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Wildfire incidence in western Kalaallit Nunaat (Greenland) from 1995 to 2020

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Abstract:

Background: Recent widely reported large tundra fires in western Greenland have focused attention on the fire regime in a region that is currently underrepresented in global fire research.

Aims: We present an analysis of fire incidence from 1995 to 2020.

Methods: A combination of satellite remote sensing and a review of reports in the online version of the national newspaper, *Sermitsiaq.AG* were used to identify wildfires.

Key results: Our analysis did not detect fires from 1995-2007. From 2008, 21 separate fire events were identified in selected study areas covering ~47% of ice-free western Greenland.. All but four of the 21 fires ignited in July or August during periods of warm and dry weather. .

Conclusions: We find no evidence of fires in our study areas until 2008, after which fires occur in most years.

Implications: Projected warming and reduced summer precipitation in this region in upcoming decades suggest the landscape will become increasingly prone to tundra fires.

Summary text: We investigated wildfire incidence in western Greenland since 1995 and found at least 21 fire events from remote sensing analysis and national news reports. Fire has been a relatively common occurrence for at least the past 12-15 years, during a period of observed regional warming and reduced precipitation.

Keywords: wildfire; tundra; remote sensing; Arctic; western Greenland

1. Introduction

The Arctic region is undergoing enhanced warming (Serreze *et al.* 2009; Miller *et al.* 2010; Sand *et al.* 2016; IPCC 2019), posing significant and growing adaptation challenges to northern communities (Daanen *et al.* 2011; Arctic Council 2016; Wrona *et al.* 2016; Teufel and Sushama 2019). One major challenge is the observed 21st century increase in tundra fire activity across the Arctic (Hu *et al.* 2010, 2015; Abbott *et al.* 2016), where a pattern of greater fire frequency, magnitude and severity has emerged in recent decades (e.g. Jones *et al.* 2009; Higuera *et al.* 2011; French *et al.* 2015; Hu *et al.* 2015; Ponomarev *et al.* 2016; Gibson *et al.* 2018; Masrur *et al.* 2018; Evangeliou *et al.* 2019; McCarty *et al.* 2020*a*).

One such Arctic region where tundra fires have recently been reported is western Kalaallit Nunaat (Greenland) (McGrath 2017; Voiland 2017*a*, 2019; Evangeliou *et al.* 2019), a region that has warmed rapidly since the 1990s (Hanna *et al.* 2012; Abermann *et al.* 2017; Saros *et al.* 2019). Fires in 2015, 2017 and 2019 received significant media attention because of their unprecedented size in a region where fires were thought to be uncommon (McGarth 2017; Voiland 2017*a*, 2019; Evangeliou *et al.* 2019; McCarty *et al.* 2020*b*). Just how unusual these fires are has not yet been established because there are no systematic records of fires in Greenland (Voiland 2017*a*). The remote sensing MODIS sensor active fire product suggests fires have occurred frequently in Greenland since the early 2000s at least (Voiland 2017*b*; Evangeliou *et al.* 2019). Coupled to this, there is likely to be a rich knowledge of the regional history of fires amongst local communities, particularly when they occur close to settlements

(McGrath 2017; Voiland 2017*b*; McCarty *et al.* 2020), and fires have been reported in the national news (e.g. *Sermitsiaq.AG* 2015*a*, 2017*a*, 2019*a*). However, a wider assessment and synthesis of fire incidence in western Greenland is yet to be explored in detail. Such an investigation would help to contextualise the recent widely reported fires against a longer decadal timeframe of fire occurrence.

Here we use satellite images and reports from the *Sermitsiaq.AG* national news online archive to investigate tundra fires in western Greenland in the 25-year period 1995-2020 in order to produce a more-complete picture of fire incidence than is currently available.

2. Study areas

Four study areas were investigated covering a latitudinal range of 60-69°N (Fig. 1). The study areas are defined by Landsat satellite Worldwide Reference System 2 (WRS-2) scene footprints and were chosen because they contain the locations of the widely reported 2015 (Scene 4: WRS-2 path 1/row 18), 2017 (hereafter referred to as 2017 (Qeqertalik)) (Scene 2: WRS-2 path 9/row 13) and 2019 (Scene 1: WRS-2 path 9/row 12) fires, and the area surrounding the largest settlement and capital of Greenland, Nuuk (Scene 3: WRS-2 path 7, row 15). This region is the most populous area of Greenland and the study areas contain the five largest settlements in Greenland (Nuuk, Sisimiut, Ilulissat, Aasiaat and Qaqortoq) (Fig. 1).

The terrain within the study areas primarily consists of ice-free land between the Greenland Ice Sheet and the coast, with some local glaciers and ice caps found in places (Fig. 1). The ice-free terrain in the study areas covers approximately 61,000 km^2, representing ~47% of the ice-free land in western Greenland (as defined by Weidick *et al.* 1992) and ~18% of Greenland's total ice-free terrain (cf. Walker *et al.* 2005). Ice-free land cover in western Greenland consists of tundra dominated by low-shrubs, dwarf-shrubs and graminoids (Walker *et al.* 2005; Petrenko *et al.* 2016), glacially-scoured bedrock, peatlands (Evangeliou *et al.* 2019), lakes, and large glacier-fed river systems. Discontinuous permafrost is thought to

underly much of study areas 1-3, compared to isolated patches of permafrost in the southernmost study area 4 (Christiansen *et al.* 2010; Daanen *et al.* 2011).

The study areas span the low-arctic (study areas 1, 2 and 3) and sub-arctic (study area 4) climate and vegetation zones (Jonasson *et al.* 2000; Jørgensen *et al.* 2015; Bradley-Cook and Virginia 2016). Mean surface air temperatures in western Greenland show very strong warming since the 1990s (Hanna *et al.* 2012; Abermann *et al.* 2017), with summer warming trends at all previously reported weather stations over the period 1991-2011 (daily mean surface air temperature, reported in °C per measurement period): Ilulissat (2.1 °C); Aasiaat (2.8 °C); Kangerlussuaq (1.9 °C); Sisimiut (3.7 °C); Nuuk (2.5 °C); and Qaqortoq (1.0 °C) (Hanna *et al.* 2012).

