and Northeast Siberian coastal tundra had a strong model fit. As fire season length increased, annual area burned increased across all ecozones with variability in model fit (R² 0.15–0.57). Earlier snowmelt corresponded to increased annual area.
Figure 3. The annual area burned (a) and fire frequency (b) across eight ecozones in eastern Siberian taiga and tundra regions, including East Siberian taiga (B1), Northeast Siberian taiga (B2), Bering tundra (T1), Cherskii-Kolyma Mountain tundra (T2), Chukchi Peninsula tundra (T3), Northeast Siberian coastal tundra (T4), Taimyr-Central Siberian tundra (T5), and Trans-Baikal Bald Mountain tundra (T6). Additional plots show area burned and frequency based on Arctic and Subarctic locations (c), (d) and taiga and tundra biomes (e), (f). See table 2 and A2 for values.

burned for all ecozones with variability in model fit ($R^2$ 0.03–0.67).

4. Discussion

Characterizing fire regimes with satellite-based approaches across eastern Siberian taiga and tundra zones is vital for understanding fire dynamics in areas increasingly vulnerable to climate warming (Gillett 2004, Kasischke and Turetsky 2006, Flannigan et al 2009, Mack et al 2011, McLauchlan et al 2020). We have created a fire perimeter database that improves understanding of fire frequency and distribution across the region over the past 20 years and can support further investigation of heterogeneity in burn severity and subsequent effects on ecosystem function and recovery. Interannual variability in area burned was primarily driven by climatic controls, and large fires dominated years with high annual area burned. Years with large annual area burned typically exhibited regional clustering, with the notable exception of 2020, when fire was extensive across the region, and half of the ecozones experienced their greatest fire seasons in the last 20 years. Our results will serve as a baseline to elucidate long-term shifts in fire regimes.
Figure 4. Plots show the cumulative area burned by ecozones (a) and by Arctic or Subarctic location (b). The cumulative area burned varies by ecozone—East Siberian taiga (B1), Northeast Siberian taiga (B2), Bering tundra (T1), Cherskii-Kolyma Mountain tundra (T2), Chukchi Peninsula tundra (T3), Northeast Siberian coastal tundra (T4), Taimyr-Central Siberian tundra (T5), and Trans-Baikal Bald Mountain tundra (T6). The cumulative area burned by the Arctic or subarctic location highlights the substantial uptick in area burned in 2019 and 2020 in the Arctic (b), which corresponds with increases in area burned for Northeast Siberian taiga, Cherskii-Kolyma Mountain tundra, Chukchi Peninsula tundra, and Northeast Siberian coastal tundra in 2019 and 2020. The y-axis was log-transformed (base 10) for area burned in hectares (ha). The x-axis shows the years 2001–2020.

Table 2. Table of annual area burned for each of eight ecozones. The total annual area burned across the entire region is tallied in the column furthest to the right, while the total area burned between 2001 and 2020 for each ecozone is tallied across the final row. The largest area burned during a fire season for each ecozone is in bold.

