Supporting information for

Human activity increases Arctic fire occurrence within and near lit areas

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Supplementary Material

Table S1. Previous studies (ordered alphabetically) showing climate variables as the primary top-down driver for fire occurrence in the Arctic."

Study	**Region**	**Climate variables / variables related to climate as fire occurrence predictor**	**Summary of model performance and variable importance for fire occurrence**
Engström et al., (2022)	Arctic Tundra & Boreal	Precipitation, Temperature (strongest predictor)	Correlation coefficient 0.74 (North America) to 0.80 (Asian Arctic)
Kharuk et al., (2022)	Siberian Arctic (> 66°N)	Summer (JJA) air temperature, Precipitation (MJJAS)	Adjusted R2 = 0.70 Intercepted dispersion = 73% Temperature contributes 57% and precipitation 16%
Masrur et al., (2018)	Circumpolar Tundra	June surface temperature, Summer surface temperature, Summer surface precipitation	Binomial model prediction success of fire occurrence 66.4%
Masrur et al., (2022)	Alaskan tundra	Summer minimum maximum temperatures, winter minimum temperatures	VSURF model relative importance of variables (in order of importance): Terrain complexity, elevation, Summer Tmax, Distance from town, Summer Tmin, Winter Tmin
Scholten et al., (2024)	Arctic Tundra -Boreal	VPD (strongest predictor)	Partial Spearman correlation = 0.45

Sedano & Randerson (2014)	Interior Alaska (62°N to 69°N)	VPD as significant driver of fire occurrence	Z test < 0.05 for lightning strikes leading to fire ignition significantly higher for the days with higher VPD values
Veraverbeke et al., (2017)	Boreal North America (> 60°N)	Lightning as main driver of fire occurrence	Linear model based on temperature, precipitation, and convective precipitation determine lightning activity.
Xing & Wang (2024)	pan-Arctic (> 60°N)	Relative humidity, Vapor pressure deficit (VPD), Land surface temperature are main predictors.	Significant q-values Relative humidity = 0.487 VPD = 0.475 Land surface temp = 0.367

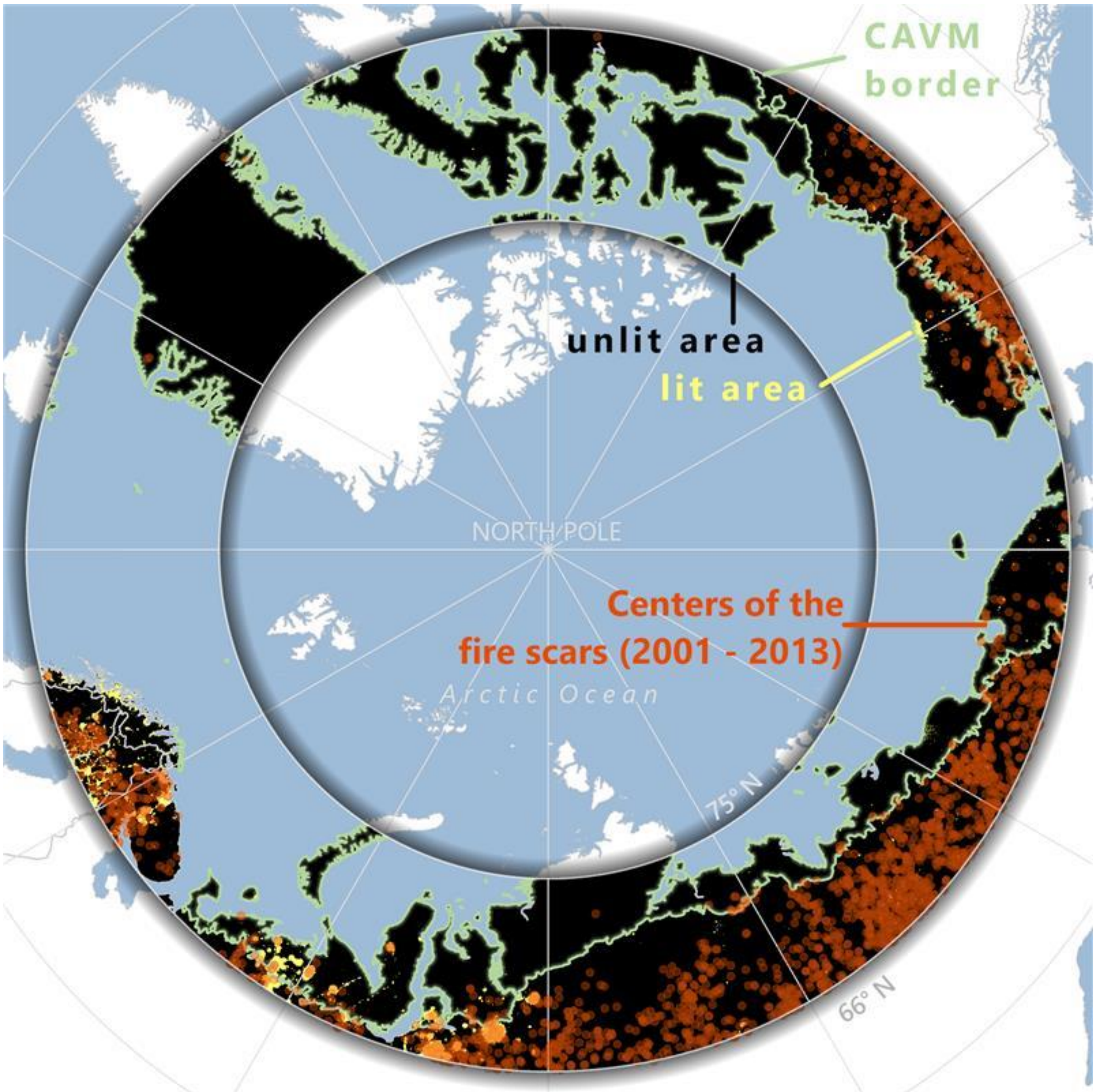

Fig. S1. Study area from 66° N to 75° N latitude, including lit (yellow) and unlit area (black) with centers of the fire scars from 2001 to 2013 (red points) including the Circumpolar Arctic Vegetation Map (CAVM) indicating the border of tundra. Note: small lit areas might not be visible due to scale. For a scale-dynamic map of lit area please visit *https://uzh.maps.arcgis.com/apps/instant/basic/index.html?appid=4af8de4e880443f18c5d1a550684bf97*

