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Impact of fire and frost drought events on vegetation greenness and albedo in Subarctic Scandinavia

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Master thesis, 30 credits, in *Physical Geography and Ecosystem Science*

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Abstract

The frequency in climate extremes such as drought, heavy rainfalls, and extreme temperatures is predicted to increase with climate change. These extremes can potentially stress and damage vegetation over large areas, leading to altered carbon cycle, vegetation greenness, albedo, and shifted species composition. This study focuses on two different types of extreme events; frost drought, caused by winter warming, and fires. The first aim was to study how these events affect vegetation greenness and albedo in the Subarctic region of Norway and Sweden. A second aim was to test whether the effects differ between land cover categories. A before-after-impact approach was applied to determine the effect of the events.

When studying all sites, the results show no impact for neither albedo nor vegetation greenness as caused by the fire events. However, when studying the impact for the different land cover categories, the category *Mosaic tree shrubs, herbaceous cover* shows a decrease in albedo after the fire events. No impact was found for the categories *Broadleaved forest* and *Needleleaved forest*. For the frost drought events, an increase in albedo was found when analysing all sites together. When studying the sites according to the land cover categories, no impact on albedo nor vegetation greenness, as caused by the frost drought events, was found. This result indicates that the impact of frost drought events on albedo must be further investigated, especially since the effect of frost drought on albedo is poorly documented. Additionally, further studies should be conducted due to important sources of error caused by uncertainties related to the analysis and limitations of the 30 m Landsat data. This study was focused on the effect of single fire and frost drought events. However, how vegetation will be affected by multiple extreme events of the same and different types interacting, as well as increased frequency in extreme events, must be further studied.

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1. Introduction

With climate change, extreme climate events such as drought, heavy rainfalls, and extreme temperatures, are predicted to be more frequent (AMAP 2017; Bokhorst et al 2009; Box et al. 2019). Extreme climate events can have a large impact on infrastructure, food security, tourism, economics, ecosystems, among others (IPCC 2012). Related to the impacts on ecosystems, extremes can potentially stress and damage vegetation over large areas, resulting in reduced uptake and loss of carbon (Bokhorst et al 2009; Parmentier et al. 2018; Phoenix and Bjerke 2016; Treharne et al. 2019), altered surface reflectance, i.e., albedo (Bright et al. 2013; Huang et al. 2014; Mack et al. 2011; Rocha and Shaver 2011), and shifts in ecosystem composition (AMAP 2017; Bret-Harte 2013; Heim et al. 2020; Parmentier et al. 2018). The knowledge of how extreme climate events affect vegetation is therefore important in multiple fields. Parmentier et al. (2018) states that this knowledge should be considered in research aiming to simulate models and predict future climate. Also, this knowledge is important for the agricultural sector, which is highly vulnerable to climate extremes, due to the dependence of water (IPCC 2012), as well as for grazing animals (Riseth et al. 2011).

This study is focused on two kinds of extreme events, frost drought and fire, especially in the Subarctic region of Sweden and Norway. Studying the distribution of fires in Siberia, Rason et al (2003) concluded that many fires are linked to human activities, and thus human-caused. However, with climate change, that leads to increased maximum air temperatures and drier conditions, the risk of fires is predicted to increase (Box et al. 2019; Jolly et al. 2015). As a result of warmer temperatures, an overall greening trend (increase in plant biomass over time) has been observed in the Arctic over the past 30 years (AMAP 2017; Box et al. 2019; Elmendorf et. al. 2012; Phoenix and Bjerke 2016). However, lately a browning trend (decline in plant biomass over time) caused by winter warming events and frost drought, has been identified as well (Bjerke et al 2014; Parmentier et al. 2018; Phoenix and Bjerke 2016). Winter warming can lead to thaw of the snow cover that insulates and protects vegetation from winter weather conditions. After a few thaw days, ground vegetation gets exposed, and hibernation is being interrupted. When temperature later drops to normal winter conditions, exposed vegetation risks to get freezing damages - a frost drought event occurs (Bokhorst et al. 2008).

Understanding how extreme climate events affect vegetation is important as it gives us a hint on how vegetation will respond to climate change and an increased frequency in extremes (Treharne et al. 2019). Studying different kinds of extremes can provide information on which vegetation is the most vulnerable to, or if different types of events affect vegetation in different ways. The effect of frost drought events is a relatively unexplored topic. A reason for this is that extreme winter warming events are given less attention than the longer summer warming events (Bokhorst et al. 2009). Especially, little is known on how albedo is affected by frost drought, while multiple studies investigate damage ratio, i.e., portion of damaged vegetation, and the Normalized Difference Vegetation Index (NDVI) – a measure of vegetation greenness (Bjerke et al. 2017; Bokhorst et al. 2009; Bokhorst et al. 2012). In general, the impact of fire on vegetation is well documented through studies of NDVI, albedo, and burn severity (Heim et al. 2020; Rocha and Shaver 2011; Sizov et al. 2021). However, studies conducted on fires are often focused on the short-term effects rather than long-term vegetation recovery (Heim et al. 2020; Jones et al 2009).

The aim of this study is to analyse the effect of fire and frost drought events on vegetation greenness and albedo in the Subarctic region of Scandinavia between year 2000 and 2020, to answer the following questions:

a) *Did the fire and frost drought events have an impact on vegetation greenness and albedo?*
b) *Does the impact on vegetation greenness and albedo of fire and frost drought events differ between land cover categories?*

Against the background of earlier studies, a decrease in both albedo and NDVI is expected directly after a fire event (Chambers et al. 2005; French et al. 2016; Rocha and Shaver 2011). However, after a reduction in NDVI, values higher than the values before the event are expected (Heim 2020). For the frost drought events, a reduction in NDVI values is expected. Regarding albedo, an increase in albedo values is expected after frost drought, except for lichen-dominated vegetation where a reduction is expected (Aartsma et al. 2020; Bjerke et al. 2014; Parmentier et al. 2018). Land coverage such as lichens, mosses, and evergreen shrubs are expected to show the greatest vulnerability to frost drought (Bokhorst et al. 2012; Bjerke et al. 2017; Bokhorst et al., 2009). Regarding fire, lichens and mosses are expected to be the most vulnerable (Jandit et al. 2008; Sizov et al. 2021).

2. Theoretical Background

2.1 Impact of Frost Drought on Vegetation Greenness and Albedo

Damage and dieback of vegetation caused by frost drought events can alter NDVI in the Arctics (Bjerke et al. 2014; Bokhorst et al. 2009). Bokhorst et al. (2009) investigated the impacts following an extreme warming event during the winter season 2007/2008. Comparing summer NDVI values the year before and after the event, a reduction of 26% was observed. The study area was the Subarctic region between Abisko (68° 21′ N, 18° 49′ E) in northern Sweden and Narvik (68° 25′ N, 17° 33′ E) at the Norwegian coast, covering 1424 km2. Furthermore, Borkhorst et al. (2008) conducted a warming experiment and found that frost drought events can harm plants in terms of development, growth, and reproduction (production of flowers and berries) in the following growing season. Contrastingly, no effect on photosynthesis was found.

Bokhorst et al. (2012) and Parmentier et al. (2018) reported an NDVI recovery time of 2 years after a frost drought event. Bokhorst et al. (2012) suggested that this rapid recovery could be caused by the recovery of non-visibly damaged, dominated species, such as *Betula nana* (dwarf birch) and *Betula pubescens* (downy birch), masking the longer recovery time of *Empetrum nigrum* (crowberry). However, Parmentier et al. (2018) noted that the damage caused by frost drought vary depending on its timing, meaning that events that occur in the absence of sunlight are not as harmful to vegetation, and associated with a relatively short recovery time of the vegetation. The fact that vegetation is capable to recover rapidly from frost drought events means that as long as these events occur infrequently, major vegetation shifts are unlikely (Bokhorst et al. 2012). However, Bokhost et al. (2008; 2012) suggests that if the frequency of these events increases, lasting damages, and shifts in vegetation may occur.

The impacts of frost drought events seem to differ between species. Evergreen dwarf shrubs, and lichens, have been reported to be more vulnerable, in favour of more resilient mosses and sedges (Bjerke 2011; Bjerke et al. 2014; Bjerke et al. 2017; Bokhorst et al., 2009; Bokhorst et al. 2012; Parmentier et al. 2018). Bokhorst et al. (2008) found that the deciduous shrub species *Vaccinium myrtillus* (blueberry) was more vulnerable to warming events than evergreen species. Bokhorst et al. suggest that the greater sensitivity of *Vaccinium myrtillus* could be related to the early bud burst and flowering of this species, and therefore show a greater vulnerability to winter warming events that occur in the beginning of the bud development. Moreover, studying *Calluna vulgaris* (heather) and *Empetrum nigrum*, Bjerke et al. (2017) found that plant damage was correlated with plant height (0-40 cm) with an increased damage ratio for increased plant height.

It is likely that frost drought events can affect other surface properties, such as albedo. In the literature, no previous study on frost drought and albedo was found. However, Parmentier et al. (2018) suggest that a vegetation shift caused by a decline in the more vulnerable species possibly could alter albedo. One study conducted on boreal forest after Bark beetle outbreak found no changes in the summer albedo (Bright et al. 2013), while another study, also in the region of boreal forest, found an increase in albedo during a drought year, and after a decade of recovering, the albedo values were back to prior drought values (Huang et al. 2014). However, lichens have been identified to have a high reflectance and thus a reduction in lichen coverage, potentially caused by frost drought, can cause a decline in albedo (Aartsma et al. 2020).

2.2 Impact of Fire Event on Vegetation Greenness and Albedo

A decrease in both NDVI and albedo has been reported for the years following fire events across the Arctic region (Barrett et al. 2012; Chambers et al. 2005; French et al. 2016; Heim et al. 2020). Heim et al. (2020) studied a fire in Western Siberia at a site with a mix of forested tundra and open treeless shrub tundra and observed a decline in NDVI directly after the fire. Also, after recovering to prior fire event values, Chambers et al. (2005) observed that NDVI continued to increase. A similar trend has been identified by Barrett et al (2012) and Sizov et al (2021). Heim et al. (2020) associated this continuous increase to an observed spread of shrubs after the fire event, and Sizov et al. (2021) suggests that the recovered vegetation is characterised by a larger amount of biomass, likely related to a shift in species. However, studies have identified burn severity as an important regulator for the vegetation composition seen after a fire event (Euskirchen et al. 2009), where the largest change in composition is associated with greater burn severity (Bernhardt et al. 2011; Barrett et al. 2012). Increased burn severity has also been identified to cause greater reduction in NDVI after the fire event (Díaz-Delgado et al. 2003; Rocha and Shaver 2011). For the NDVI recovery time, a range of 2-28 years has been reported (Barrett et al 2012; Heim et al. 2020; Sizov et al 2021).

Studies have reported a decline in albedo after fire events (Chambers et al. 2005; French et al. 2016; Rocha and Shaver 2011). Also, Chambers et al. (2005) found that the decline in albedo was greater at tundra sites compared to a spruce forest. However, Payette and Delwaide (2018) studied lichen woodland in Subarctic North America and suggested an increase in albedo after a fire event due to a shift in vegetation composition from closed-crowned forest stand to lichen dominated vegetation. Alexander et al. (2012) conducted a study on burned sites 20-50 years after the fire events in Alaska and found a shift from evergreen tree species to deciduous tree species, and an associated increase in albedo due to the higher albedo of deciduous forest than evergreen forest.

Like NDVI, the reduction in albedo has been found to be greater with increased burn severity (Rocha and Shaver 2011). Studies report a relatively rapid recovery of albedo for tundra vegetation (French et al. 2016; Rocha and Shaver 2011). However, the albedo recovery time seems to differ in relation to burn severity (French et al 2016; Rocha and Shaver 2011). The change and recovery after a fire event mentioned above is presented in Table 1 for NDVI, and Table 2 for albedo.

Studying tundra fires and the recovery process, lichens have been reported to have a poor recovery, with a recovery time of decades to centuries (Jandit et al. 2008; Sizov et al. 2021; Racine et al 2004). Additionally, Racine et al (2004), also found low recovery of mosses and 20 to 30 years after the fire a large spread of shrubs was observed. However, generally the damage on moss and plant coverage increases with increased burn severity (Rocha and Shaver 2011).

Table 1. Change in NDVI and recovery time after fire event.

Vegetation type	Change	Recovery (years)	Reference
Tundra	-40%	8	Heim et al. (2020)
Tundra	-	3	Barrett et al (2012)
Tundra and woodlands	-	2-28	Sizov et al (2021)

Table 2. Change in albedo and recovery time after fire event.

Vegetation type	Change	Recovery (years)	Reference
Tundra	-75%	-	Chambers et al. (2005)
Spruce forest	-24%	-	Chambers et al. (2005)
Tundra	-	3	Rocha and Shaver (2011)
Tundra	-	4-5	French et al. (2016)

3. Material and Method

3.1 Study Area

Events compared were fire and frost drought events that occurred between year 2000 and 2020. The study area was limited to the Subarctic region of Sweden and Norway. The study sites were located in the northern part of Norway and Sweden, and the central and south-western part of Norway. Geographical placement of the study area and distribution of the affected sites and the control sites for the frost drought and fire events are visualised in Fig. 1 and Fig. 2, respectively. The climate conditions at the northern study area (Lofoten, Tromsø Nothern Sweden; Fig. 1 and Fig. 2) are snowy, humid with cool summers and cold winters (Köppen-Geiger climate classification: Dfc), or tundra climate (ET). The study region in south-western part of Norway (Rogaland county; Fig. 1) and central Norway (Municipality of Flatanger and Frøya) has a warm temperate, humid climate with cool summers and cold winters (Cfc) (Kottek et. al. 2006).