| Year | East Siberian taiga (B1) | Northeast Siberian taiga (B2) | Bering tundra (T1) | Cherskii-Kolyma Mountain tundra (T2) | Chukchi Peninsula tundra (T3) | Northeast Siberian coastal tundra (T4) | Taimyr-Central Siberian tundra (T5) | Trans-Baikal Bald Mountain tundra (T6) | Total annual area burned (ha) |
|------|--------------------------|------------------------------|-------------------|--------------------------------------|-----------------------------|-------------------------------------|---------------------------------|----------------------------------------|-------------------------------|
| 2001 | 2742 514                 | 1929 395                     | 50 816            | 234 819                               | —                           | 14 743                              | 2419                            | 55 708                                  | 5032 414                      |
| 2002 | 13 394 713               | 366 046                      | 440 703           | 82 527                                | 14 257                      | —                                   | 300                             | 155 222                                 | 14 455 768                    |
| 2003 | **18 440 667**           | 1831 323                     | 1334 839          | 370 739                               | 7337                        | —                                   | 20 691                          | 199 873                                 | 22 207 472                    |
| 2004 | 567 160                  | 107 733                      | 43 201            | 20 804                                | 22 960                      | —                                   | 4288                            | 45 672                                  | 813 822                       |
| 2005 | 1604 952                 | 339 192                      | 60 867            | 52 592                                | 9872                        | 24 601                              | 3130                            | 64 362                                  | 2161 571                      |
| 2006 | 3566 438                 | 43 647                       | 43 272            | 26 532                                | 1117                        | —                                   | 8032                            | 97 859                                  | 3788 902                      |
| 2007 | 5032 992                 | 99 644                       | 208 753           | 45 477                                | 19 448                      | —                                   | 8753                            | 165 134                                 | 5582 207                      |
| 2008 | 3189 529                 | 258 267                      | 87 550            | 57 052                                | 4679                        | 7531                                | 1325                            | 382 516                                 | 3990 456                      |
| 2009 | 1313 271                 | 1218 947                     | 26 389            | 273 523                               | —                           | 29 862                              | 38 284                          | 2912 284                                | 8229 944                      |
| 2010 | 1119 592                 | 1172 038                     | 1165 665          | 173 767                               | 11 035                      | 7313                                | 8557                            | 31 016                                  | 3690 994                      |
| 2011 | 8431 207                 | 229 388                      | 71 491            | 57 856                                | 3709                        | —                                   | 806                            | 430 748                                 | 9227 216                      |
| 2012 | 6697 355                 | 567 600                      | 17 192            | 233 542                               | 4018                        | —                                   | 5407                            | 217 635                                 | 7744 761                      |
| 2013 | 4492 327                 | 81 692                       | —                 | 34 317                                | 2564                        | 2889                                | **164 292**                     | 20 694                                  | 4800 787                      |
| 2014 | 8695 147                 | 180 525                      | 376               | 60 194                                | 8801                        | 4687                                | 18 912                          | 236 552                                 | 9207 208                      |
| 2015 | 8339 446                 | 83 152                       | 24 849            | 13 625                                | 19 645                      | —                                   | **626 989**                     | 9111 643                                 | 1006 523                      |
| 2016 | 8028 168                 | 177 628                      | 622 004           | 47 839                                | —                           | 39 399                              | 150 470                         | 9067 523                                | 11 610 252                    |
| 2017 | 4303 835                 | 33 856                       | 26 926            | 18 348                                | —                           | 13 110                              | 138 644                         | 4536 737                                | 15 244 668                    |
| 2018 | 6391 194                 | 526 533                      | 12 051            | 142 912                               | 2711                        | 12 147                              | 26 314                          | 62 869                                  | 7178 747                      |
| 2019 | 7988 818                 | 2977 529                     | 302 771           | 194 616                               | 5292                        | 56 144                              | 2344                            | 170 720                                 | 11 610 252                    |
| 2020 | 7250 273                 | **641 133**                  | 508 774           | **734 728**                           | **40 398**                  | **169 967**                         | 45 546                          | 79 829                                  | 15 244 668                    |
| Total area | 121 499 598          | 18 647 306                   | 504 487           | 2875 807                              | 177 843                    | 300 021                             | 405 366                         | 3370 796                                | 152 365 432                   |
Table 3. Fire regime characteristics for 2001–2020. For each of the eight ecozones, we report the mean annual area burned, mean annual fire frequency, the largest fire, the fire rotation, and the mean fire season length, along with the range of variability.

| Biome | Taiga | Tundra |
|-------|-------|--------|
| Ecozone | East Siberian taiga (B1) | Northeast Siberian taiga (B2) | Bering tundra (T1) | Cherskii-Kolyma mountain tundra (T2) | Chukchi Peninsula tundra (T3) | Northeast Siberian coastal tundra (T4) | Taimyr-Central Siberian tundra (T5) | Trans-Baikal Bald Mountain tundra (T6) |
| Mean Annual area burned in ha yr$^{-1}$ (standard error) | 6074 980 (977 432) | 932 365 (338 877) | 265 710 (90 477) | 143 790 (38 517) | 11 115 (2578) | 33 336 (17 931) | 20 268 (8149) | 168 540 (34 588) |
| Mean number of fires per year per 10 000 km$^2$ (range) | 2.1 (0.8–3.1) | 1.2 (0.2–4.1) | 0.6 (0–2.3) | 0.8 (0.2–3.1) | 0.1 (0–0.4) | 0.2 (0–0.7) | 0.2 (0–0.5) | 2.3 (0.7–5.0) |
| Largest fire size (ha) | 10 866 634 65 | 710 545 122 | 401 565 189 | 119 005 390 | 14 758 3380 | 122 896 1495 | 27 287 4747 | 229 300 130 |
| Fire Rotation (years) | 224 (193–244) | 138 (81–193) | 90 (4–164) | 91 (19–128) | 27 (0–70) | 40 (1–68) | 111 (0–190) | 155 (60–226) |