Supplementary Note 1: Choice of fire occurrence dataset FireCCI5.1

For the fire product, we chose the MODIS FireCCI5.1 dataset as it has been shown to result in better performance compared to most other available fire products[1]. While it has been shown that the Arctic Boreal Burned Area (ABBA) fire dataset[2] outperforms FireCCI5.1, especially concerning omission errors[3], ABBA only starts from 2002. FireCCI5.1 starts one year earlier which is especially critical for our study as the overlap between the fire and ALAN datasets is not very long, so each extra year that we could analyze improves our study. Further, FireCCI5.1 has a higher spatial resolution (250m) compared to ABBA (463m)[2], allowing us to detect smaller fires (e.g. Fig. S2).

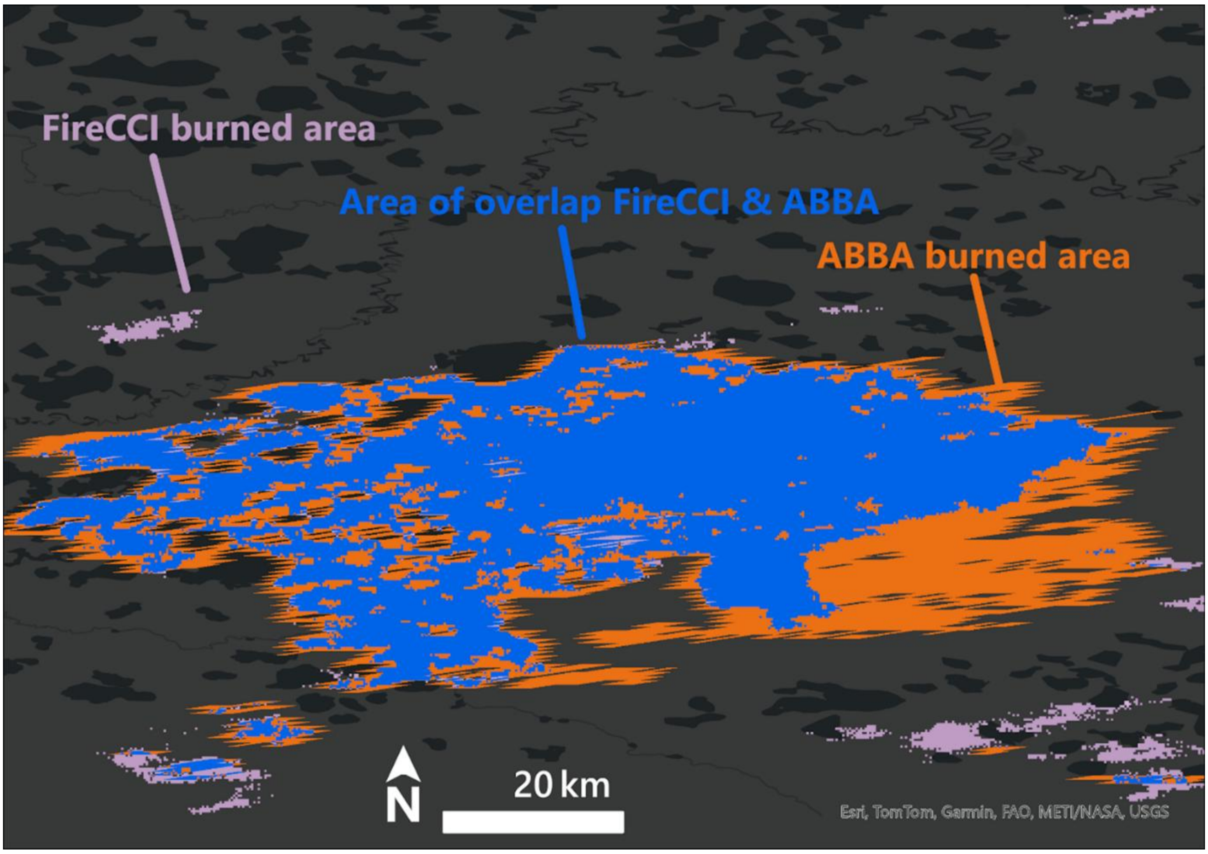

Fig. S2. Comparison of FireCCI5.1 and ABBA fire products in an example fire in Siberia that shows lower burned area for CCI but also better detection ability of smaller fires for CCI. Blue indicates the overlap between CCI and ABBA, orange shows the extent of ABBA and purple shows the extent of CCI.

The omission error reported for the FireCCI5.1 dataset[3] may create uncertainties in our distance results. However, our clustering approach should reduce omission errors. As the center of the fire scar is used to calculate the distance to the nearest lit area, the spatial shift in the center due to omission error of a part of the burn scar will impact the distance calculations. Because distances were calculated using fire centroids, omission of portions of a burn scar may shift the estimated centroid location relative to the true fire perimeter. The magnitude and direction of such shifts depend on the spatial distribution of omission errors within individual burn scars. Omission errors in burned-area detection are primarily driven by sensor limitations, burn severity, and cloud cover rather than proximity to human activity. Additionally, the centroid shifts can occur in any direction. Therefore, there is no clear mechanism by which such errors would systematically bias distance estimates to lit areas.

Omission errors may also affect the extraction of climate variables because climate information was derived from burn scar polygons rather than fire centroids. Consequently, the spatial extent used to characterize climatic conditions may differ slightly from the true burned area. Nevertheless, because the climate matching procedure was based on a large pool of potential control locations and resulted in close climatic correspondence between fire and control locations, we expect any residual influence of burn-scar omission errors on the matching procedure to be negligible.

We acknowledge that omission errors in FireCCI5.1 may vary spatially and therefore cannot be assumed to be entirely random with respect to landscape characteristics or human activity. Future studies using multiple burned-area products or higher-resolution fire datasets could help further quantify the potential influence of detection uncertainty between lit area and fire occurrence.