3. Methods

Multispectral satellite images (Landsat 4/5 TM, Landsat 7 ETM+, Landsat 8 OLI [spatial resolution of 30 m] and Sentinel-2A [spatial resolution of 10 m in visible and near-infrared bands, 20 m in shortwave infrared band]) covering 1995-2020 were acquired from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/). Where possible, one image was acquired from early summer (June/July) and one from late summer/early autumn (August/September) for each year and study area. This increased the likelihood of capturing a pre-fire and post-fire scene for each year based on the 2017 (Qeqertalik) and 2019 fires both initiating in July, whilst also avoiding snow cover obscuring the ground surface. Landsat 7 ETM+ images captured following the Scan Line Corrector (SLC) fault on the 31st May 2003 were processed using the focal analysis gap-filling method.

The Normalised Burn Ratio (NBR) spectral index was applied to the satellite images in order to identify burned areas (Key and Benson 2006; Escuin *et al.* 2007; Miller *et al.* 2009; Veraverbeke *et al.* 2010). NBR images were first created for the established 2015, 2017 (Qeqertalik) and 2019 fires in order to test its applicability and reliability for identifying previously unidentified/unreported fires elsewhere in the study areas since 1995. Areas of

densely-clustered negative pixels of at least ~1 km^2 were manually investigated to see if they represented burn scars.

The search for reports of fires in the national news was undertaken by using key search terms within the *Sermitsiaq.AG* website (https://sermitsiaq.ag/). This returned results from 2008 onwards that were investigated and cross-referenced in order to produce a database of fires.

4. Results

Our analysis identified 21 fires in the study areas (Table 1). Of these, seven fires were identified from NBR images (Fig. 2) and 19 were reported in *Sermitsiaq.AG* (including five of the fires identified from remote sensing). No fires were identified from NBR images between 1995-2007. Online versions of *Sermitsiaq.AG* articles only date back to 2008, so we were unable to assess news reports of fires prior to this in our study.

The five fires found using both approaches are: the July 2010 fire in Buksefjord, Sermersooq Kommunia (*Sermitsiaq.AG* 2010); the August 2015 fire in the Itillersuaq valley, Kujalleq Kommunia (*Sermitsiaq.AG* 2015*a*; Voiland 2017*b*); the July-August 2017 (Qaqortalik) fire on the Nassuttooq peninsula, now Qaqortalik Kommunia (McGrath 2017; Voiland 2017*b*; *Sermitsiaq.AG* 2017*a*); the August 2017 (Qeqqata) fire at Amitsorsuaq, Qeqqata Kommunia (*Sermitsiaq.AG* 2017*c*); and the July-August 2019 fire at Kangerluarsuk Tulleq, Qeqqata Kommunia (Voiland 2019; *Sermitsiaq.AG* 2019*a*). We did not find reports of fires on *Sermitsiaq.AG* that could be matched to the locations and dates of the July 2009 fire in Klobbefjord, Sermersooq Kommunia or the July-August 2016 fire near Tasersuaq, Qeqqata Kommunia that were identified from NBR images (Fig. 2).

Of the seven fires identified from NBR images, the 2017 (Qeqertalik) and 2019 fires burned the largest areas of 23.7 km^2 and 8.4 km^2, respectively. The remaining five fires were much smaller, burning areas ranging from 0.2-1.2 km^2, with a mean of 0.6 km^2. These measured areas are comparable to the estimated size of fires reported in *Sermitsiaq.AG*

articles: in the six cases where estimates are given, they range from ~0.1-2.5 km^2 (Table 1). The three largest fires by area occurred in the last three years of our observation period (the 2017 – Qeqertalik, 2017 – Qeqqata and 2019 fires).

Our dataset also allows us to summarise additional information on fire characteristics in western Greenland, hitherto limited to the 2017 (Qeqertalik) and 2019 fires (e.g. McGrath, 2017; Evangeliou *et al.*, 2019; McGwinn, 2019). The 2009 and 2010 fires occurred close to Nuuk in Sermersooq Kommunia. The 2009 fire (64°10'14 "N, 51°25'29"W) burned an area of 0.23 km^2 on the north side of Kobbefjord, ~10 km east of Nuuk, between 29th August 2008 and 15th July 2009 (Fig. 2F). The clarity of the burn signature in the 2009 image indicates the fire occurred not long before 15th July. The 2010 fire (63°48'12"N, 51°12'31"W) occurred at the mouth of Buksefjord, ~50 km southeast of Nuuk, and burned an area of ~0.67 km^2 (Fig. 2G). The Buksefjord fire corresponds to a fire reported as being first observed on 11th July and burning for at least three days in a steep area close to a cabin (*Sermitsiaq.AG* 2010*c*) (Table 1). The 2015 fire in the Ittilersuaq valley (60°10'50"N, 44°35'27"W) was active for about a week (*Sermitsiaq.AG* 2015*a*, 2015*b*, 2015*c*; Voiland 2017*a*, 2017*b*) and burned an area of 0.95 km^2 on the north side of the valley. The fire burned in moderately sloping terrain (~15-30°) that steepens (up to ~40°) towards the upper limits of the burned area (~400 m a.s.l.). The 2016 fire scar (66°58'22"N, 52°10'01"W) is located close to Tasersuaq lake in Qeqqata Kommunia, ~70 km east of Sisimiut (Figs 1 and 2D). The fire burned an area of 0.31 km^2 between two small lakes and was active at some point between 21st July and 30th August. The burned area surrounds the Ikkattooq hut on the Arctic Circle Trail hiking route. A second 2017 fire (66°55'14"N, 51°49'22"W) was identified in what is now Qeqqata Kommunia, ~80 km east of Sisimiut (Figs 1 and 2E). The 2017 (Qeqqata) fire, also located on the Arctic Circle Trail hiking route, burned an area of 1.16 km^2 at the western end of Amitsorsuaq lake and was reported in *Sermitsiaq.AG* on 3rd August (*Sermitsiaq.AG* 2017*c*; Table 1).

5. Discussion

None of the 21 fires we identified occurred before 2008 (Table 1). Whilst the *Sermitsiaq.AG* archive does not cover this earlier period, we did process satellite images from 1995. From our remote sensing approach, we cannot categorically say there were no fires during this earlier period, only that any fires that did occur were likely much smaller in scale than those we detected using remote sensing from 2008 onwards. It is worth noting that initial outputs from the MODIS sensor active fire product, which covers the whole of Greenland, suggests fire activity in all years since the early 2000s. The MODIS data also suggests that some years have been exceptional for fires, with high numbers of active fire pixels detected in 2008, 2015 and 2017 (Voiland 2017*b*; Evangeliou *et al.* 2019). Based on the 21 fires we have identified, 2009 (n=3), 2010 (n=5), 2016 (n=3) and 2017 (n=4) were the most active fire years in western Greenland (Table 1).