3.2 Data Collection

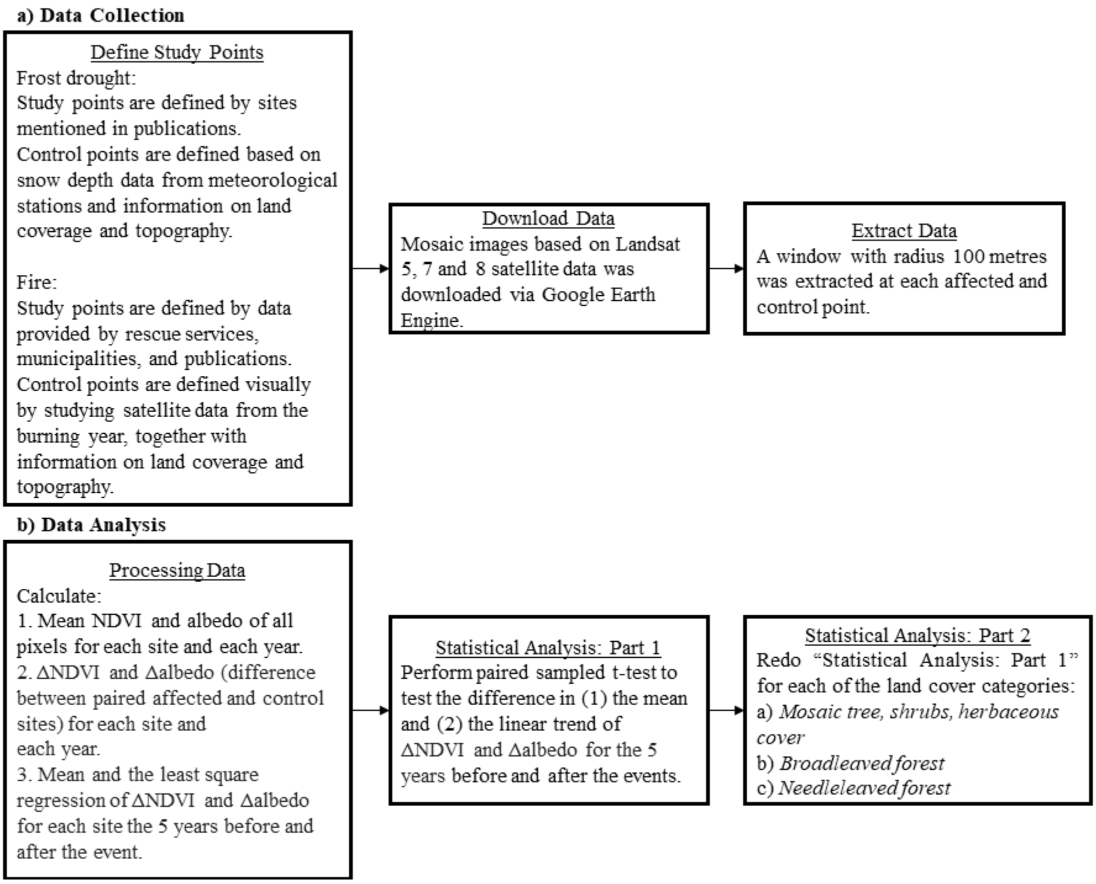

Fig. 1. Methodological flow of data collection and data analysis.

3.2.1 Frost Drought Events and their Control Sites

All sites used for analysis of the impact of frost drought events were located in Norway. The study sites were given by Bjerke et al. (2017), Parmentier et al. (2018), and Stavanger Aftenblad (2013). Sites based on Bjerke et al. (2017) and Parmentier et al. (2018) were defined by the coordinates used in the publications. The sites studied by Bjerke et al. (2017) are all from the frost drought event that occurred along the Norwegian coast in 2014. This has been documented as a severe event that led to widespread damage on vegetation. The event studied by Parmentier et al. (2018), and also included in the paper by Bjerke et al. (2017), did severely damage shrubs and lead to a reduction in both NDVI and CO_2 uptake. The frost drought event from Stavanger Aftenblad (2013) did severely damaged vegetation, especially *Vaccinium myrtillus* and juniper trees, in many parts of the county Rogaland in south Norway. No information on intensity of the frost drought events was found. If some coordinates given by the publication were located within 100 m from each other, they were combined into a new point in between the coordinates. Additionally, 7 regions affected by frost drought events were given by Stavanger Aftenblad (2013). Sites derived from these regions were randomly generated within the mentioned region.

Land coverage was defined by the Land Cover Map (version v2.0.7) for year 2015 provided by the European Space Agency (ESA) (2015), with a spatial resolution of 300 m. For each site, the land cover category was defined based on the midpoint of the sites, with the assumption that this applies for the entire site. In case study sites were located within water bodies or urban areas, the point was removed from the data set (1 point was removed because of this). In total 36 points were used. The majority was in north-western Norway, at Lofoten, 1 site was close to Tromsø, and 7 sites were in the south-western Norway, in Rogaland county.

Snow covered control sites, paired with the affected sites, were selected based on snow depth data obtained from the Norwegian meteorological stations Botnhamn, Kvitfossen i Vågan, Kongsmarka, Gausvik, Breivikeidet, and Bangdalen (Norsk klimaservicesenter n.d.). These stations indicated a steady snow coverage the entire winter season for when the specific frost drought event occurred. Using the meteorological stations as starting points, control sites with similar elevation and land coverage as the frost damaged sites were selected. Topography data was derived from the European Digital Elevation Model (version 1.1), with a spatial resolution of 25 m and provided by the European Environment Agency (Copernicus programme) (2016). The land cover was defined by the Land Cover Map from ESA (2015). The distance between the study points and the control point were in the range 20-80 km, except for the sites in south west of Norway. These sites were located ~800 km from the meteorological station (Fig. 2). This large distance is due to the lack of station data, and that other stations further south did not have steady snow coverage the entire winter that the specific event occurred. The large distance introduces a risk that the sites do not have the same climate conditions. However, both regions have a warm temperate, humid climate with cool summers and cold winters (Cfc) according to the Köppen-Geiger climate classification (Kottek et. al. 2006). For more details on affected sites and control sites, see Appendix I.

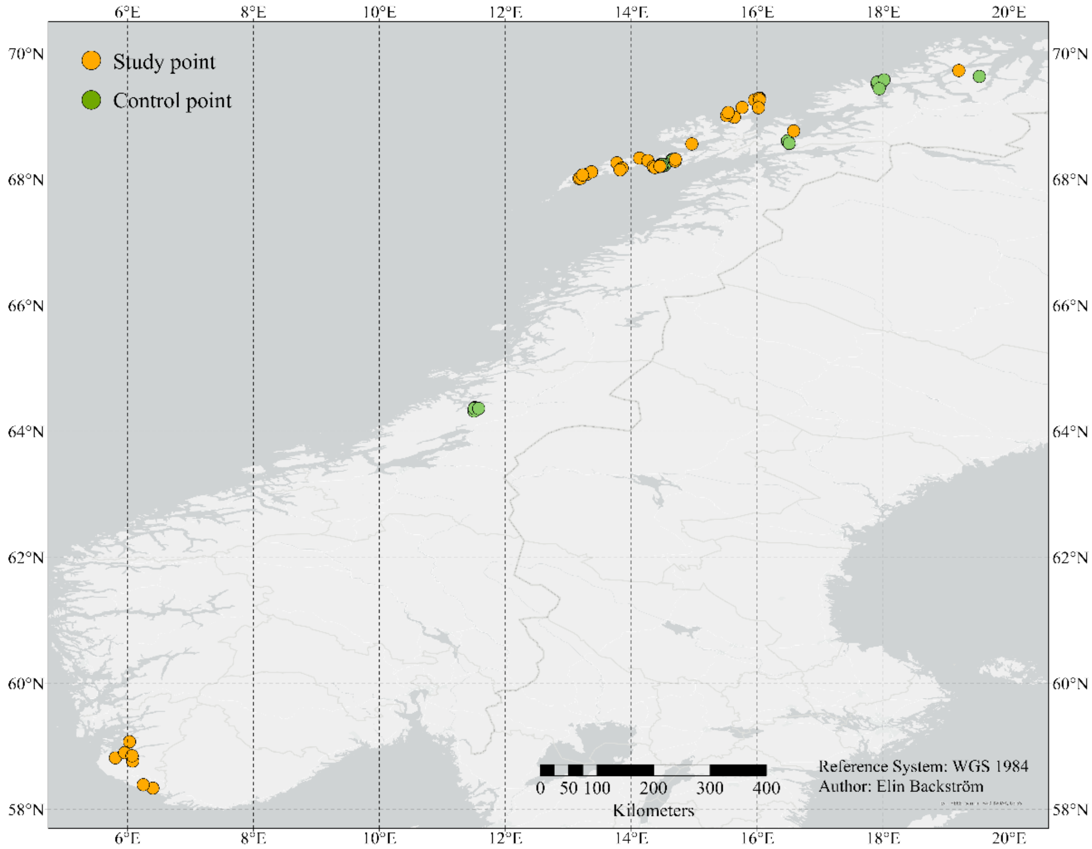

Fig 2. Spatial distribution for the studied frost drought events (study point: orange and control point: green) across Scandinavia.

3.2.2 Fire Events and their Control Sites

Sites selected to study the fire events were based on data collected by the Swedish rescue service Myndigheten för samhällsskydd och beredskap (MSB), Hamarøy municipality, and Direktoratet for Samfunnssikkerhet og Beredskap (DSB). From the MSB data set (2021), 29 fire affected sites were used, all located in the municipalities Jokkmokk, Kiruna or Gällivare, and defined by coordinates and date. Hamarøy municipality (2020) provided information on 7 affected sites, also defined by coordinates and date. Lastly, DSB (2014) reports 2 fire events. Study coordinates for these 2 events were randomly selected within the burned area mapped by Brakstad (2014) and Svarstad (2014). No information was found on damage area, intensity of the fire, and burn severity of the sites given by Hamarøy municipality (2020). The burned area of the sites given by MSB (2021) vary largely. 16 of the sites have an area smaller than 1000 m^2, 12 sites have an area between 1000 and 30000 m^2, and 4 sites and area greater than 30000 m^2. The intensity and burn severity of these fire events is unknown. The 2 fire events given by DSB (2014) covered a large area, both approximately 8km^2. These fires are described as great and prolonged, but the burn severity is unknown, as well as the intensity of the fire.

Like for the frost drought events, the land cover category was defined based on the midpoint of the sites, and in case an affected site was located within the land cover classes water or urban (ESA 2015), the site was removed from the data set (3 sites were excluded because of this). In total 38 points were selected for the fire events.

To define the control sites, paired with affected sites, Red Green Blue (RGB) colour composites based on Landsat 5, 7, and 8 satellite data, covering the affected sites and their surrounding area within a radius of 100 km, were used. The burning year and the years before and after the fire events were studied visually, with the aim to define areas of unaffected vegetation. This information, together with information on land coverage from the Land Coverage Map by ESA (2015), elevation data from the European Digital Elevation Model by EEA (2016), and the location of the affected sites, was used to select control sites. For more details on the affected sites and control sites see Appendix II.

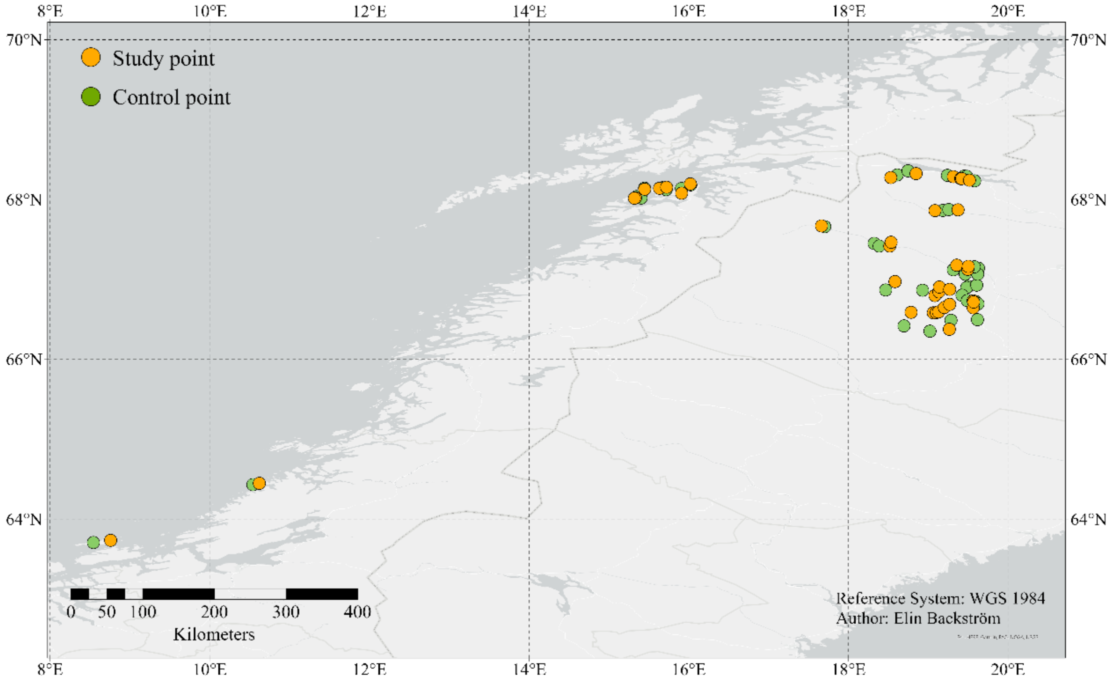

Fig 3. Spatial distribution for the studied fire events (study point: orange and control point: green) across Scandinavia.