Supplementary Note 2: Controlling for lightning using Convective Available Potential Energy (CAPE) × Precipitation

Lightning is a primary natural ignition source in boreal and Arctic fire regimes[4,5] and therefore represents a potential confounding factor for the elevated fire occurrence in lit area compared to control. Although our analysis already accounts for key climatic drivers of fire occurrence (vapor pressure deficit (VPD), land surface temperature (LST), and precipitation (P)), it remains important to assess whether fire locations are systematically associated with higher lightning probability relative to control locations.

Ideally, this assessment would rely on direct lightning observations. However, currently available lightning datasets do not provide consistent coverage for the Arctic over the study period (2001–2013). As summarized in Table S2, existing datasets suffer from a combination of limitations, including restricted latitudinal coverage, limited temporal coverage, spatially and temporally variable detection efficiency, regional constraints, or restricted accessibility. Consequently, no dataset simultaneously provides pan-Arctic coverage, interannual consistency, and free open access for the full study period of 2001-2013.

Table S2. Overview of lightning datasets and their limitations for pan-Arctic analysis.

Dataset	Coverage/Period	Main Limitation
Optical Transient Detector (OTD)[6]	1995-2000 / Global	No temporal overlap with study period
Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor (LIS)[6]	1998-2010 / 38N° to 38 S° Latitude	Does not extend to study region
LIS / OTD[6]	1995 – 2010 /Global	High latitude data comes entirely from OTD so highly uncertain
World-Wide Lightning Location Network (WWLLN)	2005-present / Global	Partial coverage of study period, dataset is reliable after only 2013 due to increased number of sensors[1]
The World Wide Lightning Location Network (WWLLN) Global Lightning Climatology (WGLC)[7]	2010-2025 / Global	Partial coverage of study period, based on WWLLN dataset

[1] Although WWLLN partially overlaps with our study period, detection efficiency increased substantially through time, creating temporal inconsistencies unsuitable for a pan-Arctic analysis.

The U.S. National Lightning Detection Network (NLDN)	1995-present / The United States	Partial coverage of study region and limited data access
Global Lightning Detection Network (GLD 360)	Global	Commercial dataset

To overcome these limitations, we employ convective available potential energy (CAPE) × P following previous studies that showed it as a "faithful proxy for lightning"[8–10]. We used CAPE by downloading ERA5 data[11] for the summer months (June–August) over the study region (65–75°N) for the period 2001–2013. Along with precipitation values that were already calculated for fire and control points, we extracted CAPE values at fire locations and their corresponding climate-matched control points. For each fire event, we computed the mean CAPE and P within the fire polygon and the mean CAPE and P across its matched control pool, resulting in paired observations (Table and the code is available at [GitHub - cengizakandil/Fire_ALAN · GitHub]). Since precipitation had already been included in our original climate matching procedure, we used the combined CAPE × precipitation metric as a conservative sensitivity test of residual imbalance in moist convective conditions between fire and matched control locations.

The sensitivity analysis revealed substantial interannual variability in both magnitude and direction of yearly differences between fire and matched control locations. Some years exhibited slightly higher CAPE × precipitation values at fire locations, whereas others showed lower values. Although significant differences were detected in individual years, specifically 2001, 2003, 2005, 2006, and 2008, these differences occurred in opposing directions. (Fig. S3). When pooled across all years, fire and matched control locations exhibited nearly identical CAPE × precipitation distributions (mean difference = −1.62; paired standardized mean difference (SMD) = −0.003; paired t-test $p = 0.87$, Fig. S4), indicating negligible overall imbalance in moist convective atmospheric conditions associated with lightning favorable environments.

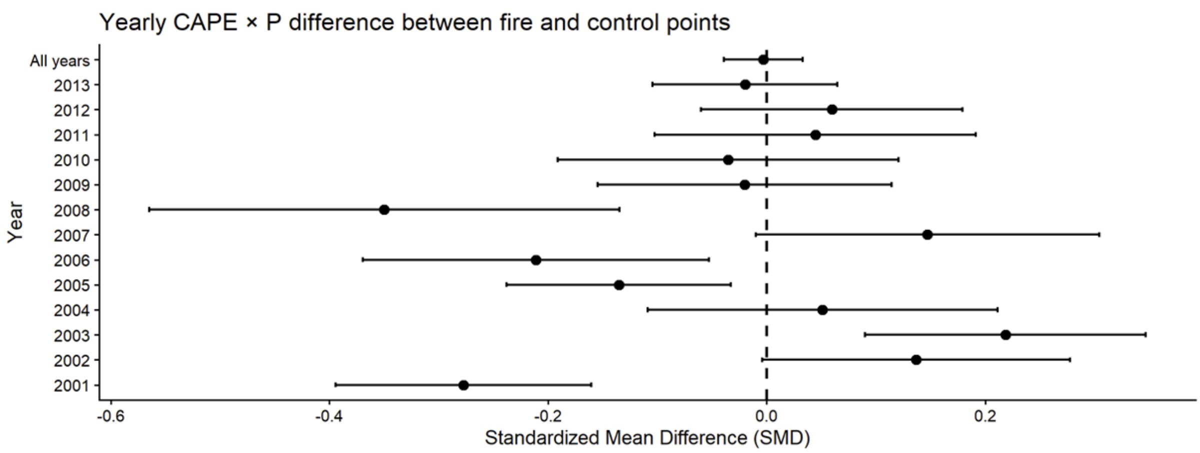

Fig. S3. Yearly standardized mean differences (SMDs) in CAPE × precipitation between fire locations and climate-matched control locations. SMD quantifies the magnitude of the difference between fire and control distributions relative to the variability of paired differences; values close to zero indicate good balance, whereas positive and negative values indicate higher or lower values at fire locations, respectively. Error bars represent 95%

confidence intervals. Significant differences (paired t-test, $p < 0.05$) in different directions were observed in 2001, 2003, 2005, 2006, and 2008, whereas most years exhibited small effect sizes and no consistent directional enrichment. The pooled estimate across all years (top row) showed good balance (SMD = -0.003; $p = 0.87$).