These data reaffirm that the 23.7 km^2 2017 (Qeqertalik) fire (and to a lesser extent the 8.4km^2 2019 fire) was unprecedently large for Greenland (Evangeliou *et al.* 2019; McCarty *et al.* 2020*b*). Based on available data, the 2017 (Qeqertalik) and 2019 fires also burned for much longer than the other examples: about three weeks and six weeks, respectively, compared to less than a week in all other cases where fire duration was reported or could be estimated (Table 1).

Although natural ignition sources are possible (e.g. Evangeliou *et al.* 2019; Teufel and Sushama 2019), most of the fires identified in this study have been, or can be, linked to human activity in landscapes primed for burning by extended warm and dry periods. Warm and dry weather creates fire-prone conditions by drying out the tundra landscape and contributing to permafrost degradation, which in turn exposes more surface fuels (Hu *et al.* 2010, 2015; Grosse *et al.* 2011; Flannigan *et al.* 2013; McCarty *et al.* 2020*a*). All but four of the 21 fires ignited in July or August (Table 1), which in western Greenland are the warmest months of the year and have been getting warmer (Hanna *et al*. 2012): for the six near-coastal climate stations at the locations shown in Fig. 1, June to August records both the highest daily mean surface air temperatures (ranging from 5.2 to 9.8°C for the period 1991-2011) and significant

(>1σ) positive daily mean surface air temperature trends (ranging from 1.0 to 3.7°C for the period 1991-2011). Direct references to warm and dry conditions are made in relation to several of the reported fires (e.g. *Sermitsiaq.AG* 2008*a*, 2015*a*; Evangeliou *et al.* 2019). This is supported by Danish Meteorological Institute (DMI) data, which shows that exceptionally warm and/or dry weather preceded all 11 of the 21 fires where measured climate data are available from a nearby station (Table 1). In addition, although measured data are unavailable for 2008 to 2010, summers were reported to be very warm (Cappelen 2009, 2010, 2011).

Of the identified 21 fires in Table 1, 14 can be located accurately enough to determine that they occurred close to settlements and/or in areas popular for hiking and hunting. For example, four fires in Qeqqata Kommunia (2016 - Kangerluarsuk Tulleq; 2016 – near Tasersuaq lake; 2017 (Qeqqata) – Amitsorsuaq lake; 2019 - Kangerluarsuk Tulleq) are all located on or very close to the route of the Arctic Circle Trail hiking route (e.g. McGwinn, 2019; *Sermitsiaq.AG* 2019*b*), and the 2017 (Qeqertalik) fire occurred in the hunting season on a peninsula known for its reindeer population (Voiland 2017*b*). Human activity was given as the ignition source in the reports of several fires, including the 2008 fire in Paakitsoq Fjord (now Avannaata Kommunia) (Voiland 2017*b*), the 2013 fire in Nuuk (*Sermitsiaq.AG* 2013), and the 2016 and 2019 fires at Kangerluarsuk Tulleq (Qeqqata Kommunia) (*Sermitsiaq.AG* 2016, 2019*a*). We therefore suggest that it is likely most of the identified fires can be attributed to human activity in a landscape primed for fire by warm and dry weather.

6. Conclusions

We investigated the incidence of tundra fires in western Greenland since 1995 using satellite remote sensing and *Sermitsiaq.AG* reports on fire occurrence. Based on our analysis, there have been at least 21 fires since 2008. We conclude that: (1) the widely reported 2017 (Qeqertalik) and 2019 fires were unprecedently large, burning areas 40 times (2017 (Qeqertalik)) and seven times (2019) greater than the average burned area of all other fires in our study; and (2) 17 of the 21 fires ignited in July or August during periods of warm and dry

weather, suggesting preconditioning of the landscape plays a key role in fire occurrence. Given the projected regional warming, western Greenland can be expected to become more fire prone in coming decades, with future large fires comparable to the 2017 (Qeqertalik) and 2019 fires likely.

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Conflicts of interest

The authors declare no conflicts of interest

Declaration of funding

This research did not receive any specific funding. For the purpose of open access, the author has applied a CC BY public copyright licence to any Author Accepted Manuscript version arising.

Data availability statement

The data that support this study will be shared upon reasonable request to the corresponding author.

References

Abbott, B. W., Jones, J. B., Schuur, E. A., Chapin III, F. S., Bowden, W. B., Bret-Harte, M. S., ... & Zimov, S. (2016). Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment. *Environmental Research Letters*, *11*(3), 034014. http://dx.doi.org/10.1088/1748-9326/11/3/034014

Abermann, J., Hansen, B., Lund, M., Wacker, S., Karami, M., Cappelen, J. (2017). Hotspots and key periods of Greenland climate change during the past six decades. *Ambio*, *46*(1), 3-11. https://doi.org/10.1007/s13280-016-0861-y

Arctic Council. (2016). Arctic Resilience Report. M. Carson and G. Peterson (eds). Stockholm Environment Institute and Stockholm Resilience Centre, Stockholm. Available at: https://oaarchive.arctic-council.org/handle/11374/1838 (Accessed: 13 April 2022).

Bradley-Cook, J. I., Virginia, R. A. (2016). Soil carbon storage, respiration potential, and organic matter quality across an age and climate gradient in southwestern Greenland. *Polar Biology*, *39*(7), 1283-1295. https://doi.org/10.1007/s00300-015-1853-2

Cappelen, J. (2009). Danmarks klima 2008 med Tórshavn, Færøerne og Nuuk, Grønland. Danmarks Meteorologiske Institut Teknisk rapport 09-01. Available at: https://www.dmi.dk/fileadmin/Rapporter/TR/tr09-01.pdf (Accessed: 13 April 2022).

Cappelen, J. (2010). Danmarks klima 2009 med Tórshavn, Færøerne og Nuuk, Grønland. Danmarks Meteorologiske Institut Teknisk rapport 10-01. Available at: https://www.dmi.dk/fileadmin/Rapporter/TR/tr10-01.pdf (Accessed: 13 April 2022).

Cappelen, J. (2011). Danmarks klima 2010 med Tórshavn, Færøerne og Nuuk, Grønland. Danmarks Meteorologiske Institut Teknisk rapport 11-01. Available at: https://www.dmi.dk/fileadmin/Rapporter/TR/tr11-01.pdf (Accessed: 13 April 2022).