3.3 Remote Sensing Data: Collection and Pre-processing

The period 2000 to 2020 was selected because of the significant improvements in the quality of satellite data that were made associated with the launch of Landsat 7 (Storey et al. 2000). Data used for this study were mainly collected by the satellites Landsat 7 and 8. In case Landsat 7 or 8 data were not available, Landsat 5 was used. Due to seasonal dynamics in NDVI and albedo only data from the period July the 1st to August the 31st was used. This specific period was defined to assure that albedo values were collected in snow-free conditions and NDVI values when the vegetation is at peak (Barrett et al. 2012; French et al. 2016; Heim et al 2020). The data set was downloaded from Google Earth Engine (GEE). GEE is a platform that allows the users to run geospatial analysis on the infrastructure of Google through the code editor. The code editor is a web-based integrated development environment for writing and running scripts using either JavaScript or Python (Google Earth Engine n.d.). For each year, a mosaic of available images for the period July the 1st to August the 31st, was created using the median pixel of the period. The images used had a spatial resolution of 30 m. However, if the fire or frost drought event occurred during the growing season, images collected before the event were removed from the mosaic. The images have been radiometrically corrected for atmospheric noise (NASA) and clouds have been masked out using the embedded pixel quality bitmask. Occasionally, the embedded quality mask (CFMask: Foga et al. 2017) did not detect obvious cloud coverage (Appendix III). Hence, RGB colour compositions were visually inspected, and sites with pixels identified as affected were manually excluded from the data set (39 site-years of the fire events and 45 site-years of the frost drought events were excluded because of this).

Based on the Landsat satellite data, NDVI and albedo were calculated. NDVI is a measure of vegetation greenness or amount of photosynthetically active vegetation calculated as:

$$NDVI = (NIR-RED)/(NIR+RED),$$

where NIR is the near-infrared reflectance (0.7–1.1 μm) and RED is the visible red (0.6–0.7 μm) (Rouse et al. 1974; Tucker 1979).

Albedo is the ratio reflected to incoming solar radiation. It is computed by the integrated amount of shortwave solar reflectance across the spectral range 0.35-2.5 μm (Chuevieco 2016; Tsuyuzaki et al. 2009). From Landsat images, converted to top of atmosphere reflectance, albedo can be computed as:

$$A_{short} = ((0.356*B1) + (0.130*B3) + (0.373*B4) + (0.085*B5) + (0.072*B7) -0.018) / (0.356 + 0.130 + 0.373 + 0.085 + 0.072),$$

where B1, B3, B4, B5 and B7 represent Landsat band 1, 3, 4, 5 and 7 respectively (Liang 2001; Smith 2010).

For the affected and control sites a window of 100 m radius around each study point was created. Water bodies and urban areas were masked out and the windows were then used to extract albedo and NDVI.

3.4 Data Analysis

3.4.1 a) *Did fire and frost drought events have an impact on vegetation greenness and albedo?*

For each site and each year, mean NDVI and albedo of all pixels in the created window (100 m radius) was calculated. To quantify the impact of the frost drought and fire events on vegetation greenness and albedo, mean NDVI and albedo of the control sites were subtracted from the values of the paired affected sites. This was done for each site and each year of the full time-series. From now on this difference between the affected and control sites is referred to as Δalbedo and ΔNDVI. The data of all study sites were then temporally aligned by defining the season following the event as year 0. If the event occurred during the growing season, the current year was defined as year 0.

Thereafter, for each site, the mean and the ordinary least square linear regression of albedo and NDVI of the affected site and the control site, as well as Δalbedo and ΔNDVI, for the 5 years before and after the event, was calculated. All analysis and statistical tests were limited to the 5 years before and after the events. To reduce the risk that long-term variations that naturally occur in ecosystems over time could obscure the effect of the studied event. The slope coefficient of the linear trend of ΔNDVI and Δalbedo, mean ΔNDVI and mean Δalbedo after the event were compared against the values before the event using paired sampled t-tests. The paired sampled t-test is used to determine differences between the means of two samples, for instance, when there are before and after observations (Bernhardt et al. 2011; Saxena et al. 2020)). Finally, the mean and the standard deviation (SD) of the mean and the linear trend of ΔNDVI and Δalbedo for all sites the years before and after the event, was calculated.

3.4.2 *b) Does the impact on vegetation greenness and albedo of fire and frost drought events differ between land cover categories?*

To study the differences between land cover categories, the classification by the Land Coverage Map by ESA (2015) was used. The original classes of the map were modified in order to allow comparisons between the frost drought events and the fire events and make the categories representable because of lack of data in some classes.

Table 3 presents the categories used and the corresponding classes defined by ESA (2015).

To determine the variations between the land cover categories, the analysis conducted for research question a) was repeated once for each of the land cover categories. Separated according to the land cover categories (Table 3) the mean and the slope coefficient of the linear trend of albedo and NDVI of the affected site and the control site as well as ΔNDVI and Δalbedo before and after the event was compared, using the paired sampled t-test. Finally, the mean and SD of the mean and the slope coefficient of the linear trend of ΔNDVI and Δalbedo for each of the land cover categories the years before and after the event, was calculated.

Table 3. Land cover categories used and derived from the Land Coverage Map by ESA (2015).

Land coverage defined by Land Coverage Map by ESA (2015)	Categories used
Tree cover, broadleaved, deciduous, closed to open (>15%)	*Broadleaved forest*
Tree cover, needleleaved, evergreen, closed to open (>15%)	*Needleleaved forest*
Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	*Mosaic tree, shrubs, herbaceous cover*
Sparse shrub (<15%)	
Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	
Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	
Cropland, rainfed	
Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	
Shrub or herbaceous cover, flooded, fresh/saline/brakish water	

4. Results

4.1 *a) Did fire and frost drought events have an impact on NDVI and albedo?*

4.1.1 Analysis of NDVI and Albedo at Affected and Control sites

The paired sampled t-test conducted to test the difference between the slope coefficient and the mean of mean albedo and NDVI of the affected and control sites, before and after the events, show no difference for the fire events and albedo, neither for the affected sites nor the control sites. For NDVI a difference was found for the control site both in the mean and the trend, indicating an increase in the NDVI values (Fig. 5, Table 4, and Table 5). For the frost drought events, an increase in NDVI was shown both when testing the difference in the mean and the slope coefficient of the linear trend at the affected sites and the control sites. For albedo, a difference indicating an increase in albedo was found for the affected site when testing the difference in mean values, while for the control site a difference was found for the slope coefficient, also indicating an increase in albedo values (Fig. 4, Table 4, and Table 5).

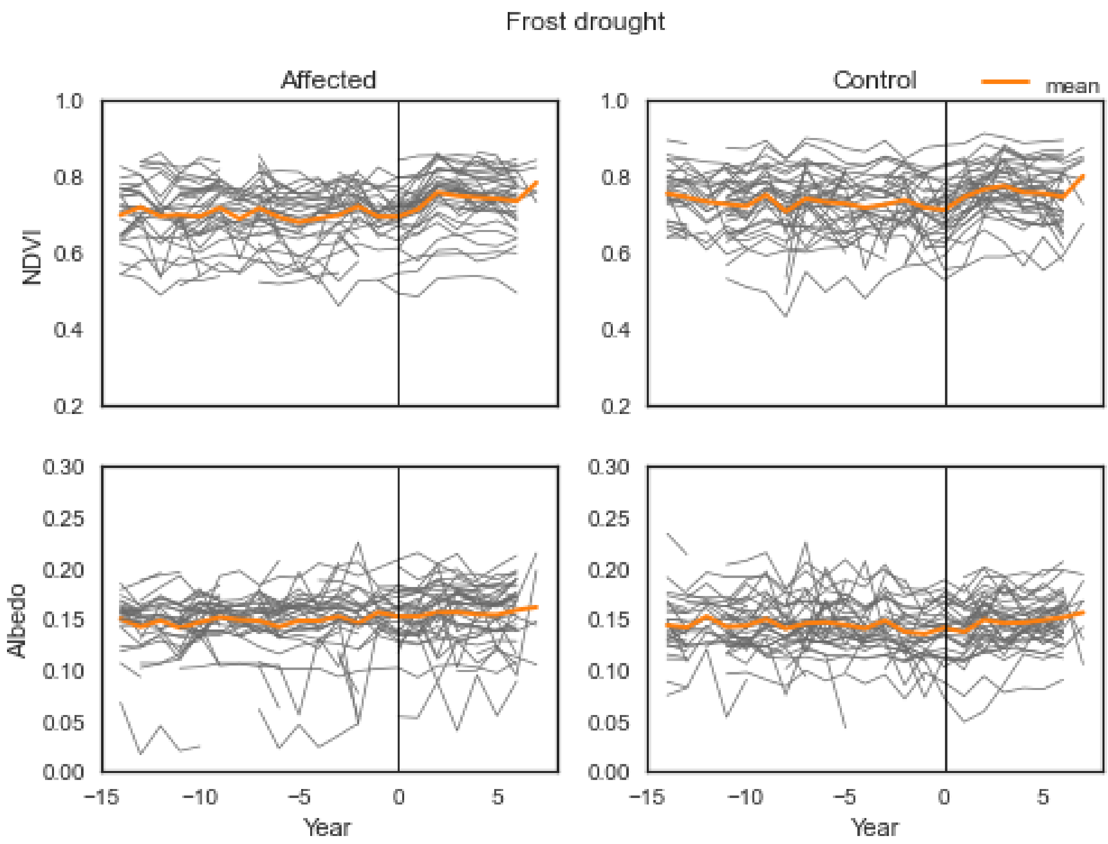

Fig. 4. Time series of albedo and NDVI mean values of the affected and control sites for the frost drought events.

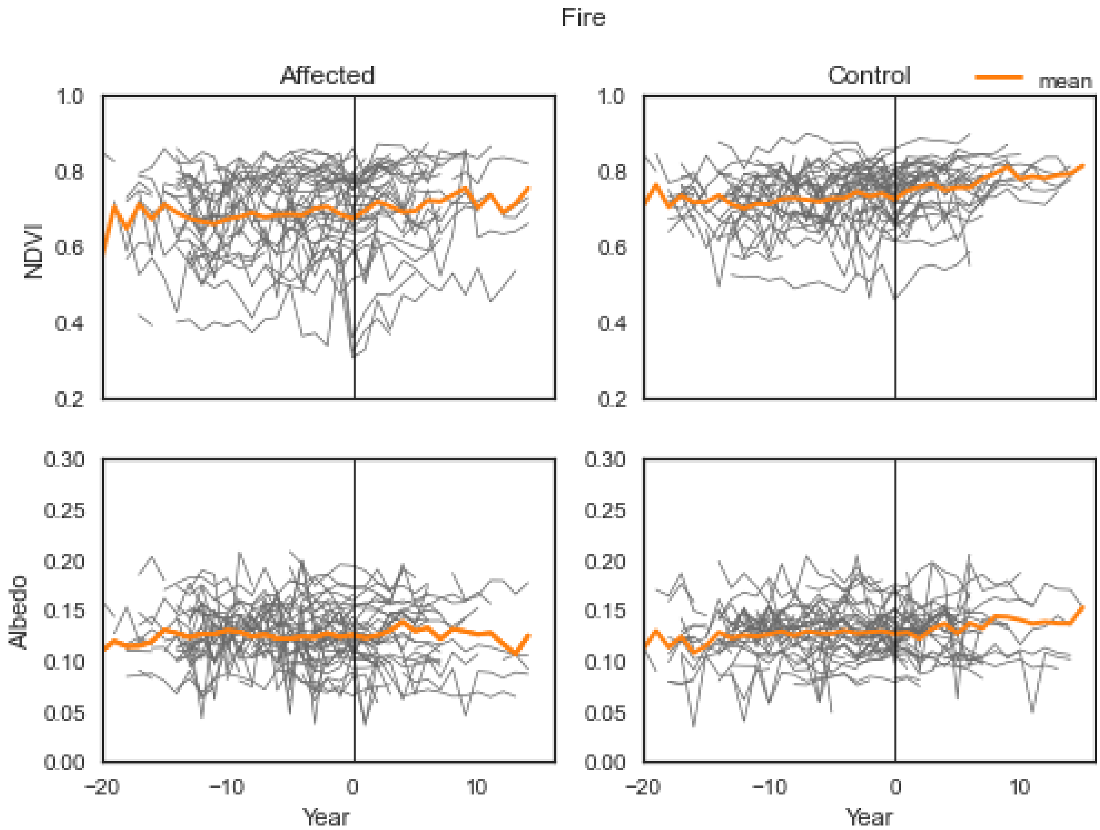

Fig. 5. Time series of albedo and NDVI mean values of the affected and control sites for the fire events.