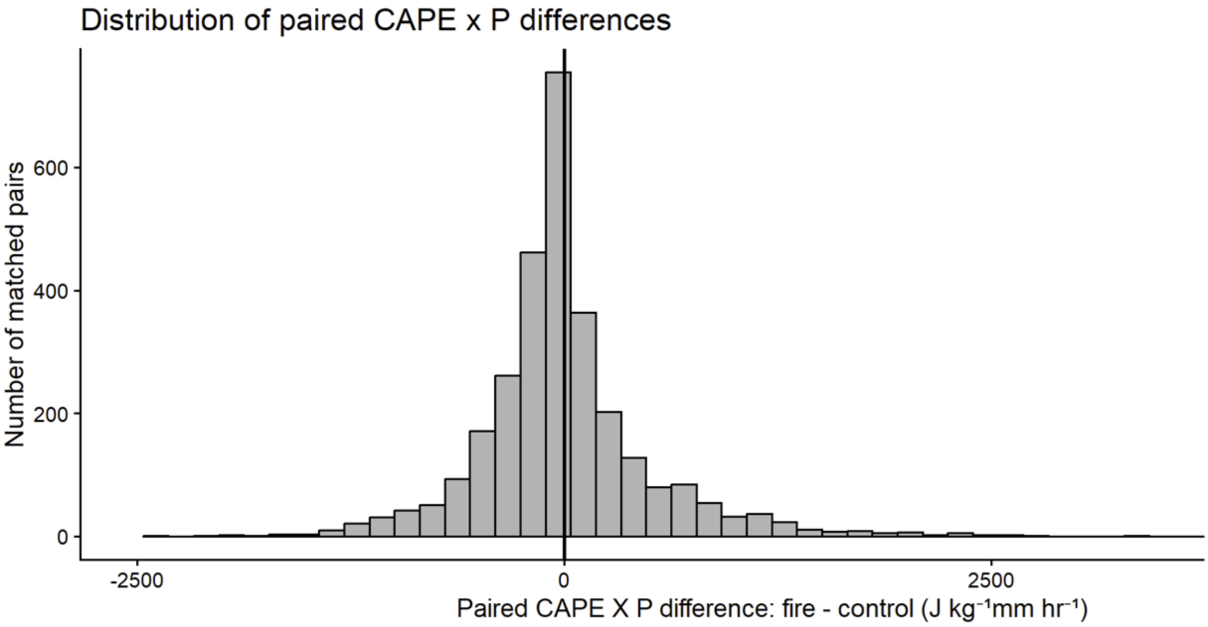

Fig. S4. Distribution of paired differences in CAPE × precipitation between fire locations and climate-matched control locations across all years. Values close to zero indicate similar moist convective conditions between matched pairs. The distribution is centred near zero (mean difference = −1.62; SMD = −0.003), indicating negligible overall imbalance in CAPE × precipitation between fire and control locations.

We note that CAPE × precipitation does not represent a direct observation of lightning occurrence and therefore cannot fully replace explicit lightning datasets. However, the absence of a consistent pan-Arctic enrichment pattern across years in this independent sensitivity analysis suggests that systematic differences in moist convective environments associated with lightning are unlikely to explain the observed enrichment of fires near human activity.

Supplementary Note 3: Case studies of fire occurrences in different major Arctic mining sites above 66 N° latitude.

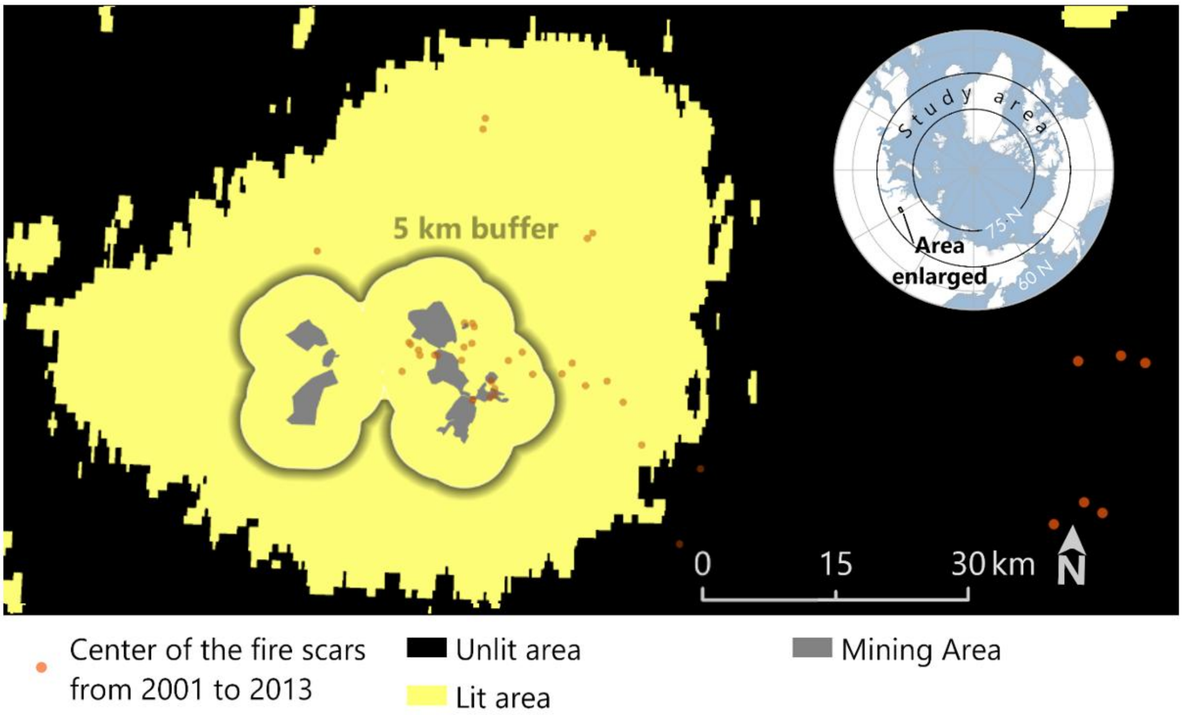

Fig. S5. Fire occurrence in the Norilsk area is strongly associated with the lit area around the mine. However, when considering the mapped mining area only, or even with a 5 km buffer around the mining area, related fires are not captured. Source of mapped mining area: Maus et al. (2020).