Christiansen, H. H., Etzelmüller, B., Isaksen, K., Juliussen, H., Farbrot, H., Humlum, O., ... Ødegård, R. S. (2010). The thermal state of permafrost in the nordic area during the international polar year 2007–2009. *Permafrost and Periglacial Processes*, *21*(2), 156-181. https://doi.org/10.1002/ppp.687

Daanen, R. P., Ingeman-Nielsen, T., Marchenko, S. S., Romanovsky, V. E., Foged, N., Stendel, M., Christensen, J. H., Svdendsen, K. H. (2011). Permafrost degradation risk zone assessment using simulation models. *The Cryosphere*, *5*, 1043-1056. https://doi.org/10.5194/tc-5-1043-2011

DMI. (2022). Vejrarkiv. Available at: https://www.dmi.dk/vejrarkiv/ (Accessed 13 April 2022).

Elmendorf, S. C., Henry, G. H., Hollister, R. D., Björk, R. G., Boulanger-Lapointe, N., Cooper, E. J., ... & Wipf, S. (2012). Plot-scale evidence of tundra vegetation change and links to recent summer warming. *Nature Climate Change*, *2*(6), 453-457. https://doi.org/10.1038/nclimate1465

Escuin, S., Navarro, R., Fernandez, P. (2007). Fire severity assessment by using NBR (Normalized Burn Ratio) and NDVI (Normalized Difference Vegetation Index) derived from LANDSAT TM/ETM images. *International Journal of Remote Sensing*, *29*(4), 1053-1073. https://doi.org/10.1080/01431160701281072

Evangeliou, N., Kylling, A., Eckhardt, S., Myroniuk, V., Stebel, K., Paugam, R., . . . Stohl, A. (2019). Open fires in Greenland in summer 2017: transport, deposition and radiative effects of BC, OC and BrC emissions. *Atmospheric Chemistry and Physics*, *2*, 1393-1411. https://doi.org/10.5194/acp-19-1393-2019

Flannigan, M., Cantin, A. S., De Groot, W. J., Wotton, M., Newbery, A., & Gowman, L. M. (2013). Global wildland fire season severity in the 21st century. *Forest Ecology and Management*, *294*, 54-61. https://doi.org/10.1016/j.foreco.2012.10.022

French, N. H., Jenkins, L. K., Loboda, T. V., Flannigan, M., Jandt, R., Bourgeau-Chavez, L. L., & Whitley, M. (2015). Fire in arctic tundra of Alaska: past fire activity, future fire potential, and significance for land management and ecology. *International Journal of Wildland Fire*, *24*(8), 1045-1061. https://doi.org/10.1071/WF14167

Gibson, C. M., Chasmer, L. E., Thompson, D. K., Quinton, W. L., Flannigan, M. D., & Olefeldt, D. (2018). Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nature communications*, *9*(1), 1-9. https://doi.org/10.1038/s41467-018-05457-1

Grosse, G., Romanovsky, V., Jorgenson, T., Anthony, K., Brown, J., Overduin, P., Wegener, A. (2011). Vulnerability and Feedbacks of Permafrost to Climate Change. *Eos*, *92*(9), 73-80. DOI: https://doi.org/10.1029/2011EO090001

Hanna, E., Mernild, S. H., Cappelen, J., Steffen, K. (2012). Recent warming in Greenland in a long-term instrumental (1881–2012) climatic context: I. Evaluation of surface air temperature records. *Environmental Research Letters*, *7*(4), 045404. http://dx.doi.org/10.1088/1748-9326/7/4/045404

Higuera, P. E., Chipman, M. L., Barnes, J. L., Urban, M. A., & Hu, F. S. (2011). Variability of tundra fire regimes in Arctic Alaska: millennial-scale patterns and ecological implications. *Ecological Applications*, *21*(8), 3211-3226. https://doi.org/10.1890/11-0387.1

Hu, F. S., Higuera, P. E., Walsh, J. E., Chapman, W. L., Duffy, P. A., Brubaker, L. B., & Chipman, M. L. (2010). Tundra burning in Alaska: linkages to climatic change and sea ice retreat. *Journal of Geophysical Research: Biogeosciences*, *115*(G4). https://doi.org/10.1029/2009JG001270

Hu, F. S., Higuera, P. E., Duffy, P., Chipman, M. L., Rocha, A. V., Young, A. M., ... & Dietze, M. C. (2015). Arctic tundra fires: natural variability and responses to climate change. *Frontiers in Ecology and the Environment*, *13*(7), 369-377. https://doi.org/10.1890/150063

IPCC (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Jonasson, S. Callaghan, T. V., Shaver, G. R., Nielsen, L. A. (2000). *Arctic terrestrial ecosystems and ecosystem function*. In: M. Nuttall, T. V. Callaghan (Eds.), The Arctic, environment, people, policy (pp. 275–313). Newark: Harwood Academic Publishers.

Jones, B. M., Kolden, C. A., Jandt, R., Abatzoglou, J. T., Urban, F., & Arp, C. D. (2009). Fire behavior, weather, and burn severity of the 2007 Anaktuvuk River tundra fire, North Slope, Alaska. *Arctic, Antarctic, and Alpine Research*, *41*(3), 309-316. https://doi.org/10.1657/1938-4246-41.3.309

Jørgensen, R. H., Hallinger, M., Ahlgrimm, S., Friemel, J., Kollmann, J., Meilby, H. (2015). Growth response to climatic change over 120 years for A lnus viridis and S alix glauca in West Greenland. *Journal of Vegetation Science*, *26*(1), 155-165. https://doi.org/10.1111/jvs.12224

Key, C. H., Benson, N. C. (2006). Landscape Assessment (LA) Sampling and Analysis Methods. In: Lutes, D. C., Keane, R. E., Caratti, J. F., Key, C. H., Benson, N. C., Sutherland, S., Gangi, L. J. (Eds.), FIREMON: Fire effects monitoring and inventory system. *Gen. Tech. Rep. RMRS-GTR-164. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 1 CD., 164.*

Masrur, A., Petrov, A. N., & DeGroote, J. (2018). Circumpolar spatio-temporal patterns and contributing climatic factors of wildfire activity in the Arctic tundra from 2001–2015. *Environmental Research Letters*, *13*(1), 014019. https://doi.org/10.1088/1748-9326/aa9a76

McCarty, J. L., Smith, T. E., & Turetsky, M. R. (2020a). Arctic fires re-emerging. *Nature Geoscience*, *13*(10), 658-660. https://doi.org/10.1038/s41561-020-00645-5

McCarty, J. L., Francis, R., Fain, J., Haynes, K. (2020b). *Wildfire Risk Models for western Greenland: Geostatistical Considerations*. Paper presented at the EGU General Assembly 2020, Online, 4–8 May, EGU2020-12660. https://doi.org/10.5194/egusphere-egu2020-12660

McGrath, M. (2017). ‘'Unusual' Greenland wildfires linked to peat’, *BBC*, 9 August. Available at: https://www.bbc.co.uk/news/science-environment-40877099 (accessed: 12 April 2022).

