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Seasonal climate drivers of peak NDVI in a series of Arctic peatlands

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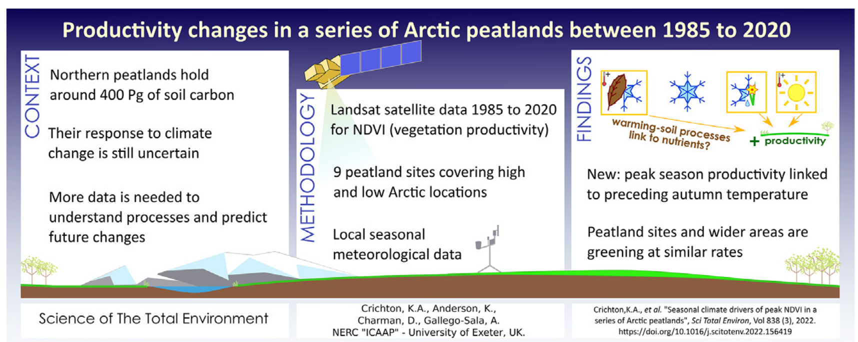
HIGHLIGHTS

- Peat dominant Arctic areas show greening trends similar to wider areas between 1985 and 2020.
- Spring conditions, and summer and previous-autumn temperature are linked to peak growing-season NDVI in Arctic Peatlands.
- Precipitation is not linked to peak NDVI, local hydrology is probably more important.
- Autumn soil processes may be an important factor driving the following growing season's peak productivity.

GRAPHICAL ABSTRACT



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ABSTRACT

Changes in plant cover and productivity are important in driving Arctic soil carbon dynamics and sequestration, especially in peatlands. Warming trends in the Arctic are known to have resulted in changes in plant productivity, extent and community composition, but more data are still needed to improve understanding of the complex controls and processes involved. Here we assess plant productivity response to climate variability between 1985 and 2020 by comparing peak growing season NDVI (Normalised Difference Vegetation Index data from Landsat 5 and 7), to seasonal-average weather data (temperature, precipitation and snow-melt timing) in nine locations containing peatlands in high- and low-Arctic regions in Europe and Canada. We find that spring (correlation 0.36 for peat dominant and 0.39 for mosaic; MLR coefficient 0.20 for peat, 0.29 for mosaic), summer (0.47, 0.42; 0.18, 0.17) and preceding-autumn (0.35, 0.25; 0.33, 0.27) temperature are linked to peak growing season NDVI at our sites between 1985 and 2020, whilst spring snow melt timing (0.42, 0.45; 0.25, 0.32) is also important, and growing season water availability is likely site-specific. According to regression trees, a warm preceding autumn (September–October–November) is more important than a warm summer (June–July–August) in predicting the highest peak season productivity in the peat-dominated areas. Mechanisms linked to soil processes may explain the importance of previous-Autumn conditions on productivity. We further find that peak productivity increases in these Arctic peatlands are comparable to those in the surrounding non-peatland-dominant vegetation. Increased productivity in and around Arctic peatlands suggests a potential to increased soil carbon sequestration with future warming, but further work is needed to test whether this is evident in observations of recent peat accumulation and extent.

1. Introduction

The Arctic has been warming faster than other regions over the last several decades, leading to longer growing seasons, downward trends in ice cover, thawing of near-surface permafrost, and an intensification of the hydrological cycle (Box et al., 2019; Post et al., 2019). These alterations can be observed in, for example, changes in productivity and in plant phenology affecting the timing of flowering and pollination in Arctic plants (Box et al., 2019). Also measurable is a "greening" trend in many Arctic terrestrial ecosystems (Box et al., 2019; Epstein et al., 2013) linked to increasing phytomass but also to changes in plant communities. This widespread trend

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in greening is not uniform across all Arctic locations, and the underlying drivers of vegetation trends are complex and variable (Myers-Smith et al., 2020).

Northern peatlands are an important store of soil carbon, storing around 400 Pg C (Hugelius et al., 2020). Some experimental warming and observational studies show that mosses, a common foundation of high-carbon peat soils at high latitudes, are out-competed by other plant types on warming (Norby et al., 2019), although other studies differ (Hudson and Henry, 2010; Keuper et al., 2011). Particularly in sub-Arctic ecosystems, "shrubification" is a strong driver for upward greening trends (Epstein et al., 2013; Box et al., 2019; Mekonnen et al., 2021) seen in satellite data, where vascular and woody plants become dominant in tundra ecosystems previously dominated by other, often lower-lying plant types. Higher latitude Arctic regions have also undergone shrubification, and shade-intolerant species such as mosses and lichens may be outcompeted by these larger, taller-canopy plants (Mekonnen et al., 2021). However, studies of past responses to changing climate conditions in the late Holocene show that peat carbon accumulation increased during warmer conditions, suggesting that overall productivity increased with higher temperatures, regardless of the plant community present (Charman et al., 2013; Gałka et al., 2018; Gallego-Sala et al., 2018; Taylor et al., 2019).

An additional complexity in Arctic ecosystems is the impact of permafrost processes, where warming can affect soil moisture content, nutrient availability, and even topography (Box et al., 2019). High Arctic and low or sub-Arctic sites can be affected differently by changes in permafrost, depending on whether they are directly underlain by permafrost, how deep the active layer depth is (the thawed layer during the warm season), and the rate of soil warming.

Arctic plant communities vary depending on local conditions, with generally colder drier regions presenting lower diversity and density, and milder conditions often incorporating a higher number of species and greater functional diversity (Callaghan et al., 2004). Furthermore, *Sphagnum* and other peat forming plants can act as ecosystem engineers, altering their environment, increasing soil moisture content, and keeping soil nutrient levels low, impeding the growth of vascular plants (Malmer et al., 2003). There is also evidence suggesting that Arctic plant communities adapted to specific environments can respond differently to similar changes in climate (López-Blanco et al., 2020), and generally of a "heterogeneous and divergent response of Arctic vegetation to climate change" (Beamish et al., 2020).

Vegetation dynamics are often measured using satellite data where metrics such as the Normalised Difference Vegetation Index (NDVI) can be used as proxies for chlorophyll activity, and can thus be used to indicate plant productivity. NDVI has been linked to aboveground biomass in the Arctic (Walker et al., 2012), to point phytomass in Svalbard (Johansen and Tømmervik, 2014) and with primary productivity in the high Arctic (north-east Greenland, Westergaard-Nielsen et al., 2017), so peak growing season NDVI can be a interpreted as a proxy for peak above-ground productivity for Arctic sites.

Long datasets for NDVI come from the Landsat programme with nearly 50 years' worth of data since 1972. Freely available Landsat data are provided at a pixel resolution of 30 m (since 1984 for the Landsat 5 TM sensor), and can be applied to site (e.g. Crichton et al., 2015), regional (Nyland et al., 2018), pan-Arctic (Paltan et al., 2015; Berner et al., 2020), or continental-level studies (Bolton et al., 2020). Other multispectral sensors such as the MODIS sensor, that offers a coarser spatial resolution (from 250 m pixel resolution) than Landsat but improved temporal monitoring, has been applied to studies of land cover changes in the pan-Arctic (Jenkins et al., 2020; Myers-Smith et al., 2020). The underlying causes of trends in greening metrics such as NDVI are very much scale-dependent (Myers-Smith et al., 2020), which can present problems for the interpretation of satellite data, especially for coarser grained data from instruments such as MODIS (Wang et al., 2018; Myers-Smith et al., 2020). Further, finer scale data are (often out of necessity) biased to certain well-studied sites (Post et al., 2019), leaving many areas of the Arctic un-studied. Due to the complexity of the climate-ecology interactions in the Arctic region (Beamish et al., 2020), more remote sensing data analyses are needed to improve understanding of the drivers and feedbacks of changes in Arctic plant communities in response to anthropogenic warming (Post et al., 2019).

Work is still needed to understand the driving mechanisms and processes that control Arctic peatland vegetation productivity and the region's capacity as a carbon sink or source under past conditions, and under current and future anthropogenic warming. This study is part of a project (ICAAP - Increasing Carbon Accumulation in Arctic Peatlands) that aims to test whether Arctic peatlands are expanding and/or increasing their carbon accumulation function in response to recent (and 20th century) warming. We measure changes in NDVI over the last ~35 years in 9 Arctic locations that contain areas of peatland, to test whether there are detectable changes in vegetation productivity and whether these are driven by inter-annual climate variability. In particular, we pose the following research questions: 1. Do Arctic plant communities show "greening" trends (we term "greening" as an increase in NDVI in a pixel over the timeseries studied), and are the peatland plant communities' trend similar to the wider (not peatland-dominated) area trends? 2. Is peak growing-season productivity (as NDVI) linked with specific seasonal climate drivers?