Norilsk is located in Krasnoyarsk, Russia and the largest palladium and class I nickel extractor globally. Platinum, copper, cobalt, and rhodium are also extracted[12]. Norilsk is known for "the world's most polluted Arctic region", with extreme increase in atmospheric sulphur, copper, and nickel concentrations leading to tree death rates of up to 100% equaling to the destruction of 24,000 km^2 of boreal forest[12]. There were more than 30 fire occurrences from 2001 to 2013, the majority within the lit area.

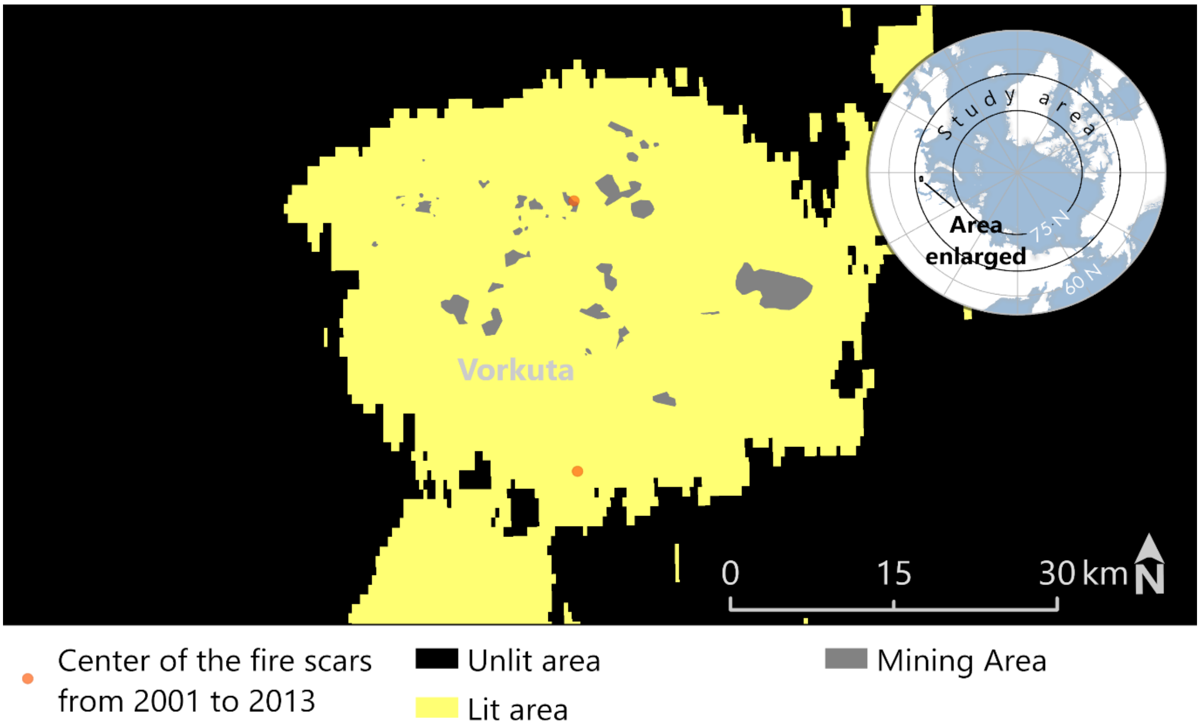

Fig. S6. Fire occurrence in Vorkuta in Russia from 2001 to 2013 (made with Natural Earth, projection EPSG: 4326).

Vorkuta was founded as a gulag prison camp by Stalin and primarily used to extract coal from the rich Pecora Basin[13]. With the collapse of the Soviet Union, Vorkuta's population dropped from more than 200,000 inhabitants in 1986 to 77,000 in 2018[13]. Currently the city still has some coal mining. There were 3 fires occurring from 2001 to 2013 within the lit area, and 2 in the nearby surrounding.

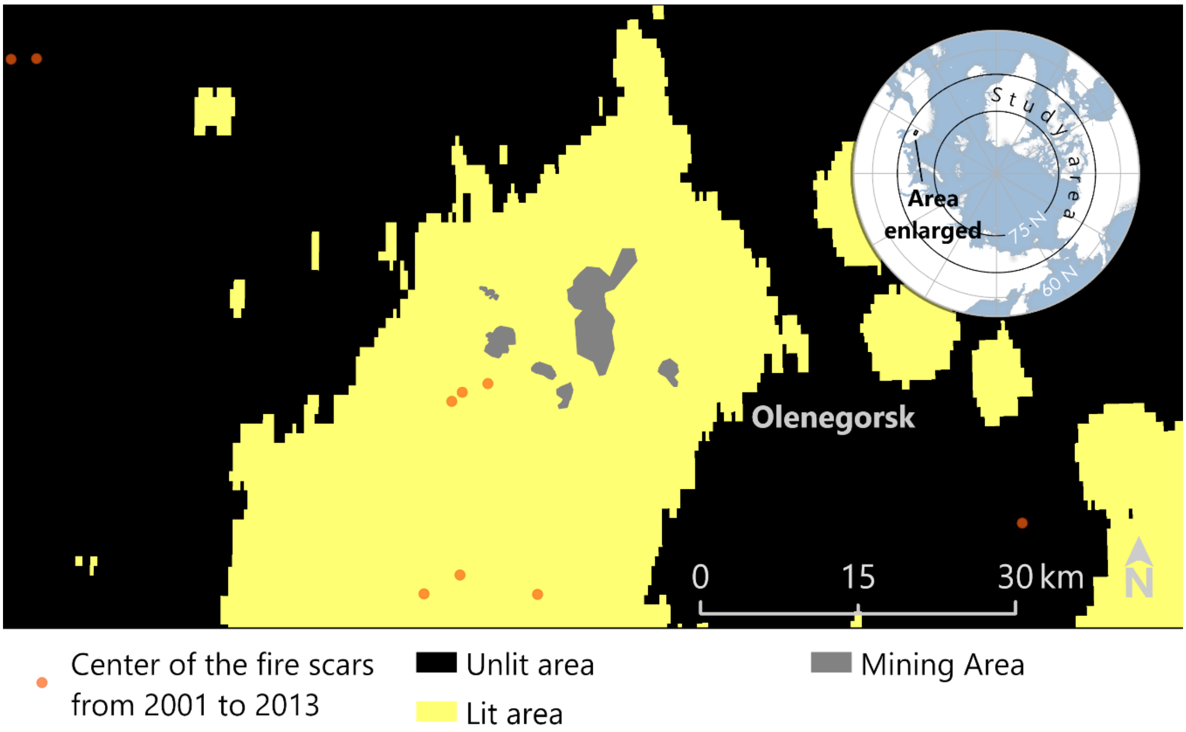

Fig. S7. Fire occurrence around the Olenegorsk mine in Russia from 2001 to 2013 (made with Natural Earth, projection EPSG: 4326).