Table 4. Results of the paired sampled t-test testing for a difference in mean albedo and NDVI of the affected and control sites for fire respective frost drought before and after the event. The mean values are the mean of mean NDVI and albedo of all sites for the fire respective frost drought events and SD is the standard deviation.

			Mean		Paired samples t-test		Sample size
			Before	After	t-value	p-value	
Fire	Albedo	Affected	0.123 ± 0.028	0.124 ± 0.030	-0.271	0.788	38
		Control	0.128 ± 0.024	0.127 ± 0.023	0.607	0.548	38
	NDVI	Affected	0.693 ± 0.100	0.697 ± 0.117	-0.578	0.566	38
		Control	0.733 ± 0.073	0.746 ± 0.067	-2.559	**0.015**	38
Frost drought	Albedo	Affected	0.147 ± 0.032	0.152 ± 0.028	-2.547	**0.015**	36
		Control	0.141 ± 0.025	0.143 ± 0.025	-1.358	0.183	36
	NDVI	Affected	0.701 ± 0.076	0.733 ± 0.074	-6.029	< **0.001**	36
		Control	0.725 ± 0.072	0.752 ± 0.067	-5.040	< **0.001**	36

Table 5. Results of the paired sampled t-test testing for difference in slope coefficient of the linear trend of mean albedo and NDVI of the affected and control sites for fire respective frost drought before and after the event. The mean values are the mean of the slope coefficient of mean NDVI and albedo of all sites for the fire respective frost drought events and SD is the standard deviation.

			Mean		Paired samples t-test		Sample size
			Before	After	t-value	p-value	
Fire	Albedo	Affected	-0.001 ± 0.007	-0.001 ±0.006	0.115	0.909	38
		Control	0.000 ± 0.005	0.002 ± 0.011	-0.935	0.356	38
	NDVI	Affected	0.003 ± 0.017	0.014 ± 0.014	-2.650	**0.012**	38
		Control	0.003 ± 0.011	0.013 ± 0.021	-2.392	**0.022**	38
Frost drought	Albedo	Affected	-0.002 ± 0.014	0.001 ± 0.003	-1.301	0.202	36
		Control	-0.001 ± 0.005	0.002 ± 0.003	-3.558	**0.001**	36
	NDVI	Affected	0.004 ± 0.020	0.013 ± 0.010	-2.678	**0.011**	36
		Control	0.000 ± 0.010	0.010 ± 0.011	-3.640	**0.001**	36

4.1.2 Analysis of ΔNDVI and Δalbedo

Analysing the difference between the slope coefficient of the linear trend and the mean of Δalbedo and ΔNDVI, before and after the events, using the paired sampled t-test, resulted in no difference for the fire events (Fig. 7, Table 6, and Table 7). For the frost drought events, an increase in Δalbedo was found, but no difference was found for ΔNDVI. No difference in slope coefficient before and after the event was found, neither for Δalbedo, nor ΔNDVI (Fig. 6, Table 6, and Table 7).

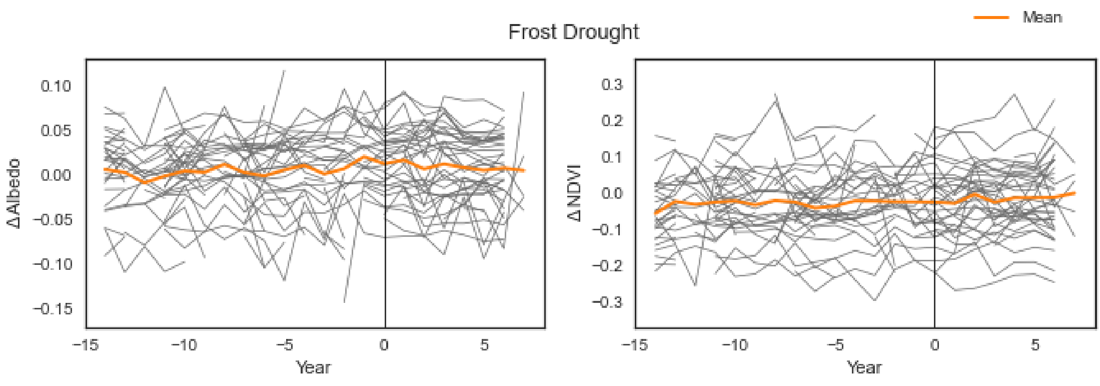

Fig. 6. Time series of a) Δalbedo; and b) ΔNDVI for the frost drought events.

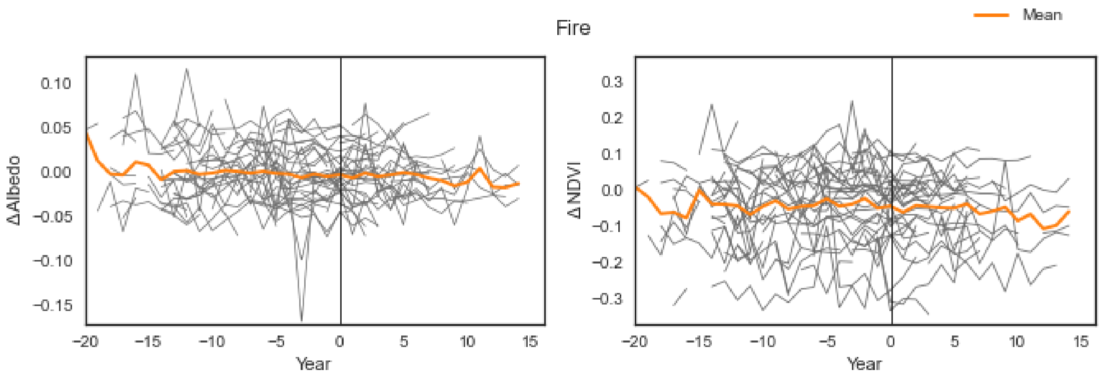

Fig. 7. Time series of a) Δalbedo; and b) ΔNDVI for the fire events.

Table 6. Results of the paired sampled t-test testing for a difference in mean Δalbedo and ΔNDVI of fire respective frost drought before and after the event. The mean values are the mean of mean ΔNDVI and Δalbedo of all sites for the fire respective frost drought events and SD is the standard deviation.

		Mean ± SD		Paired samples t-test		Sample size
		Before	After	t-value	p-value	
Fire	Albedo	-0.004 ± 0.027	-0.003 ± 0.028	-0.146	0.885	38
	NDVI	-0.040 ± 0.096	-0.051 ± 0.098	1.493	0.144	38
Frost drought	Albedo	0.004 ± 0.042	0.009 ± 0.038	-2.038	**0.049**	36
	NDVI	-0.023 ± 0.086	-0.019 ± 0.093	-0.603	0.550	36

Table 7. Results of the paired sampled t-test testing for a difference in the slope coefficient of the linear trend of Δalbedo and ΔNDVI, before and after the event. The mean values are the mean of the trend of ΔNDVI and Δalbedo of all sites for the fire respective frost drought events and SD is the standard deviation.

		Mean ± SD		Paired samples t-test		Sample size
		Before	After	t-value	p-value	
Fire	Albedo	-0.001 ± 0.006	-0.001 ± 0.005	0.410	0.684	38
	NDVI	-0.002 ± 0.018	0.003 ± 0.016	-1.104	0.277	38
Frost drought	Albedo	0.000 ± 0.014	0.000 ± 0.005	0.186	0.853	36
	NDVI	0.000 ± 0.026	0.004 ± 0.014	-0.624	0.537	36

4.2 b) *Does the impact on vegetation greenness and albedo of fire and frost drought events differ between land cover categories?*

4.2.1 Analysis of NDVI and Albedo at Affected and Control sites separated in Land Cover Categories

The paired sampled t-test conducted for each of the land cover categories, show an increase in NDVI at the affected sites after frost drought for the land cover category *Needleleaved forest*, both when analysing the mean and the slope coefficient (Fig. 10, Table 8, Table 9). The land cover category *Mosaic tree, shrubs, herbaceous cover*, a difference was found only for NDVI when analysing the difference in mean values, indicating an increase in the mean of mean NDVI after frost drought. This was shown both at the affected and control sites. Regarding the land cover category *Broadleaved forest*, an increase in mean NDVI after frost drought, both for the affected sites and the control sites, was found. This difference was reflected also in the slope coefficient for the control sites, indicating a shift from negative to positive mean slope coefficient, but no difference was found for the affected sites (Fig. 10, Table 8, Table 9). For albedo, a difference was found only for the land cover category *Broadleaved forest* when analysing the slope coefficient, with a shift from negative to positive mean slope coefficient, both for the affected sites and the control sites (Fig. 11, Table 8, Table 9).

Regarding the fire events, no impact was found when analysing the difference in mean values, neither for albedo nor NDVI (Fig. 8, Fig. 9, Table 8). When analysing the slope coefficient of NDVI before and after the events an increase in the mean slope coefficient was found for the land cover category *Mosaic tree, shrubs, herbaceous cover* at the control sites. Also, a difference in NDVI, with a shift from a negative to a positive mean slope coefficient, was found at the affected sites for the land cover category *Needleleaved forest* (Fig. 8, Table 9).

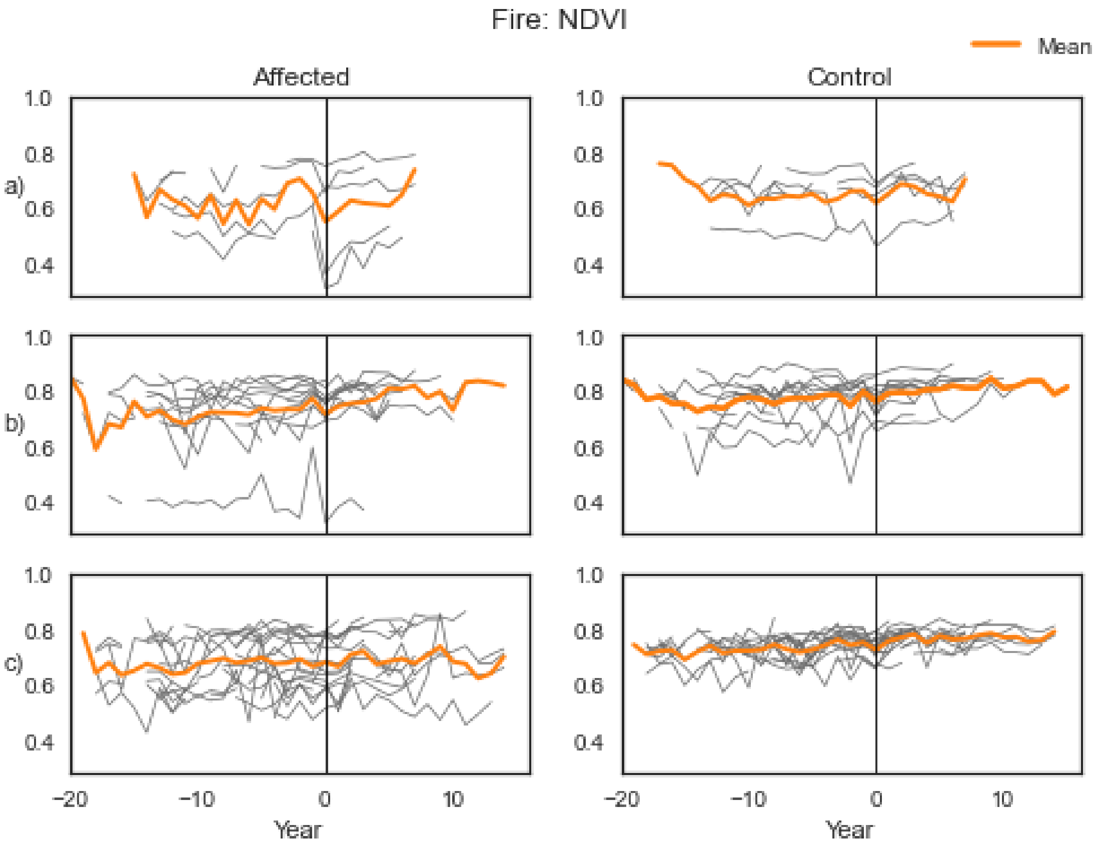

Fig. 8. NDVI for the fire events at the affected and control sites for the land cover categories a) Mosaic tree, shrubs, herbaceous cover, b) Broadleaved forest, and c) Needleleaved forest.