4.1. Fire perimeter database

Satellite imagery is paramount to developing a fire perimeter database and gaining an accurate understanding of fire regimes characteristics, including annual area burned, (Soja 2004) across eastern Siberian taiga and tundra zones. Developing a fire perimeter database is a computationally intensive task made easier by Earth Engine, which allowed us to map fire across eastern Siberia at a spatial resolution comparable to North American fire databases by generating Landsat composite images that mitigated missing data caused by weather and the scanline error from Landsat 7 (Hermosilla et al 2015). Fire perimeters developed using our approach matched closely with fire perimeters from Alaska 2004 in the MTBS database, except for large fires in close proximity that merged into a single fire perimeter. Where our approach merged large fires into a single fire complex, MTBS often delineated multiple individual fire events with overlapping boundaries. Previous fire spread research in northern Siberia has noted that large fires in close proximity may merge to form fire complexes (Loboda and Csizsar 2007).

We found that the MODIS product underestimated the area burned by ∼48% over the 20 years. This result aligns with a similar comparison between Landsat and MODIS over a smaller transect in Northeastern Siberia, where MODIS underestimated by ∼40% (Berner et al 2012). Several studies utilizing AVHRR (1.1 km) note a miscalculation of large fire events (Soja et al 2006, Shvidenko et al 2011). Underestimation of the area burned will lead to errors in quantifying regional ecological and climatic consequences of fire. Typically, the spatial extent of large fires is underestimated (Shvidenko et al 2011), and these are significant contributors to annual area burned. This miscalculation is likely a function of the pixel resolution (500 m), cloud cover, and detection of false positives (Roy et al 2005, 2008). Our fire perimeter product and MTBS varied with both overestimates and underestimates. These differences could depend on when the MTBS perimeter was drawn, with many perimeters hand digitized or drawn with field GPS points. We used composite images, where MTBS uses single scenes, likely contributing to this discrepancy. Cloud cover is a significant issue in Siberia, with summer cloud coverage averaging 60% (Warren et al 1986). Our product is based on the difference between imagery from one-year prefire and one-year post. It is not solely reliant on the intensity measures from MODIS, which can be obscured by clouds and smoke. Further, thermal intensities are lower for Siberian Taiga fires, which are predominantly surface fires (Krylov et al 2014), compared to the prevalence of crown fires in North American boreal ecosystems (Wooster 2004). Surface fires are more likely to be obscured by surviving live tree canopies and not accounted for in a burned pixel (Kolden et al 2012, Krylov et al 2014); however, by delineating fire perimeters, using Landsat and MODIS imagery we capture a range of burn severities that likely includes low severity fires where canopy trees survive and unburned refugia (Kolden et al 2012) that are commonly missed by MODIS alone. The combination of clouds, lower intensity burning, and over-estimates of small and underestimates of large fires all contribute to discrepancies between our estimates from fire perimeters and MODIS burned area product.

4.2. Fire regime characteristics

We quantify baseline fire regime characteristics, including annual area burned and the number of
Figure 5. Fire size classes by annual area burned (a) and the number of fires (b) for each of eight ecozones, including East Siberian taiga (B1), Northeast Siberian taiga (B2), Bering tundra (T1), Cherskii–Kolyma Mountain tundra (T2), Chukchi Peninsula tundra (T3), Northeast Siberian coastal tundra (T4), Taimyr–Central Siberian tundra (T5), and Trans-Baikal Bald Mountain tundra (T6). Large fire years are dominated by fires <10,000 ha, while fires >10,000 are more frequent but account for less area burned. For Northeast Siberian coastal tundra (T4), and Northeast Siberian taiga (B2), 2019 and 2020 were exceptionally large fire years for the region with large fire events occurring.