2. Methods

2.1. Overview

We sample a series of Pan-Arctic locations to measure productivity and climate-productivity links to consider trends and relationships that may be common to these habitats. This work is part of a wider project that is also collecting field data as peat cores, to consider changes in carbon accumulation and extent, the findings of which will be compared against satellite data at a future date.

We measured peak NDVI in the growing season as an indicator of maximum growing season productivity.

To test whether trends in peak-NDVI are apparent over the last 35 years, we applied a simple linear regression to the annual-mean peak-NDVI, and carried out the Mann Kendall test. To test whether there are links between variability in climate and peak-NDVI we performed statistical analyses in the form of multiple linear regression (MLR) and regression trees, considering links between annual mean peak-NDVI and seasonal climate parameters and snow melt timing.

The climate parameters we use are based on data measured from climate stations, with time-series of comparable length to the satellite-based NDVI dataset. As such, we only consider seasonal climate (as temperature and precipitation) and snow melt timing (based on a satellite measure of the number of pixels identified as snow in the study areas). We do not consider PAR0 as a climate driver (identified as important in determining productivity by Charman et al., 2013), as this requires data on cloud cover that is not possible to reconstruct from Landsat data (for a 35 year timeseries) with a high enough level of confidence, due to gaps in the data (driven by the return time for the Landsat 5 and 7 satellite, and by the lack of cloud cover data in many meteorological stations).

2.2. Sites

We collected data from four Arctic regions, focusing primarily on two European regions where we have remotely sensed and additional field data, supplemented by two Canadian sites where we used only remotely sensed data. In Europe, we sampled at four sites in Svalbard (High Arctic) and three sites in Lapland (Low Arctic). Two supplementary individual sites were sampled in Canada: in the High Arctic (Bylot Island in Nunavut) and in the Low Arctic (Salluit in Nunavik), making nine sites in total (Fig. 1).

To compare areas with peat to the wider landscape at each site we first selected a likely-peat ("small peat") area for each site (based on our field

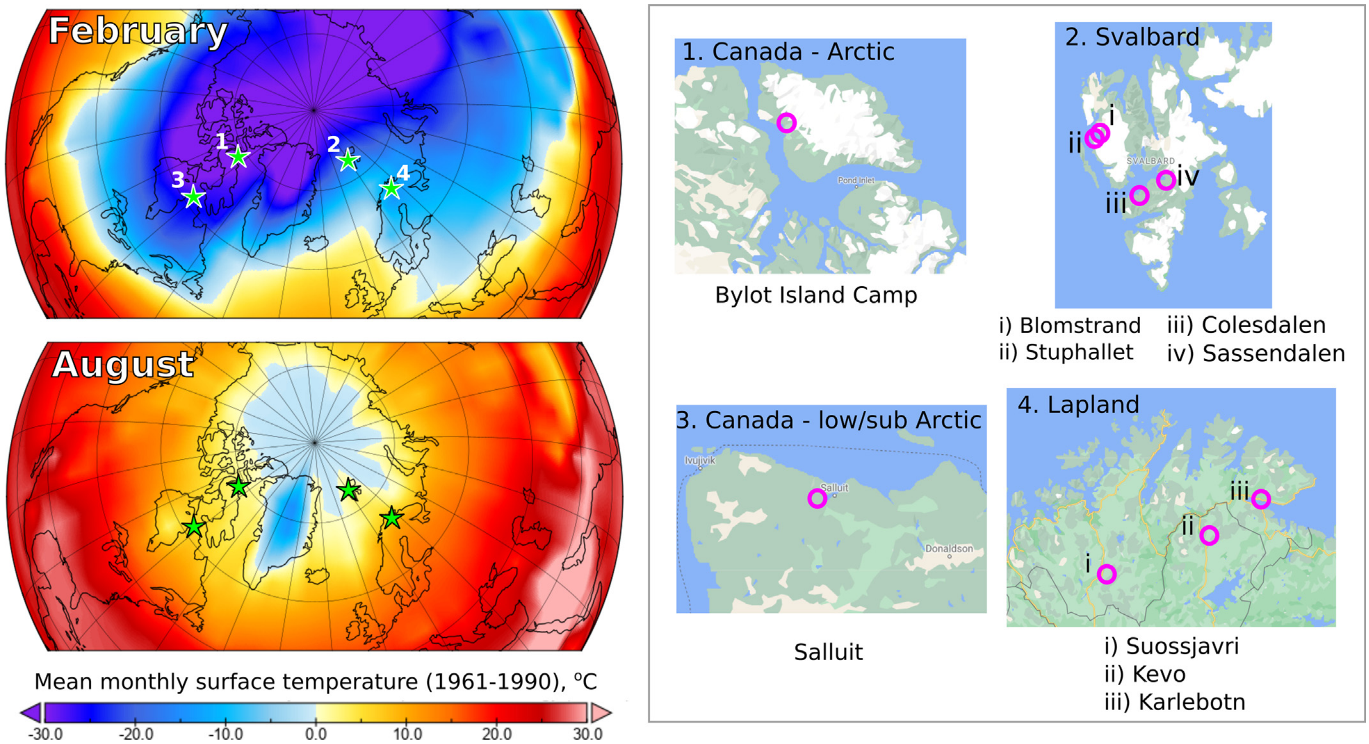

Fig. 1. Regions with study sites in the ICAAP project, locations overlaid on 1961–1990 CRU mean monthly surface temperature climatology for February and August (New et al., 2000). Location of field sites in each region included in this study listed per region. (Maps from Google Maps).

data), as well as a wider area containing multiple ground cover types ("large mosaic"). For sites in Canada, where no ground-based validation was possible due to travel restrictions, the peat area was selected as a small area with particularly high NDVI relative to the wider area. For Salluit, this peat area is classified as grassland with some herbaceous wetland in the ESA Worldview classification; the Bylot small peat area is classified as herbaceous wetland (Zanaga et al., 2021).

We characterise present day plant communities based on field data (from summer 2019) in the main text (Table 1); present-day field photographs and the orthomosaic of our peat areas from drone images are available in supplementary information (SI) Figs. S4 to S6.

2.3. Climatological characteristics, land cover and plant communities at the study sites

The location of the study sites and mean February and August temperatures (for 1961 to 1990, near the start of our timeseries data in 1985) are shown in Fig. 1, illustrating the far colder winter climate in the Canada locations relative to the European ones. The mean annual climate conditions for the years 1985 to 2020 from data collected for this study are shown in Fig. 2, as well the location of the meteorological stations relative to the study sites. A summary of the characteristics of each study site is provided in Table 1.

2.4. Retrieving NDVI data

We create mean-area NDVI timeseries from the Landsat satellite data (at 30 m pixel size), from 1985 to 2020, by combining data from the TM and ETM+ sensors (Claverie et al., 2015). We apply an adjustment to the Landsat 5 data using that proposed by Ju and Masek (2016) based on Arctic-Boreal region data in North America. This correction accounts for small differences in near infrared (NIR) between the two satellite sensors (Ju and Masek, 2016) where Landsat 5 NIR reflectance was relatively smaller than the Landsat 7 NIR over high latitude Canada and US Alaska. As our data is also from high-latitude locations, we applied their proposed correction to Landsat-5 NDVI. This adjustment acts to raise slightly the NDVI values as measured by Landsat 5 (see SI B for a summary of the effect of this correction). We did not include images from Landsat 8 due to the differences between NDVI in Landsat 8 OLI and Landsat 5/7 TM/ETM+ sensors, which were present even after applying a widely-used generalised correction (Roy et al., 2016; see SI section C. and Fig. S3).

The mean-area NDVI was calculated by finding the NDVI in each pixel in the defined area (that is cloud, snow and water-free at every point in our timeseries, Fig. S1, but not discounting scenes that have some cloud, allowing us to maximise the number of datapoints) and taking the arithmetic mean (see SI A for a full description of the methods employed). The number of pixels making up each of these areas is summarised in Table S1. The timeseries is for peak growing season only, determined as being between day 190 and 230 of the year (the 9 July to the 17 August for 2021, as an example) at all our sites. The day of year was identified from inspection of Sentinel-2 seasonal NDVI profiles such that peak NDVI values fall within these bounds at all our sites.

We have used Landsat Collection 1 to create this timeseries; at the time this study was carried out Landsat Collection 2 was not available through Google Earth Engine (GEE) (Gorelick et al., 2017) where algorithms to process multiple images efficiently can be applied. Landsat Collection 2 is now also available on this platform, but we had already completed all analysis when it became available (see SI B. for a comparison of the NDVI results for these two collections, we are confident that using collection 1 is not detrimental to our study). We found that in both collections, georeferencing was very inaccurate for large amounts of Landsat 5 data over Svalbard, so applied a different method to extract NDVI data there (see SI A.).