The Olenegorsk iron mine is the northernmost iron extraction in Murmansk, Russia and there have been more than 10 fire occurrences from 2001 until 2013 within the lit area.

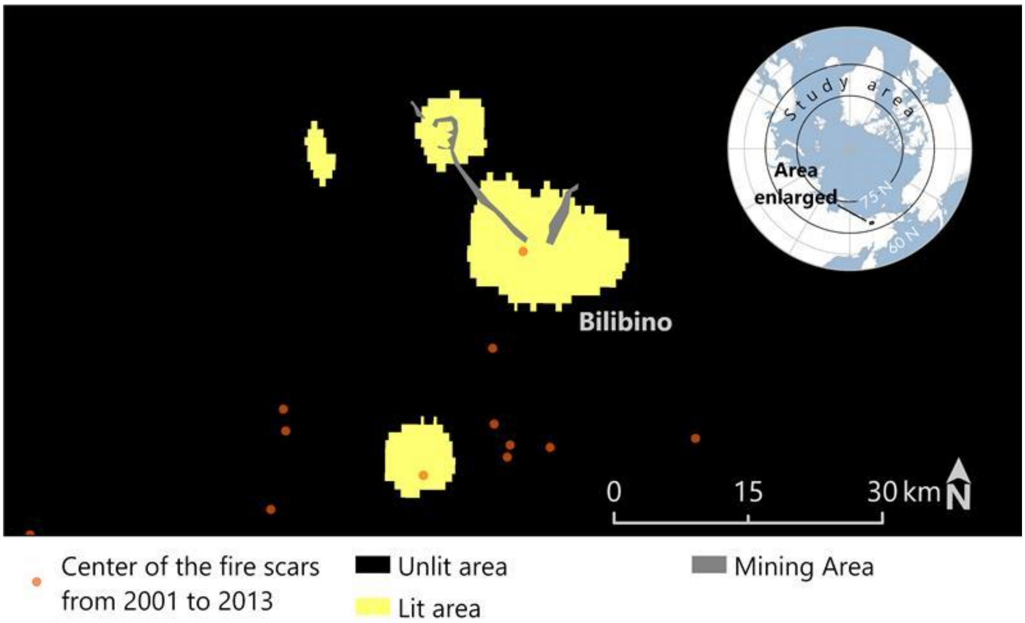

Fig. S8. Fire occurrence in the Bilibino mine in Russia from 2001 to 2013 (made with Natural Earth, projection EPSG: 4326).

The Bilibino mine in Chukotka, Russia has one of the largest undeveloped copper deposits in the world. We only observe 1 fire occurrence within the lit area.

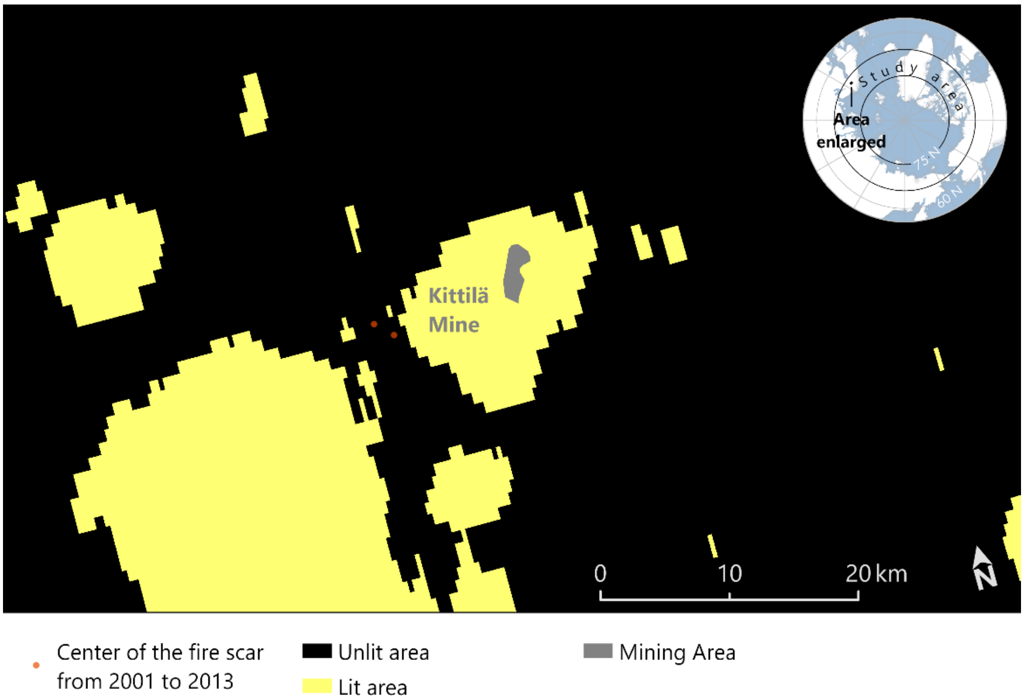

Fig. S9. Fire occurrence in Kittilä mine in Finland from 2001 to 2013 (made with Natural Earth, projection EPSG: 4326).

Kittilä mine in Finland is the largest gold deposit in Europe[14]. Open pit mining began in 2002 with two open pits. There were 2 fire occurrences outside of the lit area from 2001 to 2013.