McGwinn, K. (2019). ‘Hikers warned as Greenland wildfire burns out of control’, *Arctic Today,* 16 July. Available at: https://www.arctictoday.com/hikers-warned-as-greenland-wildfire-burns-out-of-control/ (Accessed: 12 April 2022).

Mernild, S. H., Hanna, E., McConnell, J. R., Sigl, M., Beckerman, A. P., Yde, J. C., ... Steffen, K. (2015). Greenland precipitation trends in a long-term instrumental climate context

(1890–2012): Evaluation of coastal and ice core records. *International Journal of Climatology*, *35*(2), 303-320. https://doi.org/10.1002/joc.3986

Miller, J. D., Knapp, E. E., Key, C. H., Skinner, C. N., Isbell, C. J., Creasy, R. M., Sherlock, J. W. (2009). Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. *Remote Sensing of Environment*, *113*(3), 645-656. https://doi.org/10.1016/j.rse.2008.11.009.

Miller, G. H., Alley, R. B., Brigham-Grette, J., Fitzpatrick, J. J., Polyak, L., Serreze, M. C., & White, J. W. (2010). Arctic amplification: can the past constrain the future? *Quaternary Science Reviews*, *29*(15-16), 1779-1790. https://doi.org/10.1016/j.quascirev.2010.02.008

Petrenko, C. L., Bradley-Cook, J., Lacroix, E. M., Friedland, A. J., Virginia, R. A. (2016). Comparison of carbon and nitrogen storage in mineral soils of graminoid and shrub tundra sites, western Greenland. *Arctic Science*, *2*(4), 165-182. dx.doi.org/10.1139/as-2015-0023. https://doi.org/10.1139/as-2015-0023

Ponomarev, E. I., Kharuk, V. I., & Ranson, K. J. (2016). Wildfires dynamics in Siberian larch forests. *Forests*, *7*(6), 125. https://doi.org/10.3390/f7060125

Sand, M., Berntsen, T. K., von Salzen, K., Flanner, M. G., Langner, J., & Victor, D. G. (2016). Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change*, *6*(3), 286-289. http://dx.doi.org/10.1038/nclimate2880

Saros, J. E., Anderson, N. J., Juggins, S., McGowan, S., Yde, J. C., Telling, J., ... & Post, E. (2019). Arctic climate shifts drive rapid ecosystem responses across the West Greenland landscape. *Environmental Research Letters*, *14*(7), 074027. https://doi.org/10.1088/1748-9326/ab2928

Sermitsiaq.AG. (2008a). Forbudt at bruge åben ild i Ilulissat, 12 August. Available at: https://sermitsiaq.AG/node/65109 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2008b). To naturbrande hærger ved Ilulissat, 12 August. Available at: https://sermitsiaq.ag/to-naturbrande-haerger-ved-ilulissat (Accessed: 12 April 2022).

Sermitsiaq.AG. (2009a). Politiet: Sluk ordentligt efter jer, 28 July. Available at: https://sermitsiaq.ag/node/69941 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2009b). Stor brandfare i Ilulissat, 10 August. Available at: https://sermitsiaq.ag/node/70362 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2010a). Fjeldbrand i Sydgrønland, 29 May. Available at: https://sermitsiaq.ag/fjeldbrand-sydgroenland (Accessed: 12 April 2022).

Sermitsiaq.AG. (2010b). Naturbrand i Saattut passer sig selv, 30 May. Available at: https://sermitsiaq.ag/naturbrand-saattut-passer (Accessed: 12 April 2022).

Sermitsiaq.AG. (2010c). Stort område brænder i Buksefjorden, 13 July. Available at: https://sermitsiaq.AG/stort-omraade-braender-buksefjorden (Accessed: 12 April 2022).

Sermitsiaq.AG. (2010d). Flere naturbrande under opsyn, 13 July. Available at: https://sermitsiaq.ag/flere-naturbrande-opsyn (Accessed: 12 April 2022).

Sermitsiaq.AG. (2013). Pas på - det er tørt i nature, 11 June. Available at: https://sermitsiaq.AG/pas-toert-i-naturen (Accessed: 12 April 2022).

Sermitsiaq.AG. (2015a). Fjeldbrand i Sydgrønland, 13 August. Available at: https://sermitsiaq.AG/fjeldbrand-i-sydgroenland (Accessed: 12 April 2022).

Sermitsiaq.AG. (2015b). Beredskabchef: Område som 20 fodboldbaner er brændt af, 15 August. Available at: https://sermitsiaq.AG/beredskabchef-omraade-20-fodboldbaner-braendt (Accessed: 12 April 2022).

Sermitsiaq.AG. (2015c). Se fjeldbrand fra oven, 19 August. Available at: https://sermitsiaq.AG/se-fjeldbrand-oven (Accessed: 12 April 2022).

Sermitsiaq.AG. (2016a). Glasflasker mistænkes for omfattende brand, 20 July. Available at: https://sermitsiaq.AG/glasflasker-mistaenkes-omfattende-brand (Accessed: 12 April 2022).