We also extracted NDVI from the Sentinel-2 satellite (at 10 m pixel resolution) and for a visual comparison plotted these against 10-day running-mean temperature, the snow fraction, and the hours of daylight. The Sentinel-2 satellite provides a shorter return-time over the sites, so provides more information on phenology, green-up and senescence, but has a maximum of 6 years of data so we do not focus statistical analysis on it.

Table 1
Overview of our study sites, area description and brief summary of plant communities present.

Site	Climate	Description	Plant communities
Svalbard			
Blomstrand	Continuous permafrost zone. High Arctic	Blomstrandhalvoya is an island located in Kongsfjorden. It has some areas of vegetation cover mainly on flat or low sloping ground towards the coast, but also has extensive areas of bare rock with sloping ground rising towards the centre of the island. The peat site is on gently sloping ground, beneath low cliffs (cliffs located to the east of the peat site).	Small peat area: vegetation height 1 to 5 cm, majority mosses, with some grasses and few vascular plants, no shrubs. Large mosaic area: mostly bare ground, with some areas of flowering plants/peat forming plants and lichens.
Stuphallet	Continuous permafrost zone. High Arctic	The large site is a peninsula in Kongsfjorden, some 5 km from Blomstrandhalvoya and Ny Alesund. The peat site is next to the coast inside a post-glacial moraine, on a raised beach beneath cliffs (cliffs located to the south-west of the peat site) populated by birds in the nesting season.	Small peat area: vegetation height 0 to 5 cm, mosses dominant (including dry mosses), some vascular plants and few grasses, no shrubs. Large mosaic area: mostly bare ground with some areas of flowering plants/peat forming plants and lichens
Colesdalen	Continuous permafrost zone. High Arctic	The large site is a glacial river valley located in Ijsfjorden, to the east of Longyearbyen. The peat site is located on shallow sloping ground down from the foot of cliffs, not far from the mouth of the river.	Small peat area: majority mosses, with few vascular plants and few grasses, no shrubs. Large mosaic area: post-glacial valley, with valley floor vegetated with mosses/vascular plants, generally vegetation free upper slopes to surrounding higher ground/mountains.
Sassendalen	Continuous permafrost zone. High Arctic	The large site is a glacial valley to the west of Longyearbyen, the small peat area is located on a raised beach on a small headland along the coast from the river mouth.	Small peat area: majority mosses, with some vascular plants Large mosaic area: from the shoreline, vegetated ground rising towards lower mountain slopes, on higher inclined slopes little vegetation.
Lapland			
Karlebotn	Discontinuous/sporadic permafrost zone. Low Arctic	The large site encompasses an area between the Varangerfjorden and the Tana river, with a mix of wide valleys and some higher ground. The peat site, a palsa mire, is located ~5 km to the west of Karlebotn on mostly flat fairly low-lying ground, with some gentle slopes.	Small peat area is a mix of palsa-top-like vegetation (small shrubs and lichens), and mosses and grasses on lower wetter ground; peat forming with varying accumulation rates. Large mosaic area: similar to peat site but with areas of small trees and shrubs and river banks generally dominated by tree cover.
Kevo	Discontinuous permafrost zone. Low Arctic	The large site is to the west of Kevo, a combination of raised gently sloping and flat ground. The peat site is located ~5 km to the north-west of Kevo on raised, but mostly flat ground.	Small peat area is a mix of palsa-top like vegetation (small shrubs and lichens), mosses and grasses on lower/flatter wetter ground, and scattered low woody plants. Large mosaic area: similar to peat site, but in the valley and on lower ground more trees and shrubs.
Suossjavri	Discontinuous permafrost zone. Low Arctic	The large site encompasses the Suossjavri lake, and land surrounding, which includes some raised ground and the wide river valley. The peat site is to the west of the lake on flat ground.	Small peat area: Areas of mixed plant types, mosses, grasses, and low woody plants. Large mosaic area: similar in appearance to peat site but with more shrubs and trees.
Canada			
Bylot	Continuous permafrost zone. High Arctic	Bylot is a high-Arctic research station. The area selected is near the base camp in a post glacial valley on mostly flat or low sloping ground. The peat site was identified by selecting an area with particularly high NDVI, it is near the glacial river mouth and high resolution satellite images indicate it is extensively patterned as ice-wedge polygons.	Both small peat and large mosaic areas are classified as Herbaceous Wetland in ESA Worldview (Zanaga et al.2021), but highest NDVI values are seen in the small likely-peat location
Salluit	Continuous permafrost zone. Low Arctic	The area is low-Arctic tundra. Possible peat site identified by selecting very high (relative to other areas in the images) NDVI locations. This site is in a river/glacial valley, sloping towards the river.	The ground appears to be wholly vegetated (except near the river sediment depositional areas) without any clearly-evident ground patterning. Classified as grassland and herbaceous wetland in ESA Worldview (Zanaga et al., 2021)

2.5. Climatological data

Climate data were retrieved from meteorological stations located near to the field sites (Fig. 2, and see SI A.3). For each site, the selected station was one that provided long-enough time series data to allow a meaningful statistical comparison between our 35-year peak-NDVI timeseries and seasonal temperature and rainfall patterns.

Data from meteorological stations show that the sites experienced differing conditions over the 1985 to 2020 year range investigated, with low Arctic sites warmer than high Arctic sites (as expected), Canadian sites cooler than European sites, mean precipitation being site-dependent, and Svalbard sites showing the latest snow melt (Fig. 2). However, through all our sites (although not always statistically significant) annual mean temperature increased, annual precipitation increased, and the first snow free day of the year occurred earlier over the period 1985 to 2020.

Seasonal average weather and trends for the years 1985 to 2020 corresponding to each of the study sites are show in Fig. 3. We present the data starting from autumn (SON) for consistency, as we want to focus on seasonal climate running up to the summer peak growing season in any year, not after it. The seasonal data (Fig. 3) revealed further differences between our sites, particularly the colder winter and spring temperatures in the Canadian sites, compared to the European sites.

2.6. Statistical analyses

We carried out linear regressions, and the Mann-Kendall test (in Matlab using algorithm from Fatichi, 2021) for underlying trends for the NDVI timeseries data using annual-mean values, and for the mean-adjusted (to account for changes in NDVI over the timeseries and differences between sites) standard deviation for our NDVI timeseries.

We used the annual-mean peak NDVI value from pixels in each of our sites (see SI A.4), and compared this to seasonal mean climate indicators of temperature and precipitation, as well as to an indicator of spring snow melt timing that we created using Landsat's pixel classifier band for surface reflectance data (see SI A.2). To consider controllers on productivity common to all the sites, we standardised the annual-mean NDVI and climate data for each site (using the site-specific mean and standard deviation of each timeseries) and collated this standardised data to create one All-sites dataset. Using this standardised data, we performed statistical analyses on the relationships between NDVI and climate parameters. For climate parameters, we considered all seasonal data in the year before the growing season peak NDVI, and also included the previous summer conditions, and timing of snow melt. More information on these methods can be found in the SI section A.4.

To evaluate correlations between and within the NDVI and climate parameters, we performed a Principal Component Analysis (PCA) and created