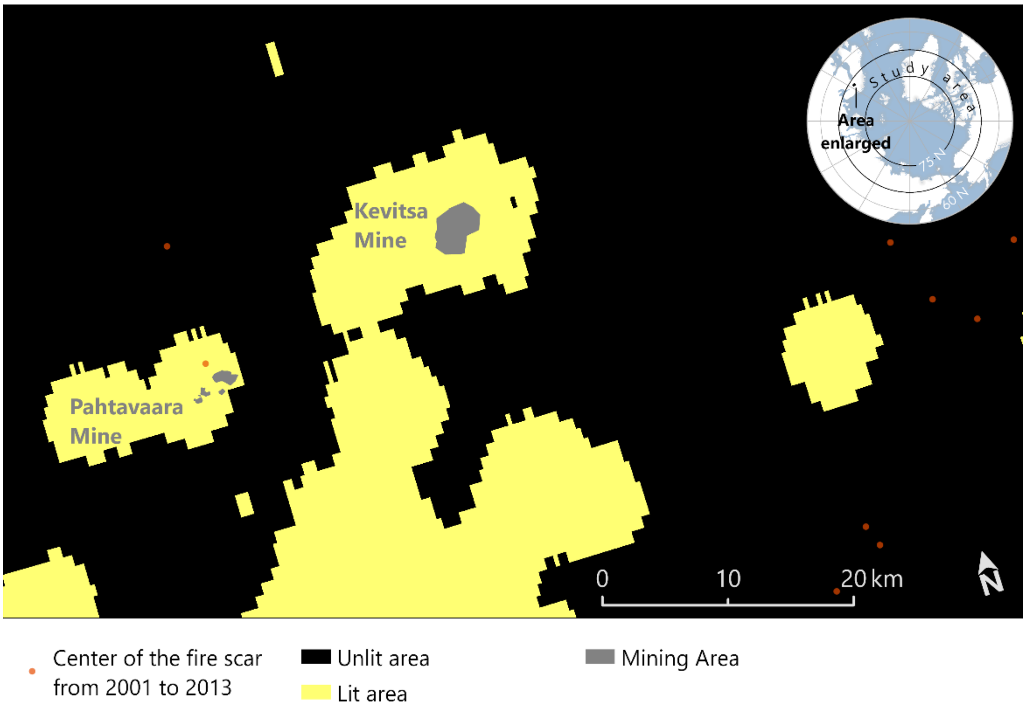

Fig. S10. Fire occurrence in the Kevitsa and Pahtavaara mine in Finland from 2001 to 2013 (made with Natural Earth, projection EPSG: 4326).

Kevitsa is a copper and nickel mine located in Finland, 140 kilometers north of the Arctic circle. Drilling at the site started in the 1980s for diamond drilling. But only after nickel and copper mineralization was found, the construction at the site started in 2010[15].

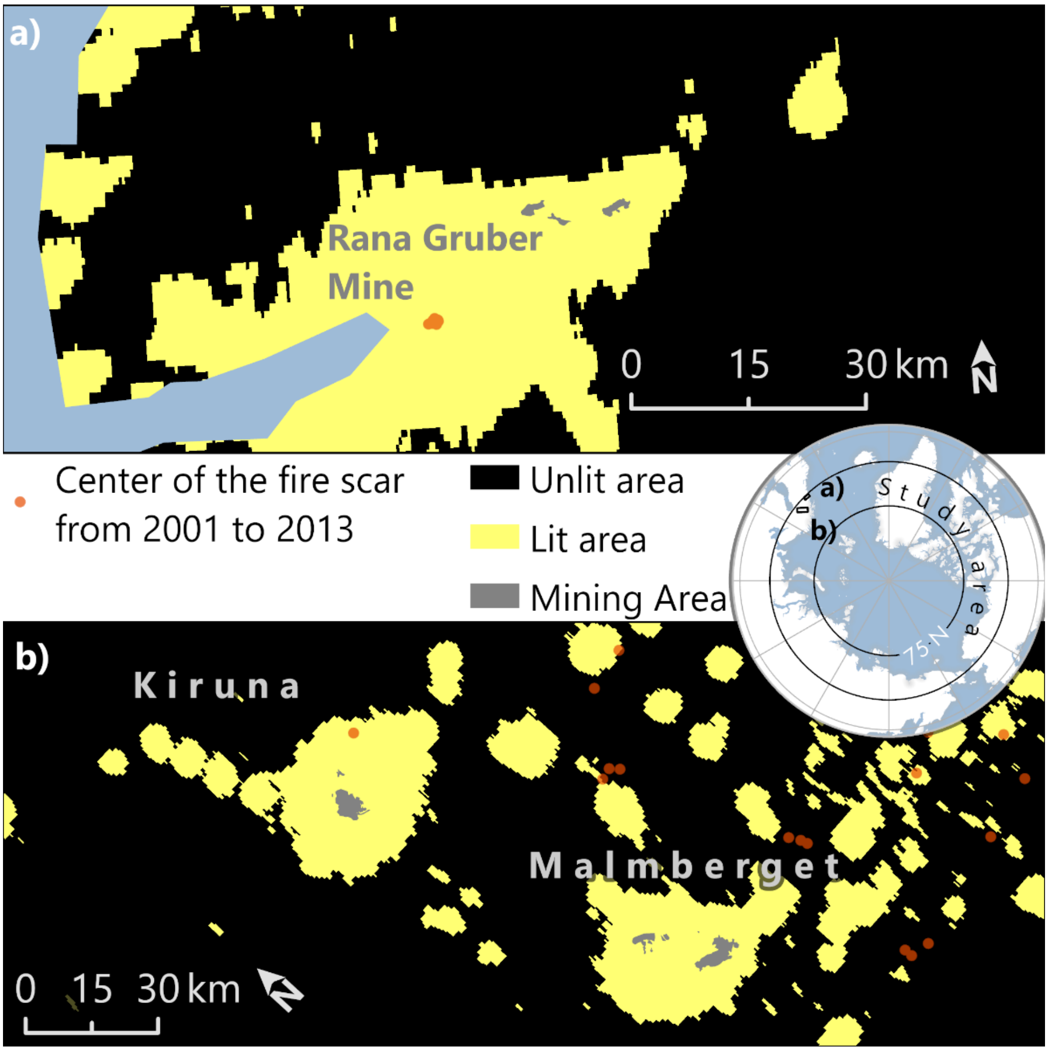

Fig. S11. Fire occurrence in a) Rana Gruber Mine in Norway, and b) Kiruna and Malmberget mine in Sweden from 2001 to 2013 (made with Natural Earth, projection EPSG: 4326).