Sermitsiaq.AG. (2016b). Stor brand i Ameralik, 22 September. Available at: https://sermitsiaq.ag/node/190501 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017a). Naturbranden i Nassuttoq er under control, 18 August. Available at: https://sermitsiaq.AG/naturbranden-i-nassuttoq-kontrol (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017b). Beredskab arbejder i døgndrift for at slukke naturbranden, 14 August. Available at: https://sermitsiaq.AG/node/199624 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017c). Røg fra naturbrand i Sisimiut, 3 August. Available at: https://sermitsiaq.AG/node/197860 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017d). Naturbrand hærger ved Nassuttooq, 1 August. Available at: https://sermitsiaq.ag/node/197902 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017e). Naturbrande får politiet til at udsende advarsel, 4 August. Available at: https://sermitsiaq.ag/naturbrande-faar-politiet-udsende-advarsel (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017f). Ny brand hærger i Nordgrønland, 8 August. Available at: https://sermitsiaq.ag/ny-brand-haerger-ved-ilulissat (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017g). Naturbranden i Nordgrønland er nu under kontrol, 10 August. Available at: https://sermitsiaq.ag/node/199721 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2017h). Ny fjeldbrand slukket efter hurtig indsats, 16 August. Available at: https://sermitsiaq.ag/ny-fjeldbrand-slukket-hurtig-indsats (Accessed: 12 April 2022).

Sermitsiaq.AG. (2019a). Brandfolk har fået naturbrand under control, 9 July. Available at: https://sermitsiaq.AG/node/214786 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2019b). Naturbrand er blusset op igen, 1 August. Available at: https://sermitsiaq.AG/naturbrand-blusset-igen (Accessed: 12 April 2022).

Sermitsiaq.AG. (2019c). Naturbrand tæt på at blive slukket, 17 August. Available at: https://sermitsiaq.AG/naturbrand-taet-slukket (Accessed: 12 April 2022).

Sermitsiaq.AG. (2019d). Naturbrand er slukket: Danske brandfolk vender hjem, 19 August. Available at: https://sermitsiaq.AG/node/215491 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2019e). Svært at slukke naturbrand, 5 August. Available at: https://sermitsiaq.AG/node/215230 (Accessed: 12 April 2022).

Sermitsiaq.AG. (2020). Vidner til naturbrand hjalp med slukning, 31 August. Available at: https://sermitsiaq.ag/node/223945 (Accessed: 12 April 2022).

Serreze, M. C., Barrett, A. P., Stroeve, J. C., Kindig, D. N., & Holland, M. M. (2009). The emergence of surface-based Arctic amplification. *The Cryosphere*, *3*(1), 11-19. https://doi.org/10.5194/tc-3-11-2009

Teufel, B., & Sushama, L. (2019). Abrupt changes across the Arctic permafrost region endanger northern development. *Nature Climate Change*, *9*(11), 858-862. https://doi.org/10.1038/s41558-019-0614-6

Veraverbeke, S., Verstraeten, W. W., Lhermitte, S., Goossens, R. (2010). Evaluating Landsat Thematic Mapper spectral indices for estimating burn severity of the 2007 Peloponnese wildfires in Greece. *International Journal of Wildland Fire*, *19*(5), 558-569. https://doi.org/10.1071/WF09069

Voiland, A. (2017a). *Fire and Ice in Greenland*. Available at: https://earthobservatory.nasa.gov/images/90709/fire-and-ice-in-greenland (Accessed: 12 April 2022).

Voiland, A. (2017b). *Roundtable: The Greenland Wildfire*. Available at: https://earthobservatory.nasa.gov/blogs/earthmatters/2017/08/10/roundtable-the-greenland-wildfire/ (Accessed: 12 April 2022).

Voiland, A. (2019). *Another Fire in Greenland*. Available at: https://earthobservatory.nasa.gov/images/145302/another-fire-in-greenland (Accessed: 12 April 2022).

Walker, D. A., Raynolds, M. K., Daniëls, F. J., Einarsson, E., Elvebakk, A., Gould, W. A., ... Yurtsev, B. A. (2005). The circumpolar Arctic vegetation map. *Journal of Vegetation Science*, *16*(3), 267-282.

Weidick, A., Boggild, C. E., Knudsen, N. T. (1992). *Glacier inventory and atlas of West Greenland*. Grønlands Geologiske Undersøgelse, Rapport 158.

Wrona, F. J., Johansson, M., Culp, J. M., Jenkins, A., Mård, J., Myers-Smith, I. H., ... & Wookey, P. A. (2016). Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. *Journal of Geophysical Research: Biogeosciences*, *121*(3), 650-674. https://doi.org/10.1002/2015JG003133

461 ***Table 1.*** *Fires in western Greenland since 2008 reported in Sermitsiaq.AG national news online articles and/or identified from satellite images in*
462 *this study. Climate data and information is from: Danish Meteorological Institute (DMI) reports (Cappelen 2009, 2010, 2011) and online weather*
463 *archive (DMI 2022: https://www.dmi.dk/vejrarkiv/); Hanna et al. (2012); Mernild et al. (2015).*

Year	Location	Lat/Long	Date started/first reported	Date under control/extinguished	Area burned (km^2) ^{e}=estimate	Climate information *Temp*. monthly (median)/(high) °C; *Precip.* monthly total (mm). **Values** are warmer than 1991-2011 Hanna *et al*. (2012) average JJA temp./drier than 1961-2015 Mernild *et al*. (2015) previous driest.	Source(s)
2008	Eqip Sermia (now Avannaata Kommunia)	-	Late July	-	-	Ilulissat, June/July 2008: Summer 2008 was very warm in Greenland.	*Sermitsiaq.AG* (2008b); Cappelen (2009)
2008	Paakitsoq Fjord (now Avannaata Kommunia)	-	Late July	-	-	Ilulissat, June/July 2008: Summer 2008 was very warm in Greenland.	*Sermitsiaq.AG* (2008a, 2008b); Voiland (2017b); Cappelen (2009)
2009	Kobbefjord (Sermersooq Kommunia)	64°10'14 "N, 51°25'29"W	Before 15th July	-	0.23	Nuuk, June/July 2009: Summer 2009 was very warm in Greenland, warmer than normal. The highest temperature 18.7 °C in 2009 was registered 17 July during the afternoon. July with 1.4 mm for the month as a whole was the second driest since official accepted observations began in 1890.	This study; Cappelen (2010)
2009	Niisa, south of Qasigiannguit (now Qeqertalik Kommunia)	-	25th July	26th July	~0.5^e	Ilulissat, Aasiaat, June/July 2009: Summer 2009 was very warm in Greenland, warmer than normal.	*Sermitsiaq.AG* (2009a); Cappelen (2010)