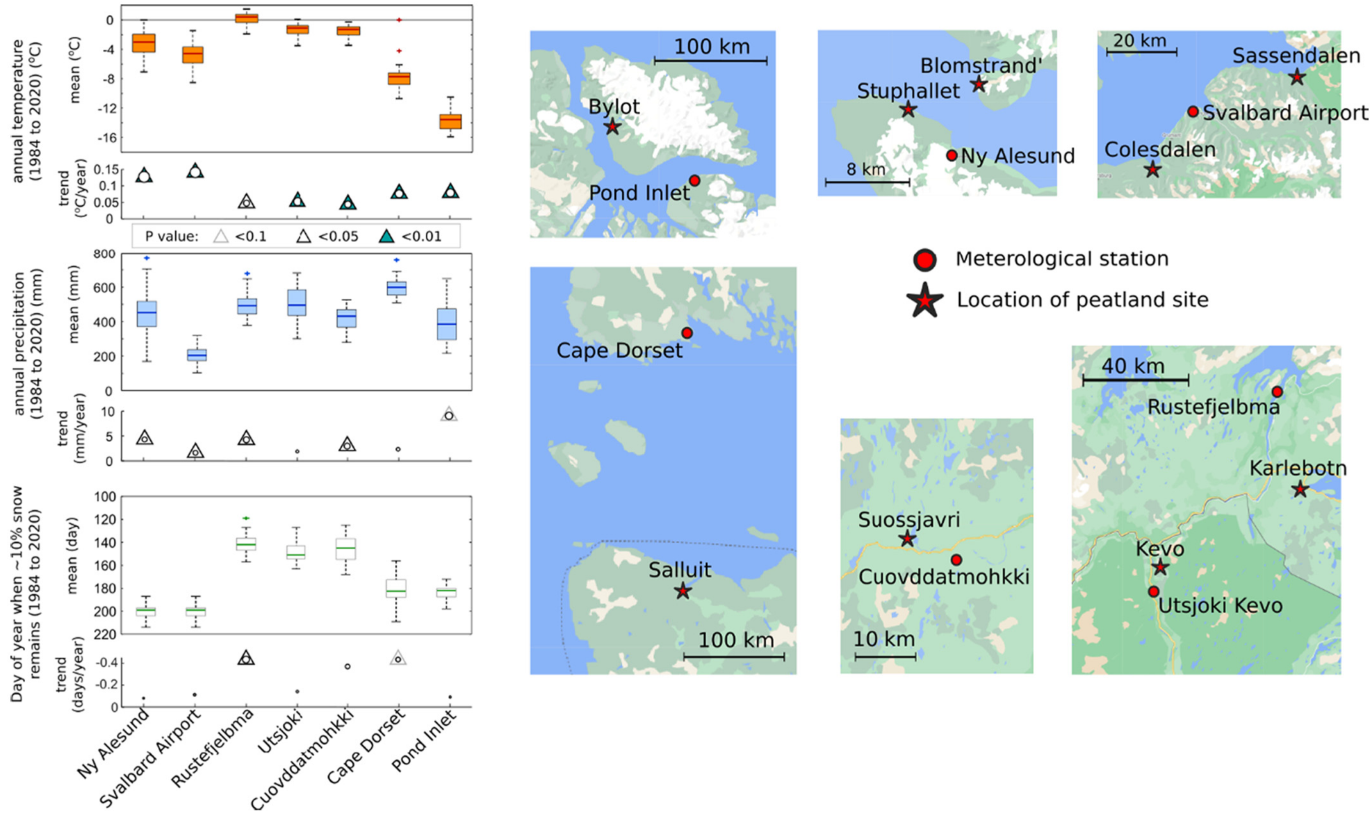

Fig. 2. Mean annual climate and locations for meteorological stations located in the vicinity of our field sites in the years 1985 to 2020, the selected meteorological stations are those with sufficient timeseries data for seasonal temperature and precipitation for statistical analyses against our NDVI data. The size of the circle on the meterological trends charts indicates the R^2 for the linear regression; a large circle is a high R^2. *p* value for significance of the linear trend is indicated by triangles. Maps from Google Maps.

correlation tables in R on our standardised dataset. To consider possible climate drivers of peak-NDVI, we further carried out multiple linear regression (MLR) analyses on the datasets also in R, looking at all the sites together (but maintaining the split into the large mosaic and small peat areas), and looking at groupings per region (i.e. Svalbard, Lapland, Salluit, Bylot) (see SI A.4).

In order to consider differences between our sites in growing season patterns, we created NDVI timeseries (in GEE) covering the last 5 to 6 years using Sentinel-2 data. We compared the growing season NDVI data to temperature and snow fraction over the growing season (see supplementary information A.5).

3. Results

3.1. Trends in NDVI from Landsat

NDVI increased in the period 1985–2020 in almost all sites but with differing statistical significance (Figs. 4 and 5). Positive trends in NDVI are apparent in both Canada sites, in two Svalbard sites (Colesdalen and Sassendalen), and in the Suossjavri Lapland site (according to the Mann Kendall trend analysis Fig. 5). Trends within the timeseries can be seen in some areas (Fig. 4), for example at Karlebotn large mosaic area, NDVI increases between 1984 to the early 2000s are followed by several years of falling NDVI. In all the Lapland small peat areas, a fall in NDVI is seen from the mid 2000's to around 2010. The trends seen in the NDVI timeseries are similar to those in other productivity-linked vegetation indices that we calculated for the Lapland and Canada sites only, see Fig. S7, showing Tasselled Cap Greenness, MSAVI2 (Modified Soil Adjusted Vegetation Index 2) and also GCC (Green Chromatic Coordinate) timeseries that we calculated as a cross-validation exercise.

The strongest trends in both NDVI and the standard deviation of NDVI are seen in the two Canada sites, and especially in the small peat areas. The standard deviation of the NDVI (shown as error bars in Fig. 4, and plotted in full in supplementary Fig. S8) indicates changes in NDVI distribution per pixel within each site. Where a statistically significant trend in the standard deviation of NDVI is found (Fig. 5), all show reductions; a reduction means that pixels within the study areas are becoming more similar to each-other, a rising standard deviation means they are becoming more dissimilar.

A subset of sites is displayed in Fig. 6 showing fine scale real-colour satellite images (from Mapcarta.com), and NDVI data for two images separated by about 20 years to demonstrate changes in spatial patterns of NDVI on the ground. The Blomstrand small peat area shows no significant trend in NDVI, but a possible increase in dissimilarity between pixels (Fig. 5). From the NDVI map (Fig. 6), it appears that NDVI is increasing in certain specific places within the peat bog, and possibly reducing in others with no clear change near the edges of the peat bog between 1985 and 2006.

At Colesdalen, NDVI shows a significant positive trend, but for the large mosaic area no statistically significant trend in similarity (or dissimilarity) between pixels (Fig. 5). The NDVI map of Colesdalen (the map shown here is larger still than the "large" area used to create our timeseries data – see supplementary Fig. S4) shows clearly increasing NDVI particularly moving upslope and on to higher ground in 2006 compared to 1985 (Fig. 6, an upslope Colesdalen area example is circled in the NDVI images).

Karlebotn small peat area shows a possible increasing NDVI and an increasing standard deviation of NDVI per pixel (Fig. 5). On the NDVI maps for 1986 and 2005 it appears that some already high NDVI areas have further increased, whilst others have decreased, and others show little change (Fig. 6). This site is partially underlain by palsas, which may have affected NDVI locally due to local thawing/slumping (Olefeldt et al., 2021; Beamish et al., 2020).

Bylot peat area shows strong trends in both NDVI and increasing similarity between pixels (Fig. 5). The NDVI maps show a general increase in