Rana Gruber is the world's first carbon free iron ore mine[14]. The Norwegian Arctic has had 10 fires from 2001 until 2013 and all located in the vicinity of the Rana Gruber mine. Fires happened every year, except 2001 and 2003.

Kiruna is Sweden's northernmost city with the world's largest underground iron ore mine in the world[14]. In 2004, it was decided that due to underground mining, the town center should be moved 3 kilometers. In 2020, an earthquake with magnitude of 4,9 was triggered due to mining. There was only 1 fire occurrence in this Swedish mine site from 2001 to 2013.

Malmberget is one of the oldest and still in operation mines in the world, mining activity extending back to 1741.

Supplementary Note 4: Distance of fire occurrence to nearest lit area in different countries in the Arctic from 2001 to 2013

The spatial distribution of fire occurrence to the nearest lit area for different countries gives a better understanding of different fire management practices across the Arctic countries (Fig. S12). Fire occurrence within lit area (distance = 0 km) as percent of total fire occurrence per country in the study area was 12.2% for Russia, 3.9% for the United States (Alaska), 3.6% for Canada, 10.6% for Finland, 20% for Sweden, and 100% for Norway.

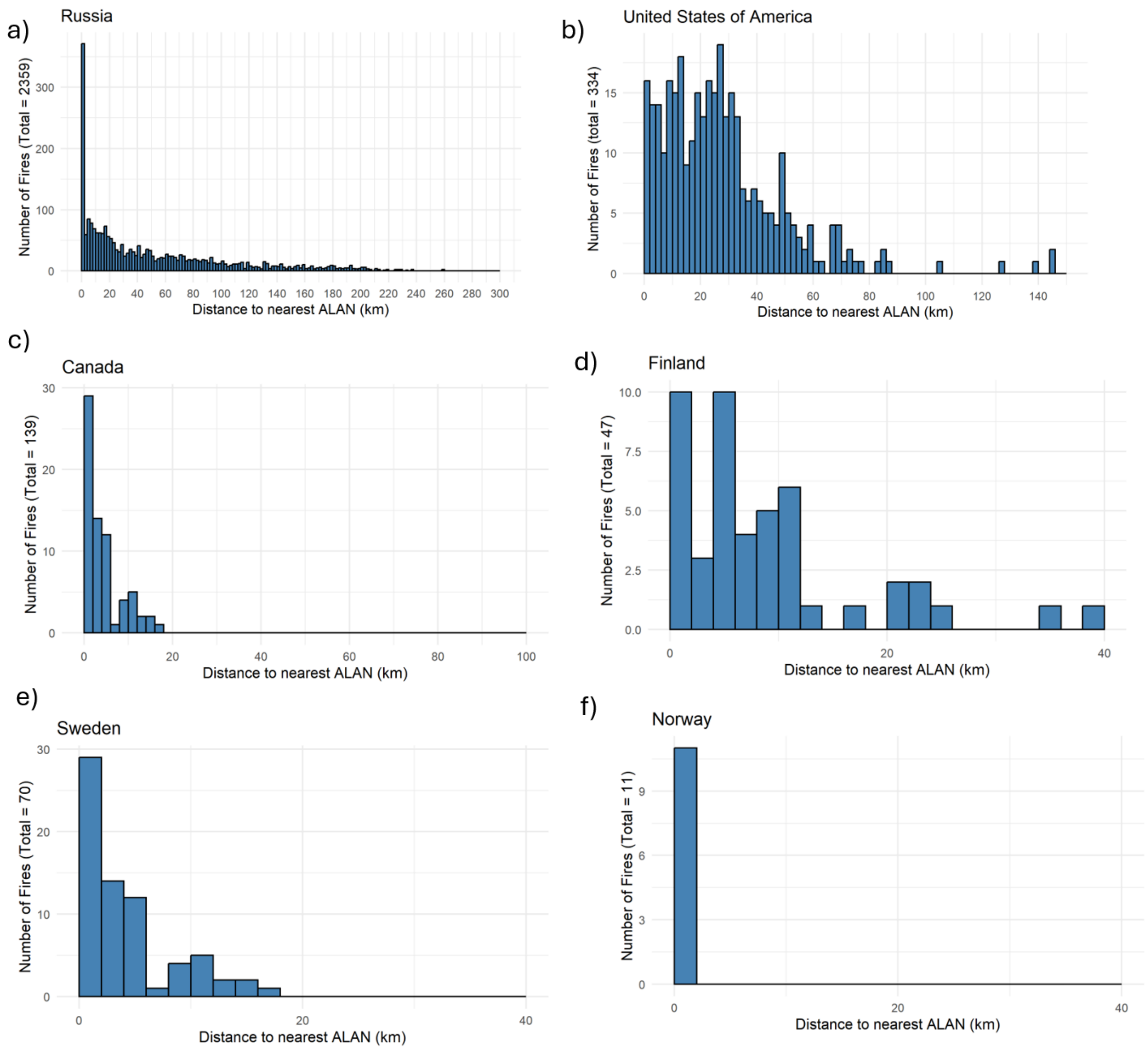

Fig. S12. Distribution of distance to nearest lit area for different countries (each bin is 2 km). a) Russia, b) United States of America, c) Canada, d) Finland, e) Sweden, and f) Norway.

To test whether the distance of fires to the nearest lit area are significantly different among the countries, we used a Kruskal-Wallis rank-sum test on distance to nearest ALAN for different countries, which is suitable for our right-skewed data and highly unbalanced group size. Before the test, we removed the countries with the two lowest fire occurrences (Greenland n = 4 and Norway n = 11). The Kruskal-Wallis test indicated a significant overall difference in distance distributions to the nearest lit area among the remaining countries (χ^2 = 144.21, $p < 0.001$). To understand the difference between the country pairs, we further applied the Dunn test, which showed significant differences for all the pairs other than Canada-Russia, Finland-Sweden, and Canada-USA. These results further point out the possible differences in fire management strategies between different countries in the Arctic.

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