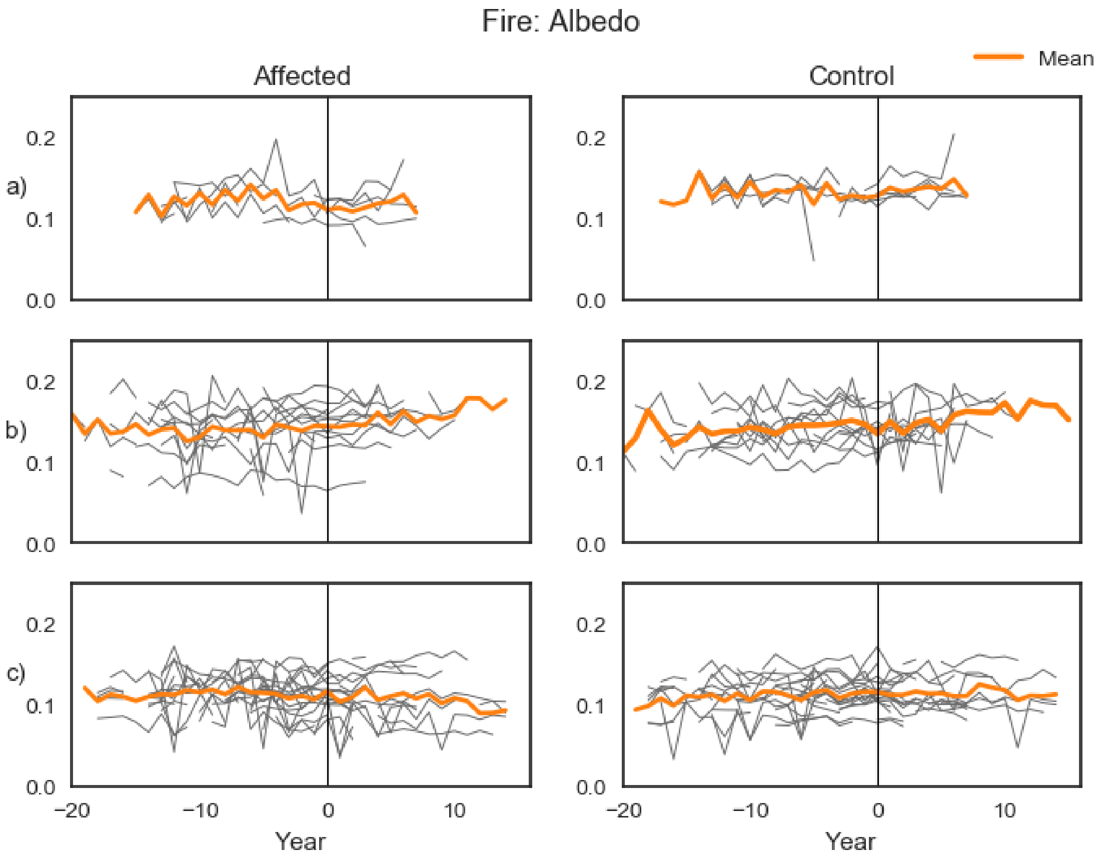

Fig. 9. Albedo for the fire events at the affected and control sites for the land cover categories a) Mosaic tree, shrubs, herbaceous cover, b) Broadleaved forest, and c) Needleleaved forest.

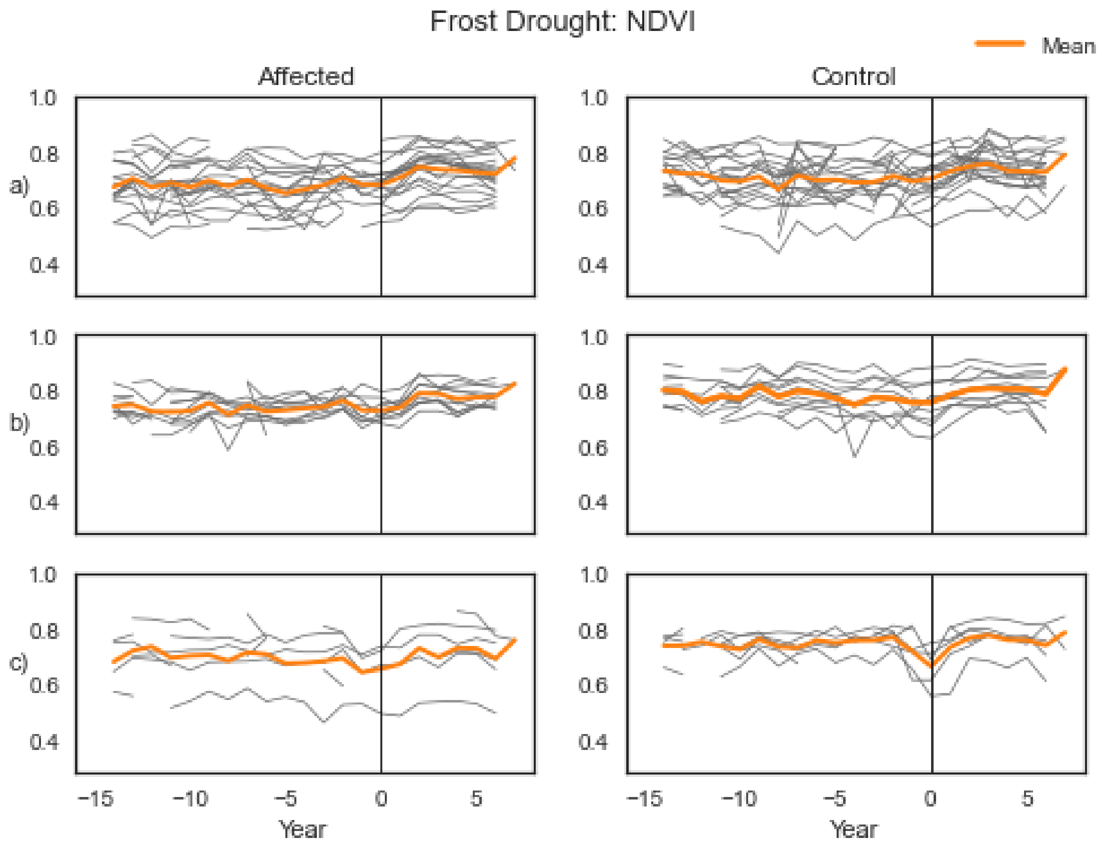

Fig. 10. NDVI for the frost drought events at the affected and control sites for the land cover categories a) Mosaic tree, shrubs, herbaceous cover, b) Broadleaved forest, and c) Needleleaved forest.

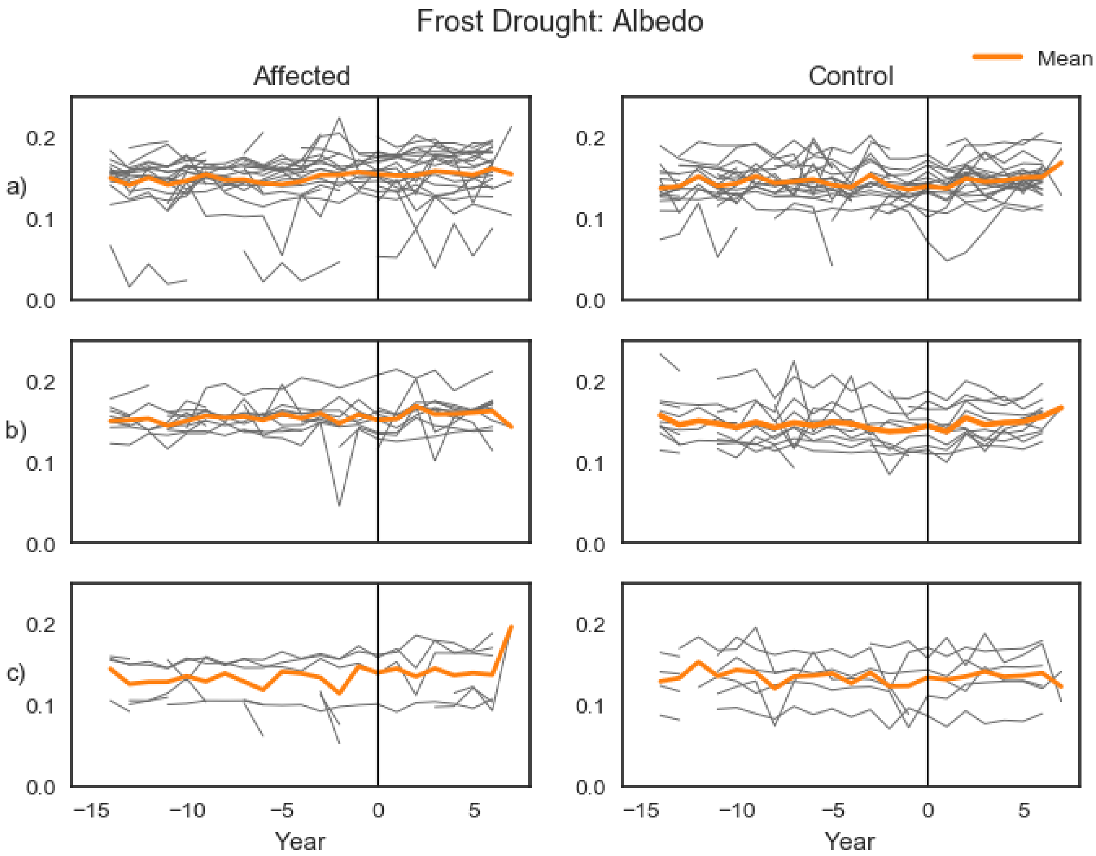

Fig. 11. Albedo for the frost drought events at the affected and control sites for the land cover categories a) Mosaic tree, shrubs, herbaceous cover, b) Broadleaved forest, and c) Needleleaved forest.

Table 8: Results of the paired sampled t-test testing the difference in the mean albedo and NDVI of fire respective frost drought before and after the event, at the affected sites and the control sites. The mean values are the mean of mean NDVI and albedo of all sites for each of the land cover categories and for the affected and control sites of the fire respective frost drought events, and SD is the standard deviation.

			Mean		Paired samples t-test		Sample size
			Before	After	t-value	p-value	
Mosaic tree, shrubs, herbaceous cover							
Fire	Albedo	Affected	0.122 ± 0.018	0.112 ± 0.016	2.732	0.052	7
		Control	0.126 ± 0.014	0.134 ± 0.011	-1.876	0.134	7
	NDVI	Affected	0.641 ± 0.103	0.600 ± 0.015	1.292	0.266	7
		Control	0.645 ± 0.078	0.657 ± 0.074	-1.366	0.244	7
Frost drought	Albedo	Affected	0.149 ± 0.033	0.155 ± 0.030	-1.841	0.081	19
		Control	0.143 ± 0.023	0.144 ± 0.024	-0.612	0.548	19
	NDVI	Affected	0.685 ± 0.078	0.720 ± 0.072	-4.510	< **0.001**	19
		Control	0.699 ± 0.074	0.734 ± 0.065	-5.240	< **0.001**	19
Broadleaved forest							
Fire	Albedo	Affected	0.139 ± 0.030	0.146 ± 0.029	-1.873	0.088	12
		Control	0.147 ± 0.024	0.141 ± 0.019	1.268	0.231	12
	NDVI	Affected	0.738 ± 0.109	0.744 ± 0.120	-0.575	0.577	12
		Control	0.773 ± 0.073	0.788 ± 0.055	-1.680	0.121	12
Frost drought	Albedo	Affected	0.156 ± 0.020	0.158 ± 0.019	-0.809	0.437	6
		Control	0.143 ± 0.024	0.146 ± 0.023	-1.266	0.234	6
	NDVI	Affected	0.738 ± 0.031	0.760 ± 0.037	-2.938	**0.015**	6
		Control	0.761 ± 0.060	0.791 ± 0.057	-4.963	**0.001**	6
Needleleaved forest							
Fire	Albedo	Affected	0.110 ± 0.020	0.111 ± 0.023	-0.283	0.780	19
		Control	0.114 ± 0.018	0.113 ± 0.020	0.670	0.511	19
	NDVI	Affected	0.678 ± 0.088	0.693 ± 0.090	-2.000	0.061	19
		Control	0.742 ± 0.034	0.753 ± 0.032	-1.454	0.163	19
Frost drought	Albedo	Affected	0.125 ± 0.033	0.134 ± 0.029	-2.195	0.080	11
		Control	0.132 ± 0.029	0.135 ± 0.029	-0.845	0.437	11
	NDVI	Affected	0.681 ± 0.092	0.715 ± 0.104	-2.578	**0.050**	11
		Control	0.751 ± 0.034	0.744 ± 0.060	0.429	0.685	11

Table 9: Results of the paired sampled t-test testing the difference in the slope coefficient of albedo and NDVI of fire respective frost drought before and after the event, at the affected sites and the control sites. The mean values are the mean of the slope coefficient of NDVI and albedo of all sites for each of the land cover categories and for the affected and control sites of the fire respective frost drought events, and SD is the standard deviation.