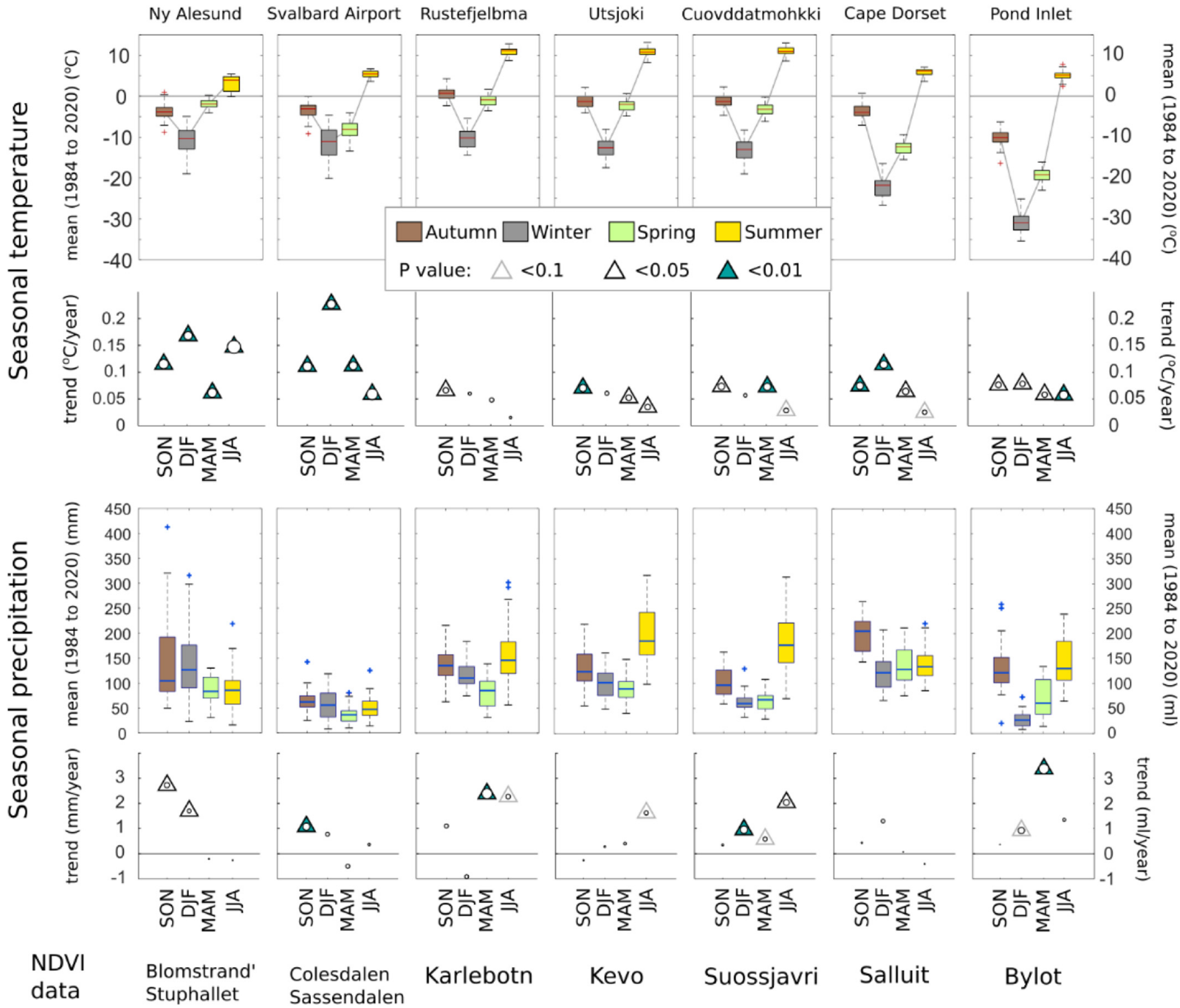

Fig. 3. Mean seasonal climate conditions, and trends. Size of the trend point indicates the R^2 of the linear regression (the trend is simply the gradient of the linear regression line), a larger circle is a higher R^2. *p* values for the significance of the trend are indicated by a triangle.

greenness everywhere, and particularly in places with lower NDVI in 1985 (some patterned ground can be identified even at this 30 m pixel resolution and gullys/frost cracks are greener than the neighbouring pixels in 1985, but the difference becomes less obvious by 2006).

3.2. Landsat NDVI-climate analysis

The PCA biplots for the large mosaic and small peat areas standardised annual-mean NDVI and our standardised climate parameters all collated together ("all data") are shown in Fig. 7. The angles between vectors indicate the correlation between parameters (shown in full in correlation tables supplementary Fig. S9), whilst the vector length shows their weight on that principal component. There are correlations between many parameters, but peak NDVI is not correlated with previous autumn, winter and spring precipitation. For both the large mosaic and small peat areas, summer temperature is correlated with peak NDVI (correlation 0.42 for the mosaic, and 0.47 for the peat areas). Except for previous-summer precipitation, all vectors are negative on PC1, and (roughly) climate components are separated into precipitation and temperature in vector direction. On the biplot are also site-specific datapoints, showing no particular clustering per site.

These principle components describe our full dataset, but we are interested in whether the variability in climate parameters can describe variability in the NDVI data, so we apply multiple linear regression analyses.

MLR results are generated using both: 1) the NDVI dataset including all datapoints, and 2) the NDVI dataset requiring a minimum of 2 points per year (except for Svalbard, where we use all datapoints for both sets due to the different method used to extract NDVI data, see SI A.). Using all datapoints gives us more data for the analysis, but may include more noise in the data due to uncertainties in the exact timing of the peak summer productivity. For every MLR, the F-statistic has a *p*-value of <0.05 (Fig. 8 and Table 2). The regression coefficient ("coeff" in Fig. 8) of each standardised climate parameter indicates the strength of the control on $NDVI_{stnd}$, so for example a coefficient of 0.3 means for every percent increase in that (standardised) climate parameter, $NDVI_{stnd}$ increases by 0.3 %. The *p*-value describes the statistical significance of this relationship; *p*-values lower than 0.05 mean a 95 % confidence level or better.

The timing of spring snow-free conditions, spring temperature, summer temperature and the previous Autumn temperature have a statistically significant ($p < 0.05$) relationship to peak-NDVI for both large mosaic and small peat areas for all-sites data (we favour the 2+ datapoints NDVI

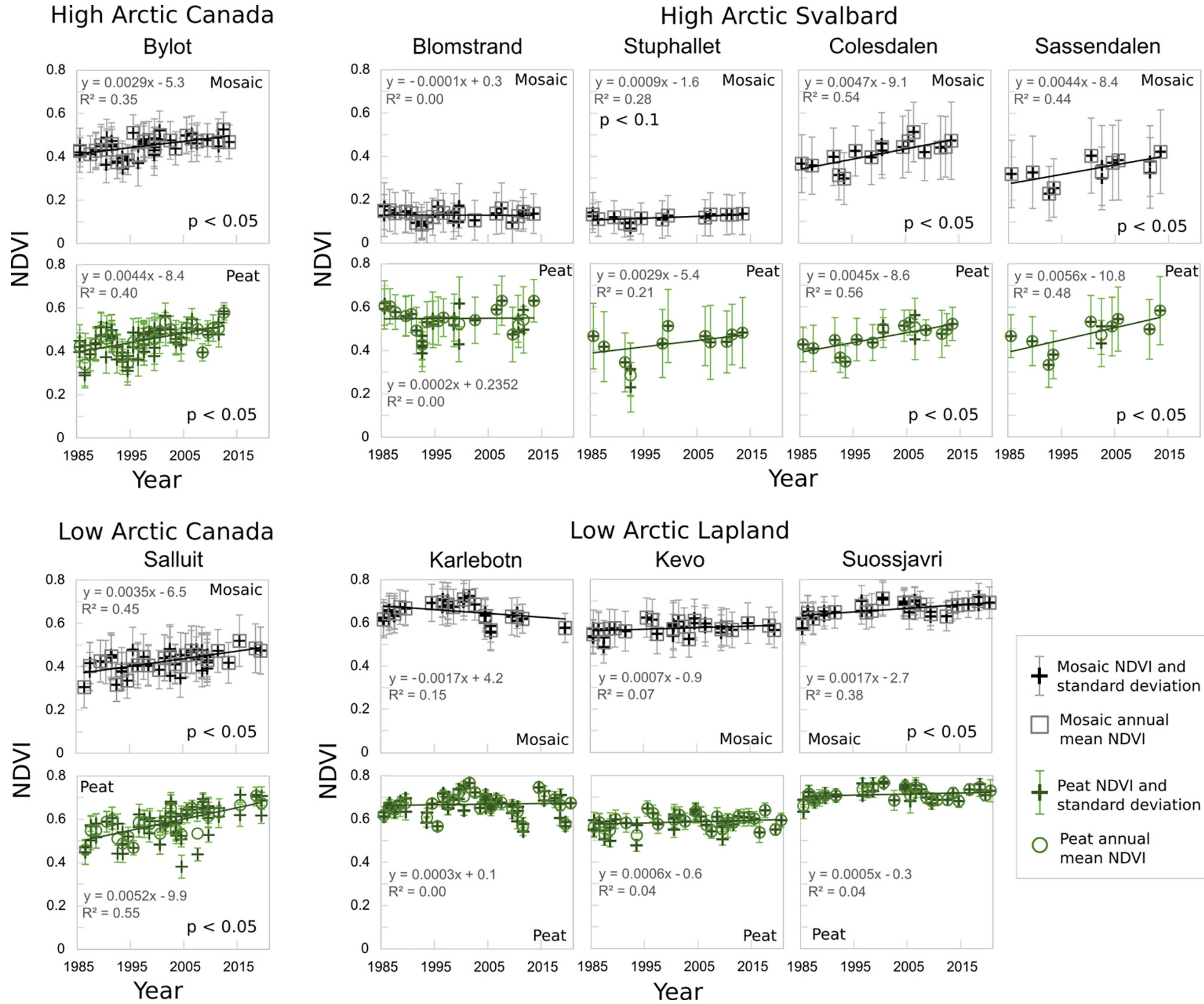

Fig. 4. Peak-growing-season (day 190 to 230) mean NDVI values for small peat and large mosaic areas, with standard deviation shown as error bars. Linear regressions shown as dashed line with equation and R^2 labelled for each. *p* value for the statistically significant linear-regressions is also shown.

dataset, and *p*-values <0.05) (Fig. 8). The previous Autumn temperature appears important for all regional groups for the peat areas, except for Salluit, whilst Summer temperature is an important predictor for peak-NDVI for all regional groups for the mosaic areas, except Svalbard. Snow melt timing appears less important for the low-Arctic Lapland region, but is an important driver of peak-NDVI in all other regional analyses. Seasonal precipitation parameters also appear less important for NDVI in the Lapland region than in other regions. In the low Arctic sites, winter temperature appears to be negatively related to NDVI (i.e. a cold winter is linked to a higher NDVI), whereas in the large mosaic Svalbard areas this relationship is reversed (i.e. a warm winter in linked to a higher NDVI). In all cases where it appears, a high winter precipitation is linked to a lower peak NDVI.

Differences between the leading drivers of peak NDVI between the All-sites mosaic and peat areas may be attributable to the different response of vegetation communities, and land cover on the ground. We discuss this further in relation to regression tree results and in the discussion section.