fires across the region, that improve understanding of regional fire dynamics over the last 20 years. The largest fire year across all ecozones was 2003, and this was primarily driven by the area burned in the Eastern Siberia Taiga. Soja et al (2006) noted 2003 as a large fire year, although 2003 was not included in their study. Shvidenko et al (2011) estimated annual area burned averaged 8 Mha between 1997 and 2010 across Russia, while across our study, the average annual area burned for the last 20 years was 7.5 Mha, indicating that more area is burning across Russia than has been previously estimated. The mean annual area burned across Canada is ~2 Mha with some years burning ~7 Mha (Stocks et al 2002), and 1–3 Mha burned annually in Alaska (Kasischke and Turetsky 2006). Russian records indicate wildfire seasons are longer and area burned has increased between 1996 and 2018 (Kirillina et al 2020). Still, Russian records have been shown to underestimate area burned (Soja et al 2006). Few studies cover the eastern portions of Siberia, and differences in spatial extent and temporal coverage between ours and previous studies make direct comparisons difficult (e.g. Soja 2004, Soja et al 2006, 2007, Berner et al 2012).
Figure 6. Estimate annual fire season length in each of eight ecozones including East Siberian taiga (B1), Northeast Siberian taiga (B2), Bering tundra (T1), Cherskii-Kolyma Mountain tundra (T2), Chukchi Peninsula tundra (T3), Northeast Siberian coastal tundra (T4), Taimyr-Central Siberian tundra (T5), and Trans-Baikal Bald Mountain tundra (T6). Fire season timing and length vary by ecozone. Note the left y-axis is Julian date (lines, red for start day and blue for the end day) and the right y-axis is season length (bars). The black dashed line is July 1.

Fire rotation and season length varied across ecozones, with taiga zones having shorter rotations than tundra, and a general increase in fire rotation along the south to north latitudinal gradient, similar to other studies (Furyaev et al 2001, Soja 2004, Kharuk et al 2011, Berner et al 2012). The Northeast Siberian Taiga (126 years), Cherskii-Kolyma mountain tundra (382 years), and Northeast Siberian coastal tundra (1166 years) overlapped with portions of the transect evaluated by Berner et al (2012), and they noted fire rotations for lowland forest-tundra at 792 years and southern mountain larch at 110 years between 2000 and 2007. Thus, we are likely capturing some combination of lowland forest-tundra in the Cherskii-Kolyma mountain tundra and Northeast Siberian coastal tundra ecozones, and the southern mountain larch overlaps with the Northeast Siberian Taiga. Similarly, our fire rotation estimates for tundra ecozones span a similar range as those calculated by Rocha et al (2012) for Alaskan tundra ecosystems. Additionally, the large fires in 2020 may skew the fire rotation estimates as extreme fire years become increasingly important as the length of the study period decreases. Our findings align with predicted positive associations between fire season length and annual area burned (Stocks et al 1998).

In 2020, area burned increased substantially along the Arctic Circle, particularly for Northeast Siberian
Taiga, Cherskii-Kolyma mountain tundra, Northeast Siberian coastal tundra, Chukchi Peninsula tundra, with several large fires occurring above the Arctic Circle. These four ecozones are underlain by continuous permafrost and thick, ice-rich Yedoma permafrost. Over the last 20 years, ∼30% of the total area burned for Northeast Siberian Taiga, Cherskii-Kolyma mountain tundra, and Chukchi Peninsula tundra, and ∼66% of the total area burned for Northeast Siberian coastal tundra occurred in 2020. The increased area burned in the Arctic in 2019 and 2020 may begin to facilitate treeline advance and/or tall shrub expansion (Frost and Epstein 2014, Sizov et al. 2021). Simultaneously, increased area burn could initiate permafrost degradation limiting larch recruitment and facilitating shrub expansion (Frost and Epstein 2014). Along the taiga-tundra ecotone, where larch forests consist of sparse open-canopy stands, the burn mosaic may enhance larch recruitment in areas of more severe burning, resulting in denser-canopy stands provided there is an available seed source (Alexander et al. 2018). The increased area burned will influence the heterogeneity of burn mosaics producing multiple post-fire recovery trajectories and changes in permafrost dynamics where waterlogged soils result in recruitment failure...
Table 4. Summary of linear models evaluating the trend between annual area burned and summer climate factors—water deficit, precipitation, and temperature, snowmelt, season length—for each of eight ecozones. We report the intercept, slope, $R^2$, and $p$-value. Relationships are visualized in figure 7.