			Mean		Paired samples t-test		Sample size
			Before	After	t-value	p-value	
Mosaic tree, shrubs, herbaceous cover							
Fire	Albedo	Affected	-0.003 ± 0.003	-0.001 ± 0.006	-0.472	0.662	7
		Control	0.002 ± 0.009	0.002 ± 0.003	0.034	0.975	7
	NDVI	Affected	0.008 ± 0.010	0.022 ± 0.013	-1.978	0.119	7
		Control	0.002 ± 0.010	0.015 ± 0.007	-3.025	**0.039**	7
Frost drought	Albedo	Affected	0.003 ± 0.007	0.001 ± 0.003	0.800	0.435	19
		Control	0.000 ± 0.005	0.001 ± 0.004	-1.237	0.231	19
	NDVI	Affected	0.008 ± 0.017	0.012 ± 0.011	-1.195	0.249	19
		Control	0.002 ± 0.010	0.006 ± 0.010	-1.500	0.150	19
Broadleaved forest							
Fire	Albedo	Affected	0.003 ± 0.009	0.002 ± 0.004	0.315	0.760	12
		Control	0.002 ± 0.003	0.007 ± 0.018	-0.980	0.350	12
	NDVI	Affected	0.008 ± 0.011	0.007 ± 0.009	0.388	0.707	12
		Control	0.002 ± 0.012	0.016 ± 0.029	-1.500	0.164	12
Frost drought	Albedo	Affected	-0.001 ± 0.003	0.002 ± 0.003	-2.256	**0.048**	6
		Control	-0.003 ± 0.003	0.002 ± 0.002	-4.377	**0.001**	6
	NDVI	Affected	0.008 ± 0.015	0.013 ± 0.008	-1.296	0.224	6
		Control	-0.002 ± 0.008	0.011 ± 0.008	-3.304	**0.008**	6
Needleleaved forest							
Fire	Albedo	Affected	-0.002 ± 0.006	-0.002 ± 0.004	-0.297	0.770	19
		Control	-0.001 ± 0.004	-0.001 ± 0.004	0.118	0.907	19
	NDVI	Affected	-0.003 ± 0.020	0.015 ± 0.011	-2.777	**0.012**	19
		Control	0.005 ± 0.011	0.012 ± 0.018	-1.317	0.204	19
Frost drought	Albedo	Affected	-0.016 ± 0.026	0.001 ± 0.004	-1.631	0.164	11
		Control	-0.004 ± 0.004	0.002 ± 0.002	-2.106	0.089	11
	NDVI	Affected	-0.016 ± 0.020	0.015 ± 0.007	-2.645	**0.046**	11
		Control	-0.005 ± 0.012	0.019 ± 0.011	-2.476	0.056	11

4.2.2 Analysis of ΔNDVI and Δalbedo separated in Land Cover Categories

It is apparent that none of the land cover categories show a difference in the slope coefficient of the linear trend of Δalbedo and ΔNDVI for the fire or frost drought events (Fig. 12, Fig. 13, Table 11). For the land cover categories, *Mosaic tree, shrubs, herbaceous cover* did show a difference comparing mean Δalbedo before and after the fire drought events, with a decrease in the mean of mean Δalbedo from -0.002 ± 0.020 to -0.023 ± 0.012. None of the other two land cover categories shown a difference in mean Δalbedo. Also, no land cover category shows a difference in mean ΔNDVI comparing before and after event values (Fig. 12, Fig. 13, Table 10).

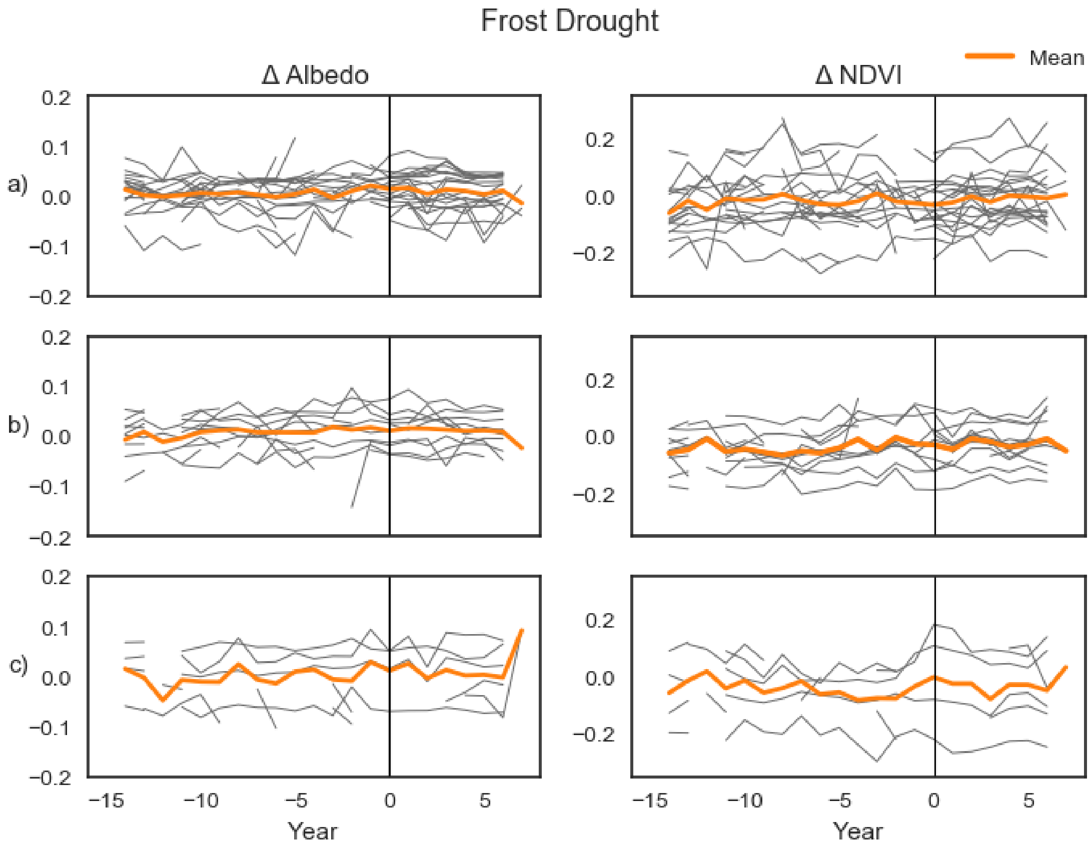

Fig. 12. Δalbedo and ΔNDVI of frost drought events for the land cover categories a) Mosaic tree, shrubs, herbaceous cover, b) Broadleaved forest, and c) Needleleaved forest.

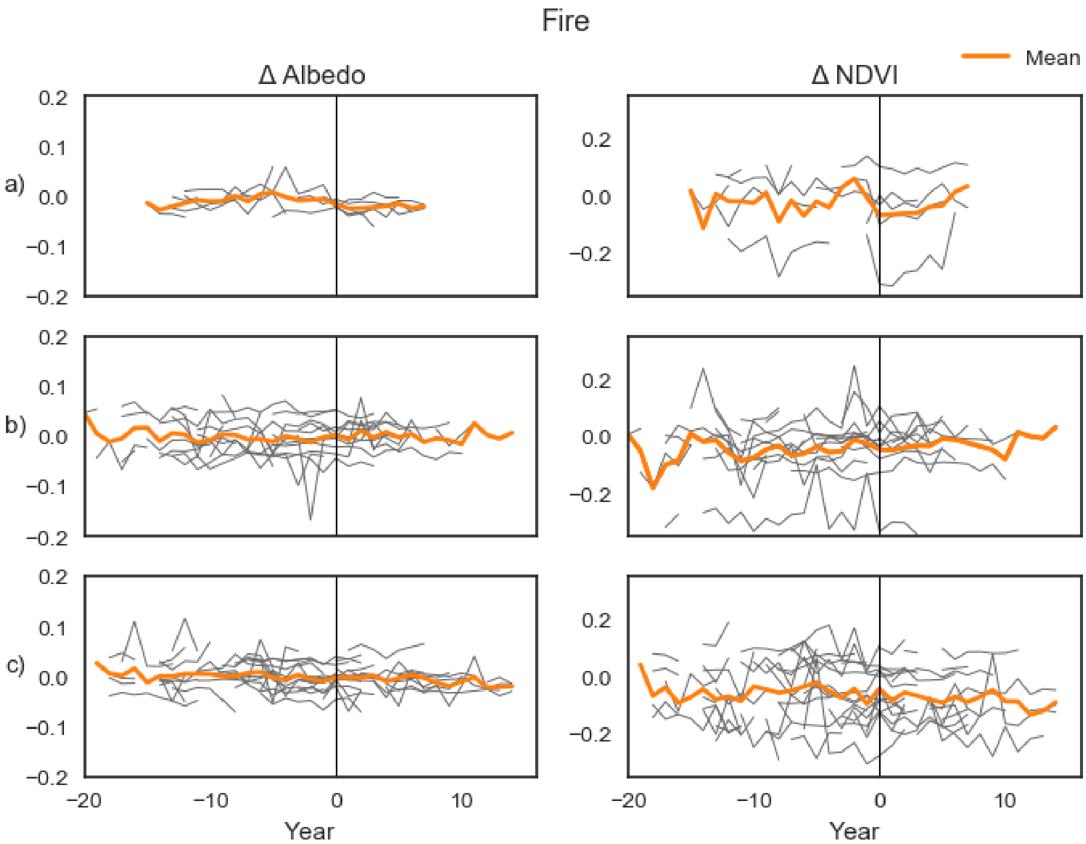

Fig. 13. Δalbedo and ΔNDVI of frost drought events for the land cover categories a) Mosaic tree, shrubs, herbaceous cover, b) Broadleaved forest, and c) Needleleaved forest.

Table 10. Results of the paired sampled t-test testing the difference in the mean Δalbedo and ΔNDVI of fire respective frost drought before and after the event. The mean values are the mean of mean ΔNDVI and Δalbedo of all sites for each of the land cover categories and for the fire respective frost drought events and SD is the standard deviation.

		Mean ± SD		Paired samples t-test		Sample size
		Before	After	t-value	p-value	
Mosaic tree, shrubs, herbaceous cover						
Fire	Albedo	-0.002 ± 0.020	-0.023 ± 0.012	3.305	**0.030**	7
	NDVI	-0.011 ± 0.085	-0.057 ± 0.119	1.530	0.201	7
Frost drought	Albedo	0.005 ± 0.037	0.011 ± 0.035	-1.630	0.120	19
	NDVI	-0.013 ± 0.083	-0.014 ± 0.088	0.079	0.938	19
Broadleaved forest						
Fire	Albedo	-0.006 ± 0.034	0.003 ± 0.300	-2.131	0.056	12
	NDVI	-0.034 ± 0.083	-0.046 ± 0.096	1.233	0.243	12
Frost drought	Albedo	0.011 ± 0.039	0.013 ± 0.033	-0.719	0.488	6
	NDVI	-0.021 ± 0.075	-0.030 ± 0.072	0.822	0.430	6
Needleleaved forest						
Fire	Albedo	-0.004 ± 0.022	-0.002 ± 0.026	-0.843	0.410	19
	NDVI	-0.063 ± 0.101	-0.063 ± 0.091	-0.037	0.971	19
Frost drought	Albedo	-0.008 ± 0.054	0.000 ± 0.049	-0.953	0.384	11
	NDVI	-0.068 ± 0.098	-0.031 ± 0.134	-1.984	0.104	11

Table 11. Results of the paired sampled t-test testing the difference in the slope coefficient of the linear trend of Δalbedo and ΔNDVI, before and after the event. The mean values are the mean of the slope coefficient of ΔNDVI and Δalbedo of all sites for each of the land cover categories and for the fire respective frost drought events and SD is the standard deviation.

		Mean ± SD		Paired samples t-test		Sample size
		Before	After	t-value	p-value	
Mosaic tree, shrubs, herbaceous cover						
Fire	Albedo	-0.004 ± 0.006	-0.002 ± 0.005	-0.326	0.761	7
	NDVI	0.004 ± 0.015	0.008 ± 0.011	-0.325	0.762	7
Frost drought	Albedo	0.003 ± 0.010	0.000 ± 0.004	1.728	0.102	19
	NDVI	-0.003 ± 0.023	0.006 ± 0.013	-1.162	0.261	19
Broadleaved forest						
Fire	Albedo	0.000 ± 0.007	0.001 ± 0.004	-0.055	0.957	12
	NDVI	0.006 ± 0.013	-0.002 ± 0.011	1.737	0.116	12
Frost drought	Albedo	0.001 ± 0.005	-0.001 ± 0.004	1.313	0.218	6
	NDVI	0.010 ± 0.014	0.001 ± 0.009	1.780	0.105	6
Needleleaved forest						
Fire	Albedo	-0.001 ± 0.006	-0.001 ± 0.005	0.002	0.999	19
	NDVI	-0.009 ± 0.019	0.003 ± 0.018	-1.678	0.111	19
Frost drought	Albedo	-0.011 ± 0.024	0.003 ± 0.008	-1.072	0.333	11
	NDVI	-0.013 ± 0.039	-0.001 ± 0.019	-0.492	0.644	11

5. Discussion

5.1 *a) Did fire and frost drought events have an impact on vegetation greenness and albedo?*

In this work, a before-after impact approach was applied to study the impact of fire and frost drought events on vegetation greenness and albedo, using Landsat satellite data. The statistical analysis of all sites together for the fire events shows no difference in mean Δalbedo and ΔNDVI or the slope coefficient of the linear trend of Δalbedo and ΔNDVI, before and after the events (Fig. 7, Table 6, Table 7). Also, there was no difference in mean ΔNDVI or the trend of ΔNDVI following frost drought events (Fig. 6, Table 6, Table 7). For mean Δalbedo, however, there was an increase in the mean from 0.004 ± 0.042 to 0.009 ± 0.038 (Table 6). Despite this, no difference was found for the slope coefficient.