The Canada sites have far fewer datapoints than other regional data (being only one site each) (Fig. 8) which leads to more variability in the results between the all-years data (in blue) and 2 + points per year data (in orange) compared to other regions. Due to the relatively small number of datapoints in much of the regional datasets, we avoid overanalysing the results and focus on the All-sites datasets. For better site-specific analyses, we would require more datapoints than we have available, so especially the Canada site MLR data shown in Fig. 8 should be considered with caution.

To consider underlying universal relationships between climate and Arctic vegetation response in our dataset we apply the MLR (multiple linear regression) with the All-sites dataset to build regression trees (in R) using the climate parameters identified as statistically significant. These climate parameters for both the large mosaic and small peat areas are: Summer temperature, snow melt timing, previous autumn temperature and spring temperature (see Fig. 8).

For the large mosaic areas (Fig. 9), the first decision node is for snow-melt timing, suggesting a very late snow melt greatly limits the potential peak season productivity. For a very late snow-melt, a warm previous autumn prevents NDVI being at its lowest value. For the higher predicted NDVI, spring temperature is high, previous autumn is not cold (near or above average for the dataset), and the timing of snow free days should not be early in the growing season. A very warm summer temperature then leads to the highest predicted peak NDVI.

For the small peat areas, the first determinant is also snow-melt timing, with a very late snow melt impeding a high NDVI (Fig. 10). Again as for the mosaic areas data, a warm previous autumn can maintain NDVI levels if snow-melt was very late. For the highest predicted NDVI values, unlike the mosaic areas, only a non-cool (rather than warm) summer temperature appears important, with a warm previous autumn determining whether the

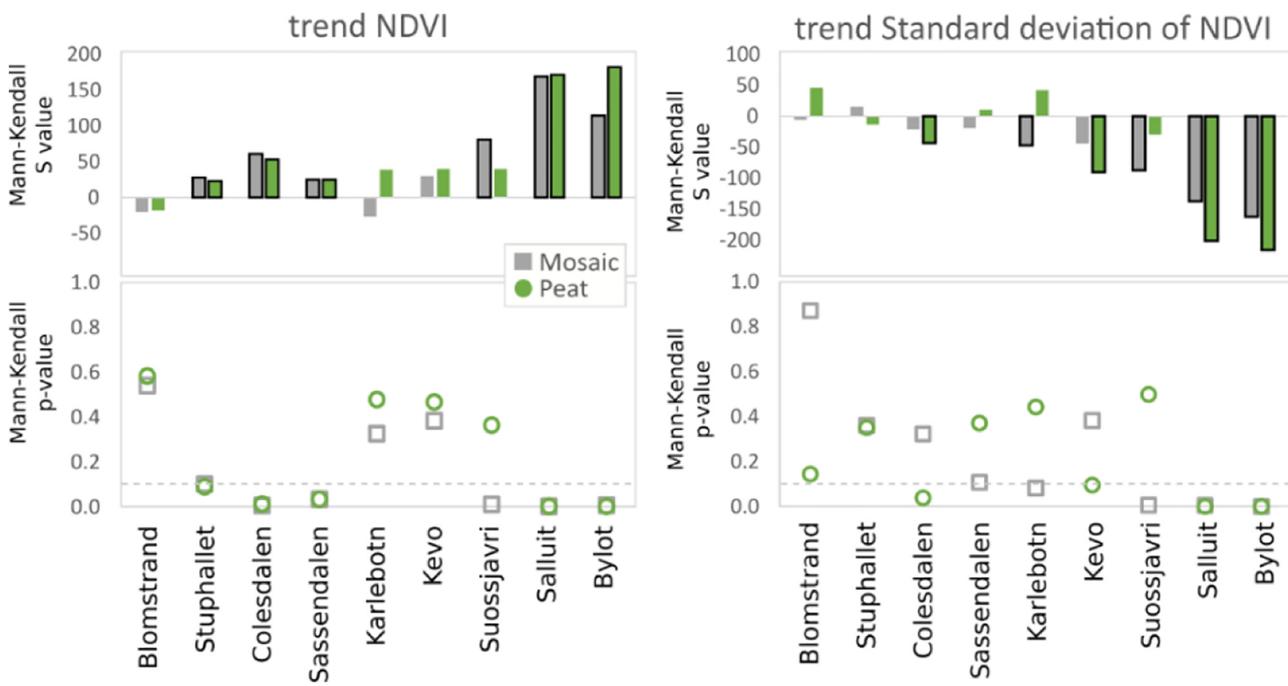

Fig. 5. Mann-Kendall trend analysis for annual mean NDVI and for the annual mean standard deviation of NDVI for each site. S value is affected by the strength of the trend, but also by the number of datapoints. P value for significance also shown, with 90 % confidence level (p-value < 0.1) shown as a dashed line. S value bars with >90 % confidence are outlined in black. Mann-Kendall statistics calculated using Fatichi (2021) in Matlab.

highest NDVI value is reached. A cool summer and a cold spring results in low NDVI, but a cool, average or warm spring (combined with a cool summer) maintains predicted NDVI around average. For an average summer, and an average autumn temperature, an early snow-melt greatly reduces the predicted NDVI even when spring is warm.

We use the regression tree to predict $NDVI_{stnd}$ from only these limited climate parameters to identify the residual error. Fig. 11 shows cross plots for the satellite-measured $NDVI_{stnd}$ (standardised NDVI, y axis) and the climate-NDVI-model predicted $NDVI_{stnd}$ (x axis). As would be expected, the measured $NDVI_{stnd}$ values on the extremes of our dataset are not well represented by the climate-NDVI model. Despite this, the climate-NDVI model appears to capture the general trends in the measured data; with correlations of 0.64 and 0.69 and RMSE of 0.78 and 0.71 for the large mosaic and small peat areas respectively. Site-specific climate-NDVI model predicted values are given in Fig. S11.

3.3. Green-up and senescence patterns from Sentinel-2

Using Sentinel-2 data, we next focus on the small peat areas only to consider phenology patterns. Within-season NDVI data along with temperature data (plotted as a 10-day running mean), and snow fraction (for small peat area) are shown in Fig. 12. Due to the high latitude locations of the sites we also show the hours of available daylight at each site per day.

A late local snow melt is accompanied by a delayed green-up in several of the sites (for example 2019 in the Svalbard sites shown as yellow circles), but not necessarily a lower peak NDVI (for example 2020 in the Bylot site, shown as orange crosses). The drivers of the timing of senescence varies between sites, but generally peak NDVI coincides with peak-temperature. In Lapland sites, senescence coincides temporally with both falling temperature, and falling hours of daylight. Senescence at Stuphallet occurs faster than at Blomstrand, despite being located very close to it, and faster than other Svalbard sites too. This may be due to the cliffs located to the south-west of the peat site that may reduce light availability sooner in the year due to shading. The end of the growing season (i.e. when NDVI falls to minimum) occurs early when snow fraction increases early (for example Blomstrand 2019, Bylot 2016 to 2018), but falling NDVI after its peak generally appears coincident with falling temperature at all sites.

The effect of a warmer previous autumn may be visible in these seasonal patterns, where a warmer autumn still results in high peak-NDVI despite a late start to the growing season. For example, Bylot shows a warm autumn 2019, and a late green-up in 2020, but high peak NDVI in 2020. Conversely, a warm summer in 2019 at Bylot is seen with a relatively early green-up, but autumn 2018 was the coolest of the years plotted, and peak NDVI in 2019 is much lower than 2020. This may also be seen at Stuphallet and Blomstrand, where a lower peak-NDVI in 2020 (despite warm summer) could be linked to a cooler autumn 2019, although this pattern is not clearly evident at Colesdalen and Sassendalen for the same years.

4. Discussion

We address each research question in turn, first looking at changes in NDVI over the timeseries, and then at links between variability in NDVI and climate over the period 1985 to 2020.

4.1. Research question 1: Do Arctic plant communities show “greening” trends and are the peatland plant communities' trend similar to the wider area trends?

We found statistically significant “greening” (indicating increased NDVI) trends at 5 (out of 9) of the large mosaic areas, and 4 (out of 9) of the small peat areas using the Mann Kendall test (Figs. 4, 5, at 95 % confidence level). This includes sites that are moss dominant, that sustain a mix of plant communities or a mix of vegetated and non-vegetated ground (Table 1), and that are characterised by patterned ground. The sites that did not show statistically significant greening trends were moss-dominant peat sites (Blomstrand and Stuphallet small areas), a mix of bare ground and vegetated ground in the high Arctic (Blomstrand and Stuphallet large areas), and fully vegetated mixed plant-type low arctic sites (Lapland sites). We did not identify “browning” (a statistically significant trend of reducing peak-NDVI). The observed greening pattern is in agreement with other published work, showing a general greening trend in the Arctic, with browning found to be far less pervasive than greening (Myers-Smith et al., 2020).