2009	Sermermiut, near Ilulissat (now Avannaata Kommunia)	-	8th August	-	-	Ilulissat, July/Aug 2009: Summer 2009 was very warm in Greenland, warmer than normal.	*Sermitsiaq.AG* (2009b); Cappelen (2010)
2010	Ammassivik (Kujalleq Kommunia)	-	27th May	-	-	Qaqortoq, April/May 2010: the weather in 2010 as a whole was record breaking warm almost everywhere in Greenland.	*Sermitsiaq.AG* (2010a); Cappelen (2011)
2010	Naajatsiaat, north of Saattut (now Avannaata Kommunia)	-	30th May	-	-	Uummannaq, April/May 2010: the weather in 2010 as a whole was record breaking warm almost everywhere in Greenland.	*Sermitsiaq.AG* (2010b); Cappelen (2011)
2010	Buksefjorden (Sermersooq Kommunia)	63°48'12"N, 51°12'31"W	11th July	-	-	Nuuk, June/July 2010: All months were warmer than normal, May was record breaking warm.	This study; *Sermitsiaq.AG* (2010c); Cappelen (2011)
2010	Near Iginniarfik, south of Aasiaat (now Qeqertalik Kommunia)	-	13th July	-	-	Aasiaat, June/July 2010: the weather in 2010 as a whole was record breaking warm almost everywhere in Greenland.	*Sermitsiaq.AG* (2010d); Cappelen (2011)
2010	Umiiviit, Kangerlussuaq fjord (Qeqqata Kommunia)	-	13th July	-	-	Kangerlussuaq, June/July 2010: the weather in 2010 as a whole was record breaking warm almost everywhere in Greenland.	*Sermitsiaq.AG* (2010d); Cappelen (2011)
2013	Tinupattak, Nuuk (Sermersooq Kommunia)	64°11'05"N, 51°42'44"W	10th June	10th June	~0.1[e]	-	*Sermitsiaq.AG* (2013)
2015	Itillersuaq valley (Kujalleq Kommunia)	60°10'50"N, 44°35'27"W	13th August	~19th August	0.95	Qaqortoq, July/Aug 2015: *Temp.* July = 6.7/20.7 °C; August = **7.6** /18.3 °C. 1991-2011 JJA = 7.5±0.8 °C (Hanna *et al*. 2012). *Precip.* July = **0.0 mm**; Aug = no data. 1961-2015 previous driest = 4.1 mm (July) 5.7 mm (Aug) (Mernild *et al.* 2015).	*Sermitsiaq.AG* (2015a, 2015b, 2015c); DMI (2022)

2016	Kangerluarsuk Tulleq (Qeqqata Kommunia)	-	17th July	19th July	~0.6[e]	Sisimiut, June/July 2016: June = 5.9/19.7 °C; July = **7.0**/17.4 °C. 1991-2011 JJA = 6.4±1.3 °C (Hanna *et al*. 2012). June = 21.9 mm; July = **2.1 mm**. 1961-2015 previous driest = 5.4 mm (June)/7.9 mm (July) (Mernild *et al.* 2015).	*Sermitsiaq.AG* (2016a); DMI (2022)
2016	Tasersuaq lake (Qeqqata Kommunia)	66°58'22"N, 52°10'01"W	After 21st July	By 31st August	0.31	Sisimiut, July/Aug 2016: *Temp.* July = **7.0**/17.4 °C; Aug = **8.0**/20.7 °C. 1991-2011 JJA = 6.4±1.3 °C (Hanna *et al*. 2012). *Precip.* July = **2.1 mm**; Aug = 21.4 mm. 1961-2015 previous driest = 7.9 mm (July)/0.5 mm (Aug) (Mernild *et al.* 2015).	This study; DMI (2022)
2016	Qajartoriorsuaq, Ameralik (Sermersooq Kommunia)	-	21st September	-	~0.3[e]	Nuuk, Aug/Sept 2016: *Temp.* Aug = **7.2**/16.9 °C; Sept = 3.5/9.7 °C. 1991-2011 JJA = 6.1±1.1 °C (Hanna *et al*. 2012). *Precip.* Aug = 19.2 mm; Sept = 59.2 mm. 1961-2015 previous driest = 0.0 mm (Aug)/1.7 mm (Sept) (Mernild *et al.* 2015).	*Sermitsiaq.AG* (2016b); DMI (2022)
2017	Nassuttooq peninsula (now Qeqertalik Kommunia)	67°51'06"N, 51°31'34"W	31st July	~19th August	23.7	Sisimiut, June/July 2017: *Temp.* June = 4.7/17.7 °C; July = **7.1**/21.7 °C. 1991-2011 JJA = 6.4±1.3 °C (Hanna *et al*. 2012). *Precip.* June = 6.6 mm; July = 24.6 mm. 1961-2015 previous driest = 5.4 mm (June)/7.9 mm (July) (Mernild *et al.* 2015). Aasiaat, June/July 2017: *Temp.* June = 3.1/11.2 °C; July = **6.3**/19.6 °C. 1991-2011 JJA = 5.6±1.0 °C (Hanna *et al*. 2012). *Precip.* June = 2.9 mm; July = 15.7 mm. 1961-2015 previous driest = 0.0 mm (June)/0.0 mm (July) (Mernild *et al.* 2015).	This study; *Sermitsiaq.AG* (2017a, 2017b, 2017d); Voiland (2017b); DMI (2022)