Analysing the difference in the mean and slope coefficient before and after the fire events for the affected and control sites separately, a difference was shown in the slope coefficient of NDVI both at the affected site and the control site. For mean NDVI a difference was found only at the control site (Table 4 and Table 5). For the frost drought events a difference was shown in both the mean and the slope coefficient of NDVI, both at the affected and control site. For albedo, a difference was shown at the affected site when analysing the difference in mean, while a difference in the control site was found when analysing the difference in the slope coefficient (Table 4 and Table 5). However, the impacts seen at the affected sites could be caused by other parameters than the fire and frost drought events and therefore ΔNDVI and Δalbedo was used. Using ΔNDVI and Δalbedo, on the other hand, introduces a risk that variability in the control sites could lead to that the values of the affected sites are less separable from values of the control sites, with the consequence that the impact of the fire and frost drought events would not be shown in Δalbedo and ΔNDVI.

The results of this report contradict the results of earlier studies on fire and frost drought events that indicate a reduction in NDVI after the events (Bokhorst et al. 2009; Bjerke et al. 2014; Bjerke et al. 2017; Heim et al. 2020). Also, earlier studies conducted on fire events found that after a reduction, NDVI tends to reach higher values, presumably caused by a shift in species towards a land coverage characterised by a larger amount of green biomass (Barrett et al; 2012; Heim et al. 2020; Sizov et al 2021). Such a trend was not identified in this study. However, given that Bernhardt et al. (2011) and Barrett et al. (2012) suggest that the largest change in composition is associated with burn severity, and because greater burn severity causes greater reduction in NDVI directly after the fire (Díaz-Delgado et al. 2003), it could be that the severity of the fire events studied are of low character, and thus does not show an effect in NDVI.

For the frost drought event an explanation for the conflicting results is the different methods used. Sites in the region of Troms and Lofoten, obtained by Bjerke et al. (2017), were examined during fieldwork and the extent of damages and NDVI values were measured and observed. In this work, the same sites were studied but NDVI and albedo values were obtained using satellite-based remote sensing. Thus, it could be that these effects are difficult to detect with the 30 m spatial resolution of Landsat, even though they were clearly visible in the field. It could also be that the effect is being obscure when using a mosaic of the median. Here the median was used to extract Landsat data for each growing season (July the 1st to August the 31st). The median can in some cases be a better measure of the "normal" values than the average. This as it does not allow extreme values to impact the results, which is especially beneficial when the sample size is small. However, Bokhorst et al. (2009) did use remote sensing to study the impact of frost drought on satellite-based NDVI and identified a reduction of 26%. The study area was in the same region as of this work but investigated a winter warming event that occurred during the season 2007/2008. Instead of having multiple study sites, Bokhorst et al. (2009) covered a large area (1424 km^2) and observed how the NDVI values over the entire area were altered. It could be that the frost drought events occur over a large area with a spatially irregular distribution, making the method used by Bokhorst et al. (2009) more suitable as it accounts for this irregularity.

For albedo, earlier studies report a decrease in albedo after a fire event (Chambers et al. 2005; Rocha and Shaver 2011). In the literature, no earlier studies conducted on albedo and frost drought were found. Parmentier et al. (2018) did not specifically study the albedo but suggest that a vegetation shift followed by a frost drought event could possibly alter it. The results of this report show an increase when comparing mean Δalbedo before and after the frost drought event (Table 6). This is an indication that frost drought do have an impact on vegetation in terms of albedo. However, this needs to be further investigated.

5.2 b) *Does the impact on vegetation greenness and albedo of fire and frost drought events differ between land cover categories?*

The second research question aimed to investigate the impact frost drought and fire events have on different land cover categories. No difference was observed when analysing the mean and the slope coefficient of the linear trend of Δalbedo and ΔNDVI for the frost drought events for each of the land cover categories (Fig. 12, Fig. 13, Table 10, Table 11). This result conflict with the results of earlier studies. Earlier studies have pointed out shrubs and lichens as especially vulnerable to frost drought (Bjerke 2011; Bjerke et al. 2014; Bjerke et al. 2017; Bokhorst et al., 2009; Bokhorst et al. 2012), while mosses and sedges have been identified as less vulnerable (Parmentier et al. 2018). One reason for the obtained result is that all of these belong to the land cover category *Mosaic tree, shrubs, herbaceous cover*. Thus, because the land coverage is a mosaic of different vegetation types where the different species are not equally vulnerable to the extreme event, it could be difficult to detect the effect of the frost drought event using these broad land cover categories. For instance, Bokhorst et al. (2012) suggested that the rapid (within 2 years) recovery of NDVI after a frost drought event could be due to non-visibly damaged, dominated species, such *Betula nana* and *B. pubescens,* masking the longer recovery time of *Empetrum nigrum*.

The observed reduction in mean Δalbedo after fire for the land cover category *Mosaic tree, shrubs, herbaceous cover,* is partly in line with the work by Chambers et al. (2005) who report a larger reduction for tundra sites than for spruce forest (-75% versus -24%). Also, lichens, which belong to the land cover category *Mosaic tree, shrubs, herbaceous cover,* have been identified as especially vulnerable with long recovery rates (Jandit et al. 2008; Sizov et al. 2021; Racine et al 2004). Earlier studies have seen altered albedo both at open tundra and in forest ecosystems (Chambers 2005; French et al. 2016; Heim et al. 2020; Payette and Delwaide 2018), while the result of this study show no impact on albedo for the categories *Broadleaved forest* and *Needleleaved forest*. However, burn severity seems to generally be an important factor for the effect of fire on albedo (French et al 2016; Rocha and Shaver 2011).

5.3 Limitations and Source of Error

An important limitation of the study is the lack of knowledge on the physical properties of the affected sites and the control sites, such as more detailed information on vegetation coverage, area of affected vegetation, intensity of event, and damage ratio. Even though the extent of affected area was unknown for some of the frost drought and the fire events, an area with radius 100 m was created for the affected and control sites, assuming this to be an area suitable to collect the signal of the effect of the fire or frost drought event. However, the known area of the fire events studied were of a large variety, and having an affected area that is smaller than the defined study site could lead to that the effect of the event is being masked, which is a source of error caused by this assumption. The intensity of the events and the damage ratio of the vegetation is unknown, which means that the effect of the events could be obscures so that it is not detectable in the spectral signal. For instance, non-affected vegetation could possibly expand and thus compensate for the negative effect the fire or frost drought event possibly had on the more vulnerable vegetation. Moreover, it was difficult to remotely define control sites due to the lack of detailed information on vegetation coverage at the affected sites and the control sites defined. This means that how well the control sites represent the affected sites is unknown. Additionally, as earlier mentioned, variability in the control sites could lead to that non-existing impacts are shown, or that the values of the affected sites are less separable from values of the control sites. Consequently, the effects of the fire and frost drought events would not be shown in Δalbedo and ΔNDVI, for all sites and the different land cover categories.

Moreover, for the burned sites, it could have been relevant to use other remotely sensed estimate of vegetation such as burn severity index to test the portion of vegetation and soil organic matter consumed in the fire and thus the damage ratio of the vegetation at the affected studied, as well as check the damage ratio at the control sites. For the frost drought events, it could be that these events are not limited to a well-defined area, such as fire events, but may occur spatially irregularly. Therefore, even though snow depth data from meteorological stations was used, there is a risk that also the selected control sites have been affected. If field studies would have been conducted information on physical properties, and the extent of the damaged area could have been collected and verified.

The limitation of only using the 5 growing seasons before and after the events was made to avoid that variations that naturally occur in ecosystems over time would obscure the effect of the event or result in a difference that was not caused by the event. Still, this limitation was made with the assumption that no trends that strongly vary from the mean occur during these years. If so, that trend could largely impact the mean that the after-event values are being compared with. Moreover, averaging the 5 growing seasons before and after the events also holds a risk that very short-lasting effect are being obscure and not shown in the results.

The CFMask algorithm did not mask out clouds as expected, which is an important uncertainty of the results. With the aim of compensating for this error, data affected by unfiltered clouds were removed manually. All mentioned uncertainties indicate the complexity of ecosystems and why both field studies and studies using remote sensing are important. Field works allow us to collect observational data, while the great advantage of remote sensing analysis is that it allows us to go back in time and analyse historical data. Furthermore, when conducting multiple tests simultaneously there is an increased risk that obtained results are caused by the chance. Therefore, it would have been relevant to apply a correction method in order to compensate for the large number of statistical tests conducted. Also, the data set used for analysis was relatively small which was problematic when assigning the sites to land coverage categories, and therefore only 3 categories were created.

Finally, this work studied single events, but increased frequency in fire and frost drought events could possibly cause pronounced effects on vegetation (Parmentier et al. 2018; Bokhorst el al. 2012; Jolly et al. 2015), as well as that extreme event can possibly interact, making the vegetation more vulnerable to other type of extremes and causing greater severity (Bjerke et al 2017). Thus, these interactions must be studied for a complete understanding.

Conclusion

The results presented in this report show no impact on vegetation greenness after single fire events. A decrease in the Δalbedo (mean of mean Δalbedo: from -0.002 ± 0.020 to -0.023 ± 0.012) was found only for the land cover category *Mosaic tree, shrubs, herbaceous cover* and albedo. Indicating that the land cover class *Mosaic tree, shrubs, herbaceous cover* is more vulnerable to the impacts of fire events than the other two studied land cover categories; *Broadleaved forest* and *Needleleaved forest*. For the frost drought events no impacts was found on vegetation greenness when analysing all sites. However, an increase in Δalbedo (mean of mean Δalbedo: from 0.004 ± 0.042 to 0.009 ± 0.038) was found. Although a weak difference ($p=0.049$), this is an indication that how frost drought impacts albedo values should be further investigated, and especially since no earlier studies investigating the impact of frost drought on albedo were found.

However, uncertainties and limitations of the 30 m Landsat data and variability in values of control sites, as well as unknown intensity of the events, size of damage areas and damage ratio of vegetation, are important sources of error of this study. Also, this work studied single events, but increased frequency in fire and frost drought events and interactions between different types of extremes could possibly cause pronounced effects on vegetation. Thus, these effects and interactions must be investigated in a more comprehensive study, including field observations, to further determine the effects of fire and frost drought event on vegetation.

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Appendix I

T1: Details on the study sites for the frost drought events. The sites are defined by Bjerke et al. (2017), Parmentier et al. (2018), and Stavanger Aftenblad (2013).