| Climate factors | Ecozone                             | Intercept ($b_0$) | Slope ($b_1$) | $R^2$ | $p$-value |
|-----------------|-------------------------------------|-------------------|---------------|-------|-----------|
| Water deficit   | East Siberian taiga                 | 5.70              | 0.01          | 0.38  | 0.002     |
| Water deficit   | Northeast Siberian taiga            | 4.09              | 0.01          | 0.67  | <0.0001   |
| Water deficit   | Bering tundra                       | 2.93              | 0.03          | 0.57  | <0.0001   |
| Water deficit   | Cherskii-Kolyma Mountain tundra    | 1.87              | 0.02          | 0.03  | 0.23      |
| Water deficit   | Chukchi Peninsula tundra           | 4.18              | 0.01          | 0.56  | <0.0001   |
| Water deficit   | Northeast Siberian coastal tundra  | -2.54             | 0.03          | 0.65  | <0.0001   |
| Water deficit   | Taimyr-Central Siberian tundra     | 3.54              | 0.01          | 0.19  | 0.031     |
| Water deficit   | Trans-Baikal Bald Mountain tundra  | 4.61              | 0.01          | 0.39  | 0.002     |
| Precipitation   | East Siberian taiga                | 8.34              | -0.01         | 0.27  | 0.01      |
| Precipitation   | Northeast Siberian taiga           | 8.07              | -0.01         | 0.41  | 0.002     |
| Precipitation   | Bering tundra                      | 8.14              | -0.02         | 0.39  | 0.002     |
| Precipitation   | Cherskii-Kolyma Mountain tundra    | 3.77              | -0.01         | -0.05 | 0.74      |
| Precipitation   | Chukchi Peninsula tundra           | 7.30              | -0.01         | 0.48  | 0.0004    |
| Precipitation   | Northeast Siberian coastal tundra  | 3.42              | -0.02         | -0.04 | 0.57      |
| Precipitation   | Taimyr-Central Siberian tundra     | 4.67              | 0.00          | 0.01  | 0.28      |
| Precipitation   | Trans-Baikal Bald Mountain tundra  | 5.72              | 0.00          | 0.02  | 0.25      |
| Temperature     | East Siberian taiga                | 2.81              | 0.24          | 0.23  | 0.02      |
| Temperature     | Northeast Siberian taiga           | 2.27              | 0.30          | 0.10  | 0.1       |
| Temperature     | Bering tundra                      | -2.98             | 0.83          | 0.41  | 0.002     |
| Temperature     | Cherskii-Kolyma Mountain tundra    | 0.04              | 0.46          | 0.16  | 0.05      |
| Temperature     | Chukchi Peninsula tundra           | 2.32              | 0.27          | 0.18  | 0.04      |
| Temperature     | Northeast Siberian coastal tundra  | -6.59             | 1.08          | 0.83  | <0.0001   |
| Temperature     | Taimyr-Central Siberian tundra     | 3.29              | 0.10          | 0.04  | 0.19      |
| Temperature     | Trans-Baikal Bald Mountain tundra  | 2.86              | 0.17          | 0.07  | 0.13      |
| Season length   | East Siberian taiga                | 3.97              | 0.01          | 0.19  | 0.03      |
| Season length   | Northeast Siberian taiga           | 3.92              | 0.01          | 0.22  | 0.02      |
| Season length   | Bering tundra                      | 3.61              | 0.01          | 0.34  | 0.005     |
| Season length   | Cherskii-Kolyma Mountain tundra    | 3.50              | 0.01          | 0.53  | <0.001    |
| Season length   | Chukchi Peninsula tundra           | 3.56              | 0.01          | 0.57  | <0.0001   |
| Season length   | Northeast Siberian coastal tundra  | 3.65              | 0.01          | 0.29  | 0.08      |
| Season length   | Taimyr-Central Siberian tundra     | 3.38              | 0.00          | 0.15  | 0.05      |
| Season length   | Trans-Baikal Bald Mountain tundra  | 4.25              | 0.01          | 0.32  | 0.005     |
| Snowmelt        | East Siberian taiga                | 11.24             | -0.04         | 0.37  | 0.003     |
| Snowmelt        | Northeast Siberian taiga           | 8.12              | -0.02         | -0.03 | 0.55      |
| Snowmelt        | Bering tundra                      | 18.33             | -0.09         | 0.15  | 0.05      |
| Snowmelt        | Cherskii-Kolyma Mountain tundra    | 15.94             | -0.08         | 0.05  | 0.17      |
| Snowmelt        | Chukchi Peninsula tundra           | 7.01              | -0.01         | -0.02 | 0.45      |
| Snowmelt        | Northeast Siberian coastal tundra  | 41.55             | -0.26         | 0.35  | 0.004     |
| Snowmelt        | Taimyr-Central Siberian tundra     | 4.53              | 0.00          | -0.05 | 0.79      |
| Snowmelt        | Trans-Baikal Bald Mountain tundra  | 7.38              | -0.02         | 0.14  | 0.06      |

(Alexander et al 2018). The extent to which changes in fire frequency and distribution will lead to post-fire shifts in vegetation communities remains unclear.