2017	Amitsorsuaq (Qeqqata Kommunia)	66°55'14"N, 51°49'22"W	3rd August	-	~0.8[e]	Sisimiut, June/July 2017: *Temp.* June = 4.7/17.7 °C; July = **7.1**/21.7 °C. 1991-2011 JJA = 6.4±1.3 °C (Hanna *et al*. 2012). *Precip.* June = 6.6 mm; July = 24.6 mm. 1961-2015 previous driest = 5.4 mm (June)/7.9 mm (July) (Mernild *et al.* 2015).	This study; *Sermitsiaq.AG* (2017c, 2017e); DMI (2022)
2017	Between Qeqertaq and Saqqaq (now Avannaata Kommunia)	70°03'08"N, 51°32'05"W	7th August	10th August	~2[e]	Ilulissat, July/Aug 2017: *Temp.* July = **8.2**/21.7 °C; Aug = 6.1/17.8 °C. 1991-2011 JJA = 6.9±1.0 °C (Hanna *et al*. 2012). *Precip.* No data.	*Sermitsiaq.AG* (2017f; 2017g); DMI (2022)
2017	South of Aasiaat (now Qeqertalik Kommunia)	-	15th August	16th August	~2.5[e]	Aasiaat, July/Aug 2017: *Temp.* July = **6.3**/19.6 °C; Aug = **5.7**/12.1 °C. 1991-2011 JJA = 5.6±1.0 °C (Hanna *et al*. 2012). *Precip.* July = 15.7 mm; Aug = 92.3 mm. 1961-2015 previous driest = 0.0 mm (July)/0.0 mm (Aug) (Mernild *et al.* 2015).	*Sermitsiaq.AG* (2017h); DMI (2022)
2019	Kangerluarsuk Tulleq (Qeqqata Kommunia)	66°59'33"N, 53°09'51"W	8th July	19th August	8.4	Sisimiut, June/July 2019: *Temp.* June = **6.9**/21.0 °C; July = **8.2**/22.2 °C. 1991-2011 JJA = 6.4±1.3 °C (Hanna *et al*. 2012). *Precip.* June = 23.4 mm; July = 27.0 mm. 1961-2015 previous driest = 5.4 mm (June)/7.9 mm (July) (Mernild *et al.* 2015).	This study; *Sermitsiaq.AG* (2019a, 2019b, 2019c, 2019d, 2019d); DMI (2022)
2020	Sermitsiaq Island (Sermersooq Kommunia)	64°16'34"N, 51°26'01"W	30th August	30th August	-	Nuuk, July/Aug 2020: *Temp.* July = **8.0**/18.6 °C; Aug = **7.4**/18.2 °C. 1991-2011 JJA = 6.1±1.1 °C (Hanna *et al*. 2012). *Precip.* July = 120.5 mm; Aug = 84.8 mm. 1961-2015 previous driest = 0.0 mm (July)/0.0 mm (Aug) (Mernild *et al.* 2015).	*Sermitsiaq.AG* (2020); DMI (2022)

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Figure 1. Location map of western Greenland showing fires identified using satellite images in this study (circles), the locations of additional fires reported in the *Sermitsiaq.AG* national news (red stars) and the main settlements in the region (grey squares). The study areas defined by Landsat scene footprints are also shown.

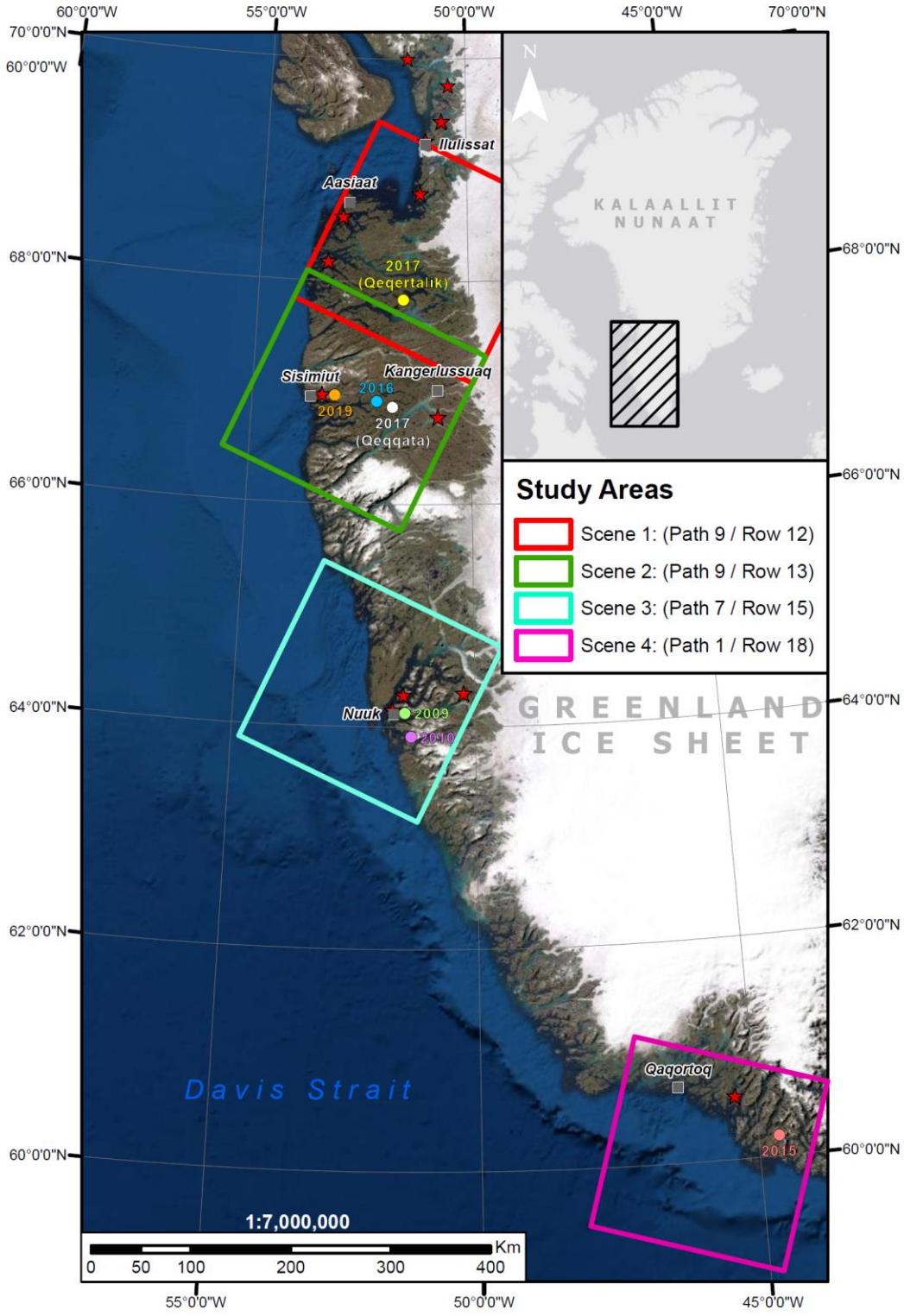

Figure 2. Burned area signatures of fires identified from satellite images in this study. (A) Location map. (B) 2017 (Qeqertalik) Nassuttooq peninsula fire. (C) 2019 Kangerluarsuk Tulleq fire, Qeqqata Kommunia. (D) 2016 fire near Tasersuaq lake, Qeqqata Kommunia. (E) 2017 (Qeqqata) fire at Amitsorsuaq. (F) 2009 Kobbefjord fire, Sermersooq Kommunia. (G) 2010 Buksefjord fire, Sermersooq Kommunia. (H) 2015 Itillersuaq valley fire, Kujalleq Kommunia.