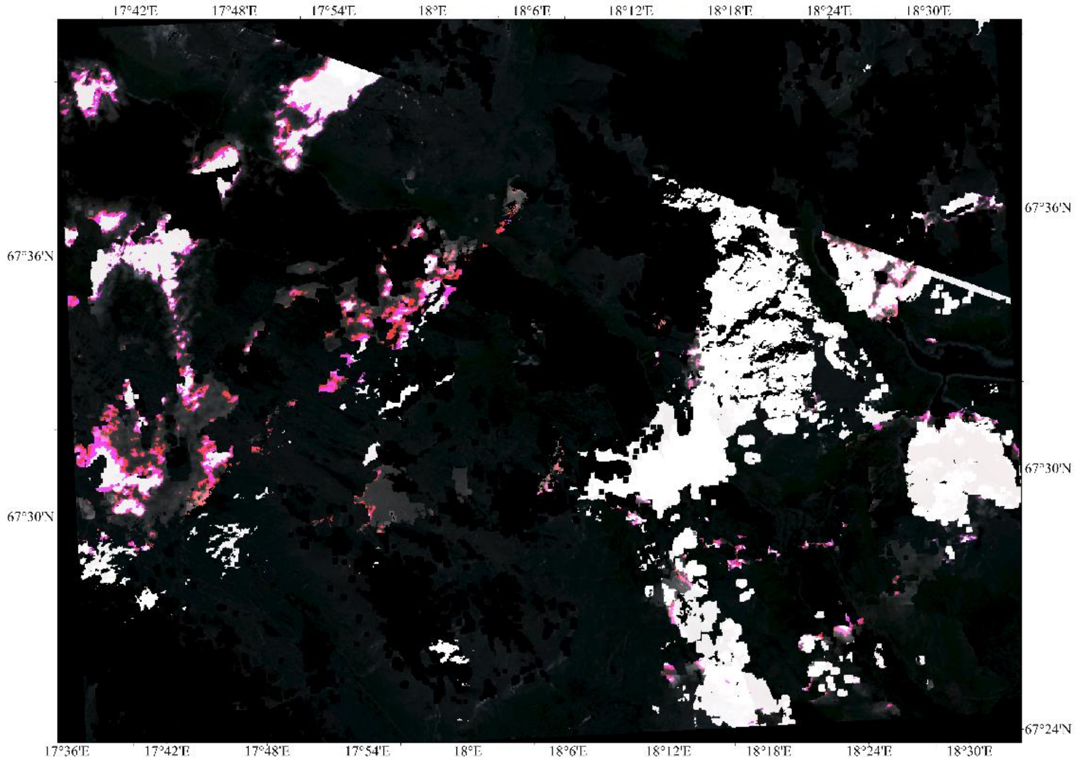
Type of event	Country	Site	Year	Land cover category	Latitude Study point	Longitude Study point	Elevation (m)	Latitude Control point	Longitude Control point	Elevation (m)
Frost drougth	Norway	Alterosen	2014	Tree cover, broadleaved, deciduous	68.2090952	14.4537837	5	68.2373606	14.5355006	19
Frost drougth	Norway	Bjørndalen #1	2014	Tree cover, broadleaved, deciduous	69.2904032	16.0288995	137	69.531897	17.9042311	130
Frost drougth	Norway	Bjørndalen #2	2014	Mosaic tree, shrubs, herbaceous	69.2688774	16.0394231	44	69.5486691	17.9123441	61
Frost drougth	Norway	Bjørnskinn gravlund	2014	Mosaic tree, shrubs, herbaceous cover	68.99052357	15.6400518	10	68.5735708	16.5096487	14
Frost drougth	Norway	Bjørheimsbygd	2013	Mosaic tree, shrubs, herbaceous	59.07702014	6.03144179	332	64.3459375	11.5374984	61
Frost drougth	Norway	Bleik	2014	Tree cover, broadleaved, deciduous	69.2654217	15.957576	23	69.5181281	17.9069012	61
Frost drougth	Norway	Borøya	2014	Mosaic tree, shrubs, herbaceous	68.5669694	14.9619665	0	68.3207696	14.6483526	2
Frost drougth	Norway	Brekko	2013	Tree cover, needleleaved, evergreen	58.76987583	6.080391005	22	64.3819474	11.5150919	46
Frost drougth	Norway	Bynuten	2013	Tree cover, needleleaved, evergreen	58.85397367	6.07247153	547	64.3682313	11.5759895	345
Frost drougth	Norway	Bømyra	2014	Mosaic tree, shrubs, herbaceous	69.0172487	15.5155585	12	68.612632	16.4790263	66
Frost drougth	Norway	Bøosen	2014	Mosaic tree, shrubs, herbaceous cover	68.0847392	13.2926434	26	68.2402564	14.5124114	33
Frost drougth	Norway	Gaudland	2013	Tree cover, broadleaved, deciduous	58.39531926	6.249304735	151	64.3679994	11.5098341	70
Frost drougth	Norway	Gimsøya	2014	Tree cover, broadleaved, deciduous	68.30184505	14.26240045	29	68.2431412	14.4766529	57
Frost drougth	Norway	Gimsøya golfpark	2014	Mosaic tree, shrubs, herbaceous cover	68.3415862	14.1330194	6	68.2180378	14.4930971	20
Frost drougth	Norway	Harstad camping	2014	Mosaic tree, shrubs, herbaceous cover	68.7725155	16.5795438	6	69.5845399	18.0149327	4
Frost drougth	Norway	Hopspollen	2014	Tree cover, broadleaved, deciduous	68.2072693	14.3502523	13	68.2346715	14.4705145	35
Frost drougth	Norway	Ims	2013	Mosaic tree, shrubs, herbaceous	58.90279136	5.955134343	295	64.3459354	11.531816	45
Frost drougth	Norway	Karlsvågen	2014	Tree cover, needleleaved, evergreen	68.21452197	14.4403746	15	68.2375072	14.4873827	35
Frost drougth	Norway	Kåkern	2014	Tree cover, needleleaved, evergreen	68.01708975	13.17421475	33	68.23469	14.4845656	35
Frost drougth	Norway	Kåkern sund	2014	Mosaic tree, shrubs, herbaceous cover	68.0205258	13.194134	21	69.4430496	17.9403585	20
Frost drougth	Norway	Napp-skardet	2014	Tree cover, broadleaved, deciduous	68.1238842	13.3700418	40	68.240476	14.4822634	45
Frost drougth	Norway	Nordmela laneset	2014	Tree cover, broadleaved, deciduous	69.0667663	15.5408998	15	68.6041549	16.4956808	20
Frost drougth	Norway	Oksebåsen	2014	Mosaic tree, shrubs, herbaceous cover	69.2962461	16.0372377	-7	69.5152988	17.959663	8
Frost drougth	Norway	Oterbekken	2014	Tree cover, broadleaved, deciduous	68.2915321	14.6962072	13	68.3178162	14.6514773	24
Frost drougth	Norway	Revskaret	2014	Mosaic tree, shrubs, herbaceous cover	68.2134232	14.45525	38	68.2374929	14.4929589	36
Frost drougth	Norway	Rogaland Arboret	2013	Mosaic tree, shrubs, herbaceous	58.82055095	5.806391296	135	64.3569853	11.5234943	82
Frost drougth	Norway	Rolvsfjord-Bogen	2014	Mosaic tree, shrubs, herbaceous cover	68.1824364	13.8564007	6	68.2180378	14.4957382	20
Frost drougth	Norway	Sandbekkgruvene	2013	Mosaic tree, shrubs, herbaceous cover	58.34006417	6.402388019	151	64.3229458	11.4998323	310
Frost drougth	Norway	Sauramyra	2014	Mosaic tree, shrubs, herbaceous	69.1414784	16.0216813	18	68.6124544	16.4846557	75
Frost drougth	Norway	Sildpollneset	2014	Tree cover, needleleaved, evergreen	68.3232995	14.7030618	5	68.3209048	14.6678954	3
Frost drougth	Norway	Skjelfjord	2014	Mosaic tree, shrubs, herbaceous	68.0732345	13.2276741	10	68.2375338	14.4960503	30
Frost drougth	Norway	Skogvoll	2014	Mosaic tree, shrubs, herbaceous cover	69.14524	15.7613516	1	68.5762871	16.509626	7
Frost drougth	Norway	Stamsund	2014	Tree cover, broadleaved, deciduous	68.1546833	13.8220392	7	68.2152124	14.4790639	17
Frost drougth	Norway	Tonsvikdalen	2014	Mosaic tree, shrubs, herbaceous cover	69.731583	19.2038653	40	69.6375709	19.5291555	47
Frost drougth	Norway	Ytterpollen	2014	Tree cover, broadleaved, deciduous	68.2655154	13.7702249	13	68.2347064	14.4734517	35
Frost drougth	Norway	Ørsvåg	2014	Mosaic tree, shrubs, herbaceous cover	68.1925902	14.3770338	20	68.2236561	14.5263268	31

Appendix II

T2: Sites studied for the fire events. The sites are based on data from MSB (2021), Hamarøy municipality (2020), and DSB (2014).

Type of event	Country	Site	Date	Land cover category	Latitude Study point	Longitude Study point	Elevation (m)	Latitude Control point	Longitude Control point	Elevation (m)
Fire	Norway	Froya	29/01/2014	Mosaic tree, shrubs, herbaceous cover	63.73400313	8.758886185	42	63.706828	8.5430796	18
Fire	Norway	Flatanger	27/01/2014	Mosaic tree, shrubs, herbaceous cover	64.44740858	10.62161528	46	64.4323489	10.5402538	41
Fire	Sweden	Gällivare #1	08/08/2009	Tree cover, needleleaved, evergreen	67.6690	17.6623	468	67.6596979	17.7034289	447
Fire	Sweden	Gällivare #2	24/06/2007	Tree cover, needleleaved, evergreen	67.1779	19.3577	400	67.1406663	19.6296487	406
Fire	Sweden	Gällivare #3	12/08/2006	Tree cover, needleleaved, evergreen	67.1621	19.5033	368	67.1573426	19.5775532	431
Fire	Norway	Hamaroy #1	22/07/2019	Tree cover, broadleaved, deciduous	68.1392872	15.6340373	38	68.146647	15.6690069	30
Fire	Norway	Hamaroy #2	22/05/2017	Tree cover, broadleaved, deciduous	68.1530716	15.7221448	0	68.1228104	15.7174729	7
Fire	Norway	Hamaroy #3	26/06/2014	Tree cover, broadleaved, deciduous	68.0199463	15.3346769	25	68.0356926	15.3458772	29
Fire	Norway	Hamaroy #4	08/05/2014	Tree cover, broadleaved, deciduous	68.016379	15.3198557	14	68.0182951	15.4041924	20
Fire	Norway	Hamaroy #5	14/05/2011	Tree cover, broadleaved, deciduous	68.1942229	16.0212881	15	68.18432	16.0240067	26
Fire	Norway	Hamaroy #6	13/05/2011	Tree cover, needleleaved, evergreen	68.0793699	15.9105312	40	68.1379096	15.9091458	39
Fire	Norway	Hamaroy #7	14/05/2010	Tree cover, broadleaved, deciduous	68.1279212	15.4478083	16	68.1414917	15.4470804	16
Fire	Sweden	Jokkmokk #1	15/09/2014	Tree cover, broadleaved, deciduous	67.4174	18.5184	538	67.4503435	18.3223291	538
Fire	Sweden	Jokkmokk #2	11/09/2014	Mosaic tree, shrubs, herbaceous cover	67.4646	18.5345	857	67.416906	18.3858754	848
Fire	Sweden	Jokkmokk #3	26/07/2013	Tree cover, needleleaved, evergreen	66.9734	18.5841	442	67.0460063	18.5682377	575
Fire	Sweden	Jokkmokk #4	20/07/2019	Tree cover, needleleaved, evergreen	66.5875	18.7856	646	66.418626	18.6979224	638
Fire	Sweden	Jokkmokk #5	04/08/2006	Tree cover, needleleaved, evergreen	66.5827	19.0649	392	66.4947546	19.6165936	397
Fire	Sweden	Jokkmokk #6	23/05/2018	Tree cover, needleleaved, evergreen	66.7982	19.0837	306	66.9125085	19.5006217	396
Fire	Sweden	Jokkmokk #7	26/07/2013	Mosaic tree, shrubs, herbaceous cover	66.5832	19.1015	375	66.352234	19.0215632	510
Fire	Sweden	Jokkmokk #8	27/07/2013	Tree cover, needleleaved, evergreen	66.5929	19.1291	390	66.8648453	18.9299377	396
Fire	Sweden	Jokkmokk #9	20/07/2018	Tree cover, needleleaved, evergreen	66.8434	19.1341	306	66.8968979	19.482524	418
Fire	Sweden	Jokkmokk #10	23/07/2018	Tree cover, needleleaved, evergreen	66.9042	19.1396	361	66.9296016	19.6079037	360
Fire	Sweden	Jokkmokk #12	03/07/2006	Tree cover, needleleaved, evergreen	66.6492	19.2017	377	67.1203411	19.3153851	379
Fire	Sweden	Jokkmokk #13	30/06/2017	Mosaic tree, shrubs, herbaceous cover	66.3752	19.2640	472	66.4876178	19.2842256	430
Fire	Sweden	Jokkmokk #14	01/06/2013	Tree cover, needleleaved, evergreen	66.8745	19.2688	387	67.0646739	19.4644282	426
Fire	Sweden	Jokkmokk #15	26/07/2013	Tree cover, needleleaved, evergreen	66.6877	19.2689	333	66.8009919	19.4230148	336
Fire	Sweden	Jokkmokk #16	04/06/2017	Tree cover, needleleaved, evergreen	67.1256	19.4949	380	67.0654386	19.6209267	381
Fire	Sweden	Jokkmokk #17	25/08/2013	Mosaic tree, shrubs, herbaceous cover	66.6445	19.5629	288	66.7346101	19.4905079	288
Fire	Sweden	Jokkmokk #18	01/06/2018	Tree cover, needleleaved, evergreen	66.7323	19.5633	263	66.7247875	19.5941684	270
Fire	Sweden	Jokkmokk #19	29/05/2018	Tree cover, needleleaved, evergreen	66.7172	19.5683	263	66.6938512	19.6247095	265
Fire	Sweden	Kiruna #1	11/07/2005	Tree cover, broadleaved, deciduous	68.2751	18.5310	649	68.3072079	18.6120914	639
Fire	Sweden	Kiruna #2	06/08/2019	Tree cover, broadleaved, deciduous	68.3245	18.8479	535	68.3581305	18.7461337	522
Fire	Sweden	Kiruna #3	17/07/2018	Mosaic tree, shrubs, herbaceous cover	67.8606	19.0840	470	67.8625084	19.1841631	471
Fire	Sweden	Kiruna #4	02/06/2018	Tree cover, needleleaved, evergreen	68.2850	19.3143	343	68.3017119	19.2409176	359
Fire	Sweden	Kiruna #5	13/06/2017	Tree cover, broadleaved, deciduous	67.8697	19.3735	502	67.8734919	19.2569424	499
Fire	Sweden	Kiruna #6	19/06/2015	Tree cover, broadleaved, deciduous	68.2618	19.4089	421	68.2929752	19.4532403	421
Fire	Sweden	Kiruna #7	15/09/2013	Tree cover, broadleaved, deciduous	68.2613	19.4200	403	68.2881537	19.4832035	401
Fire	Sweden	Kiruna #8	04/06/2014	Tree cover, needleleaved, evergreen	68.2420	19.5177	361	68.2338987	19.5812288	360

Appendix III



F1. Example of cloud pixels (white pixels) that have not been detected by the CFMask algorithm (Foga et al 2017). The image is a mosaic of 10 Landsat 7 images from 1st of July to 31 of August 2001.