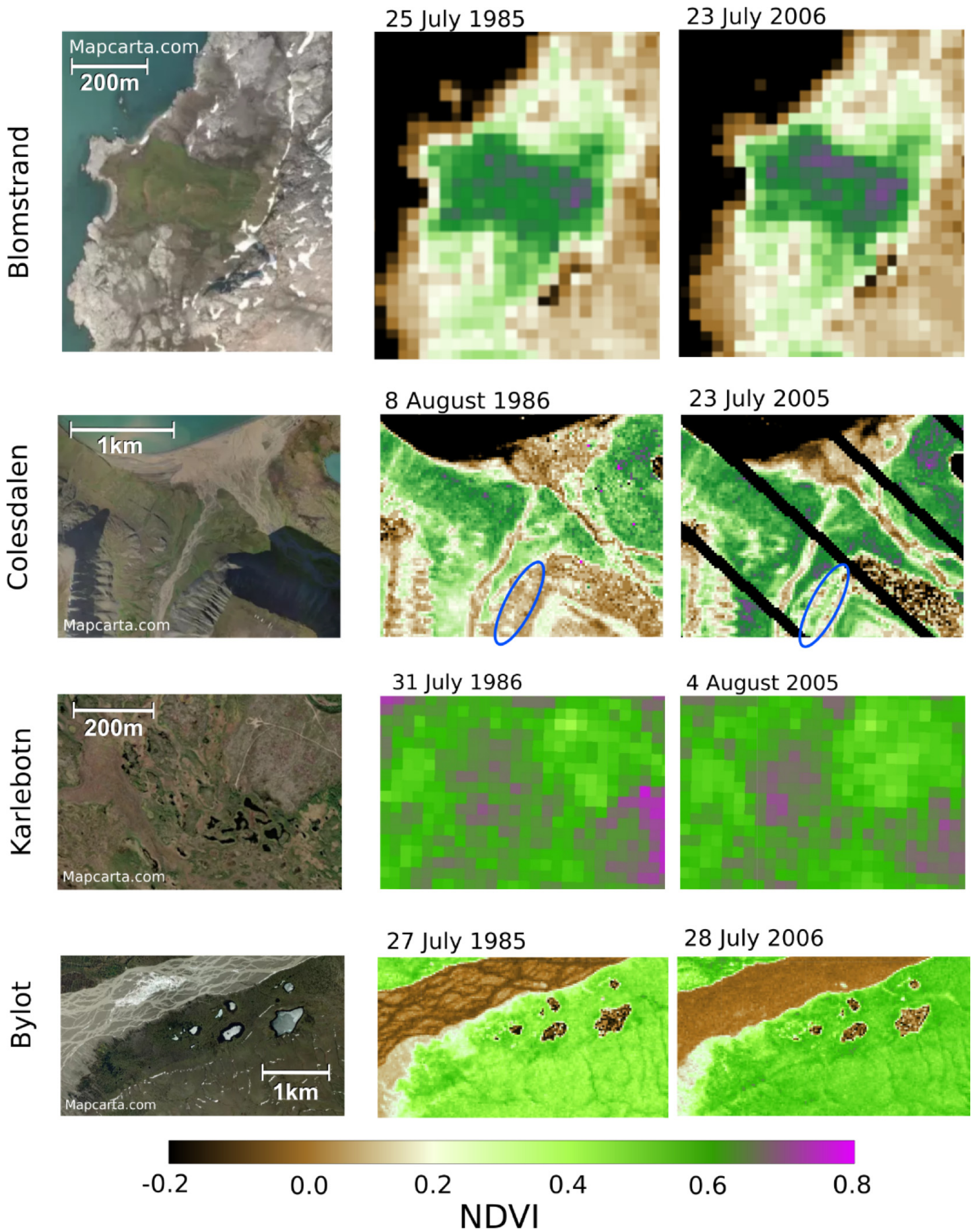

Fig. 6. Example site cases: Blomstrand experienced a within peatland NDVI increase; Colesdalen underwent an increase in NDVI but also a possible expansion of the peat areas including upslope edges (example upslope region circle in blue); Karlebotn did not experience large changes in NDVI, although some pixels experience an increase and some pixels a decrease; Bylot shows an increasing NDVI everywhere.

4.1.1. Differences between regions

Increases in growing season length (Zeng et al., 2011) and productivity (Beck and Goetz, 2011) have been found to be greater in North America relative to Europe in the recent past. We find similarly (although with very few sites in N. America) a stronger and clearer greening (increasing NDVI) trend in the Canadian sites, although at two Svalbard sites, Colesdalen and Sassendalen, greening rates are comparable (Fig. 4).

Epstein et al. (2012) found that between 1982 and 2010, increases in tundra above-ground biomass over N. America and Europe were higher in mid and southern tundra zone, and much lower in the northern zone. We found a generally lower rate of greening at the Lapland low-Arctic sites, higher rates at the two Canada sites (both low and high Arctic), and a mixed signal at the Svalbard High-Arctic sites (expressed as the gradient of the linear regression in Fig. 4). Our data show that increases in peak NDVI are not clearly divisible by more northern or southern zones, although we have relatively few sites, it appears that local conditions may be more important.

4.1.2. Differences between mosaic and peat areas

The mosaic areas represent a wider area around and including the peat areas (Figs. S4 to S6). In this sense, we have not selected specific land cover characteristics for the mosaic sites. This provides an approximation to

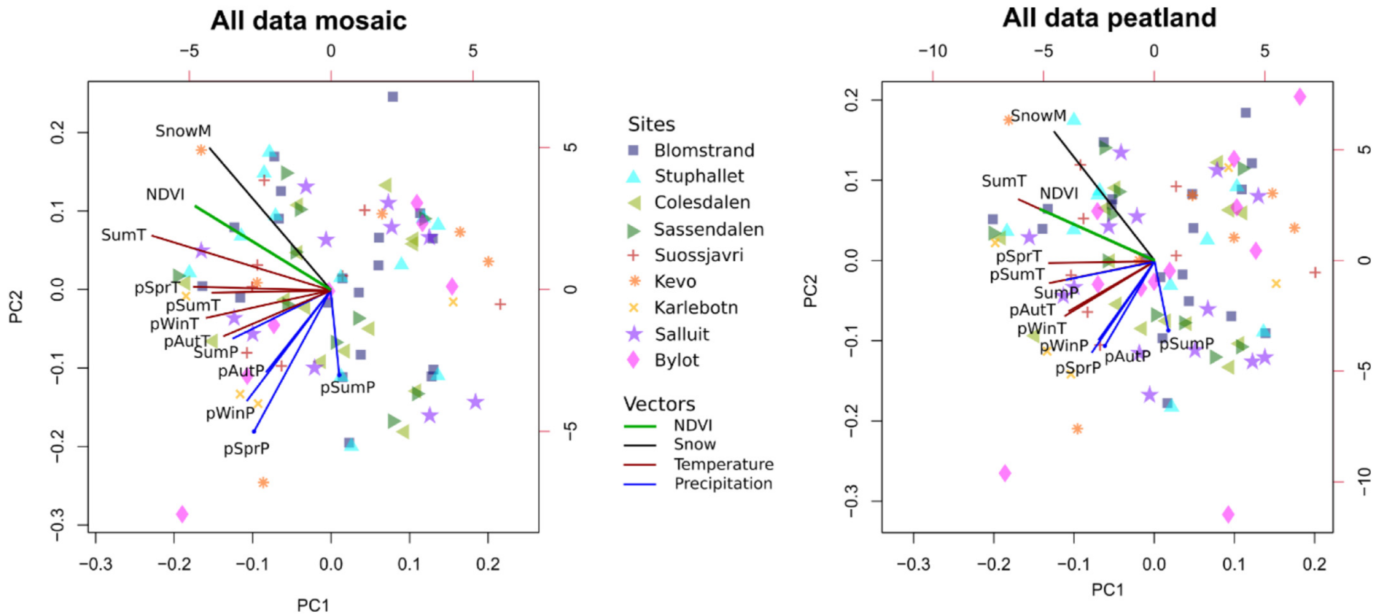

Fig. 7. PCA plot for all sites showing correlations between all (standardised) parameters including NDVI and climate for large mosaic areas (left) and small peat areas (right) (requiring 2 or more datapoints per year for the NDVI annual mean dataset).

general greening changes that may be seen in previous satellite remote sensing studies of Arctic environments. The peat areas were selected such that we have only peat-dominance, in order to specifically consider whether trends here are different to the general mosaic area. We find no clear difference between the NDVI trends between peat and mosaic areas over all sites, however in three sites with strong greening trends (the two Canada sites and Sassendalen) the linear regression shows faster rising NDVI in the peat areas than mosaic areas (Fig. 4). This is not due to initial differences in NDVI in these areas, as mosaic and peat sites mean-area NDVI are similar in these locations.