4.3. Climate controls on annual area burned

The annual area burned was influenced by climate factors—water deficit, precipitation, temperature, fire season length, and snowmelt timing—across the region. In taiga zones, annual area burned showed consistent trends with climate factors. In tundra zones, annual area burned was associated with climate factors but the strength of the relationships was variable. Previous work noted that annual area burned has been associated with declines in soil moisture, decreased precipitation, and increased summer temperature (Balzter et al 2005, Kharuk et al 2011, Masrur et al 2018) as well as the Arctic Oscillation (Balzter et al 2005). Tundra fire distribution and intensity have been linked to warm, dry conditions that occur from spring into summer (Masrur et al 2018). The Arctic Oscillation influences the large-scale weather systems across the region that dictate precipitation, temperature, and soil moisture levels (Balzter et al 2005). The water deficit was the most influential variable across the landscape because it provides a better link to ecosystem productivity and moisture levels than temperature or precipitation. It relates to water balance models that combine climatic and biophysical variables (Stephenson 1998, Abatzoglou et al 2018). Research shows portions of the region are experiencing longer fire seasons (Kirilina et al 2020) that correspond to increases in annual
area burned. Snowmelt likely influences fire activity and area burned, but by itself, it had limited influence. The water deficit captures components of snowmelt timing, precipitation, and temperature that are a more comprehensive measure of interacting climate variables over time (Stephenson 1998, Abatzoglou et al 2018). The scale of the climate data is coarse, which is why we looked at annual area burned across ecozones rather than analyzing climatic drivers for individual fires. The fine-scale climate data from local weather stations required for analysis at the individual fire scale are not available. Climate exerts strong control over ecosystem processes at northern latitudes and is considered an important driver to wildfire activity (Flannigan et al 2009, Hu et al 2015, Young et al 2017, Masrur et al 2018, Natali et al 2021). Climate modeling indicates earlier starts to fire seasons result in climate conditions that contribute to more extreme fire danger across the circumboreal (Stocks et al 1998), suggesting that many of these climatic drivers work in concert. Places like Alaska, where regional warming increases fire likelihood in areas such as tundra and treeline that had historically low fire probabilities (Hu et al 2015, Young et al 2017). Increased fire in these areas would have broader ramifications for ecosystem functions (Rocha et al 2012, Alexander et al 2018, Holloway et al 2020).

5. Conclusion

The Siberian taiga and tundra ecozones are experiencing amplified climate warming more than any other region globally (IPCC 2021). Intensifying fire regimes will impact ecosystems in ways that feedback to global climate (Gillett 2004, Kasischke and Turetsky 2006, Flannigan et al 2009, Mack et al 2011, Chen and Loboda 2018, McLauchlan et al 2020). Our regional fire perimeter database provides comprehensive and foundational knowledge of contemporary fire regime characteristics for this globally important yet relatively understudied region. In addition to refined estimates of annual area burned that capture surface fires often missed by MODIS, our Landsat-derived delineation of individual fire events provide opportunities to examine fine-scale heterogeneity in burn severity and post-fire ecosystem dynamics. The spatial-temporal distribution of fire across eight ecozones demonstrates considerable interannual variability in area burned and the number of fires. Unprecedented high temperatures in 2020 resulted in a six-fold increase in area burned in the Arctic (Natali et al 2021). Such extreme fire years are characterized by larger fires, which are otherwise relatively uncommon. Not surprisingly, our analyses indicate that continued warming, drying, and lengthening of the growing season are likely to be accompanied by increases in area burned. Increases in fire extent, severity, and frequency with continued climate warming may foster widespread vegetation change or irreversible permafrost thaw. To quantify regional and global climate feedbacks, it will be crucial to determine whether extreme fire years like 2020 will become more common and to understand the legacy effects of fire on vegetation and permafrost dynamics.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://arcticdata.io/catalog/view/doi%3A10.18739%2FA2N87311N.

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Author contributions

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