4.1.3. Within-area changes

The standard deviation of NDVI in pixels within each area shows that, at most of our sites, an increase in mean NDVI is associated with pixels that are becoming more similar to each other (a reduction in mean-adjusted standard deviation, Fig. 5). This means that NDVI increase is not simply driven by a uniform increase in productivity per pixel. This reduction in standard deviation suggests that pixels with low productivity may see greater (relative) increases in NDVI than pixels that are already high, as illustrated in Fig. 13. This could be interpreted as plants with higher NDVI expanding into places with lower-NDVI plants (an example could be shrubs encroaching on mosses or lichens) or plants expanding into previously bare ground. Each Landsat pixel is 30 m × 30 m, so an encroachment on to bare ground can also be seen as equivalent to an increase in vegetation density (given that arctic plants are far smaller than the size of the Landsat pixel).

4.2. Research question 2: Is peak growing-season productivity (as NDVI) linked with specific seasonal climate drivers?

Annual temperature rise is statistically significant for all the meteorological sites (at greater than 95 % confidence), but this is not true for every season. Rainfall trends are less consistent, with most (6 out of 9) sites showing a significant rise in annual rainfall, but seasonal trends being site-dependent. Our MLR suggests that spring, summer and previous-autumn temperature are controllers on peak NDVI for both small peatland and large mosaic areas, along with snow melt timing. Autumn temperature shows statistically significant warming trends at all our sites, spring warming at 8 out of 9 sites, and summer temperature has warming trends at 6 out of 9 sites (over 95 % confidence level, Fig. 3). However, local autumn, spring, and summer temperature trends alone do not predict where the highest rates of greening are found; highest rates of warming are seen in Svalbard, but two of the four sites do not show statistically significant greening trends, and strongest greening trends are seen in the Canada sites. Our MLR and regression trees show that an interplay between seasonal climate parameters may be driving variability in peak season NDVI.

4.2.1. Spring conditions and snow melt

We find that the timing of snow free conditions, and the spring temperature are both linked to peak summer NDVI, which agree with Kelsey et al. (2021) who found that both snow melt timing and air temperature had a strong control on vegetation growing season timing and productivity. Like that study, we identify an interplay between temperature and snow-free timing, where although a late snow-melt seems to greatly limit potential productivity (NDVI), an early snow-melt if combined with a previous Autumn that was not warm is also linked to lower productivity (see regressions trees Figs. 9, 10).

A negative correlation between winter snowfall and peak NDVI is identified for the small peat areas that appear to be strongly driven by Svalbard data (Fig. 8), but also present in the Salluit peat site. If low winter snowfall means a smaller snowpack, this could then be linked to an earlier start to the growing season, where mosses can grow as soon as temperature rises above zero (Lindholm, 1990).

Increasing winter snowfall decreased root productivity in an experimental study (D'Imperio et al., 2018) in west Greenland, suggesting that sites with vascular dominant plants should also be sensitive to winter precipitation, although we do not identify it as a major diver of productivity in this study.

4.2.2. Autumn temperature impact on the following years' productivity

Summer temperature has been identified as a driver for productivity and greening trends in the Arctic before (Charman et al., 2013; Berner et al., 2020), and spring temperature may be linked to a longer more favourable early growing season. We identify that the previous autumn conditions (i.e. after the previous year's peak growing season, Fig. 12 shows seasonal characteristics) are also a driver for peak-productivity. A warming autumn as seen in the meteorological data (Fig. 3) pushes the date of freeze later, extending the length of the growing season and often delaying senescence (May et al., 2020). This does not directly explain,

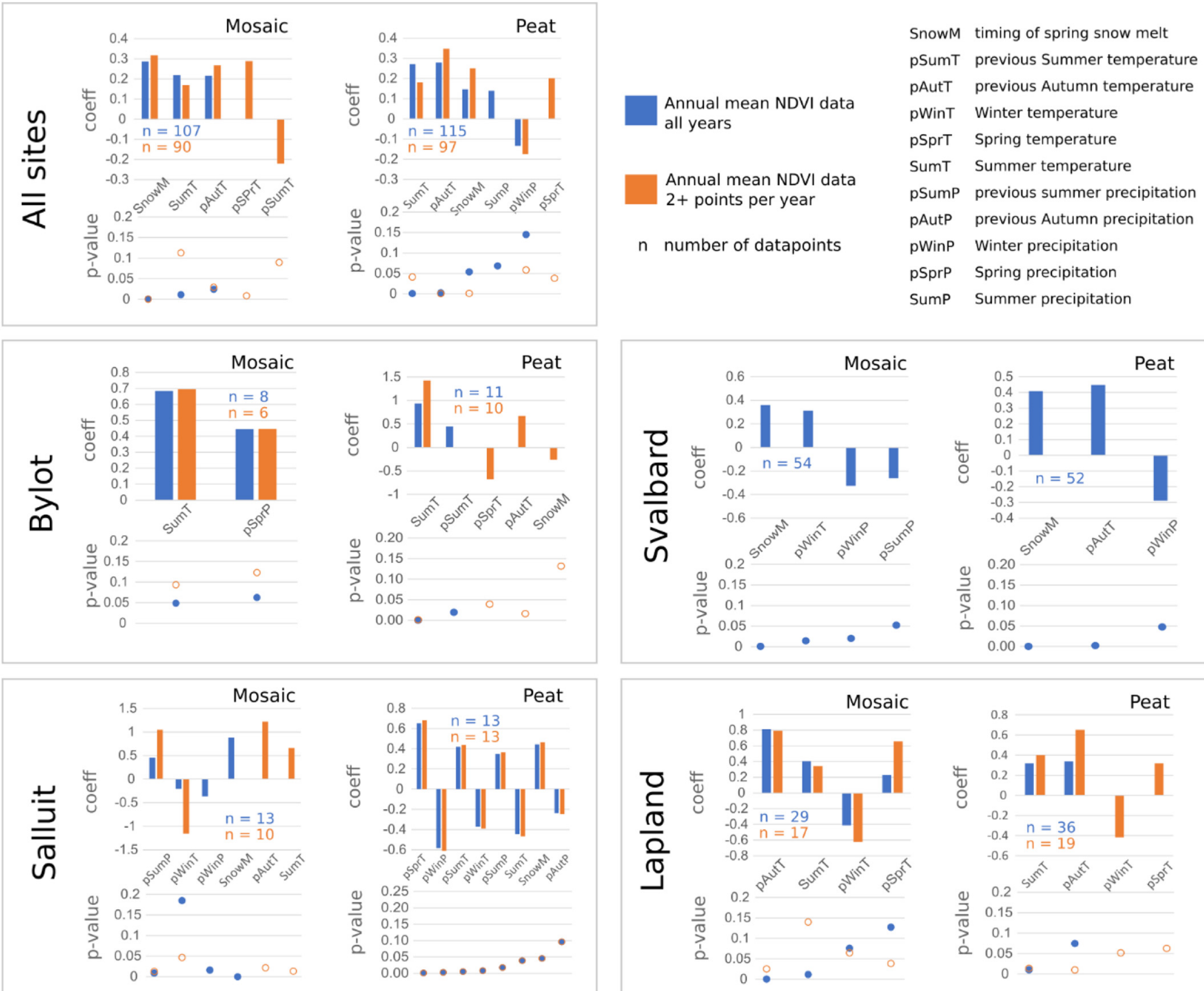

Fig. 8. Results of the multiple linear regression showing regression coefficient and *p*-value for climate parameters with statistically significant correlation to annual peak NDVI. All data was standardised before compiling the dataset for this analysis. MLR carried out for all sites' data, and for region specific. The number of datapoints in each is marked on the charts as "n". Two datasets for NDVI data is applied; using all mean annual data (blue) or requiring at least 2 datapoints per year (orange). Due to fewer datapoints, all Svalbard data was used for both datasets.

however, why the conditions in autumn could then go on to affect the following year's peak productivity (NDVI).

The growing season has been found to be 50 % longer below than above ground along an Arctic elevation gradient (Blume-Werry et al., 2016, although in this study mosses were excluded). High Arctic plants actively forage for nitrogen past the peak above-ground growing season before freezing sets in (Pedersen et al., 2020); providing a possible link between autumn climate parameters and nutrient availability. Graminoids (grass-like) and mosses were found to not increase nitrogen content between October and June in a tracer study in Northern Sweden (Larsen et al., 2012), suggesting that they may rely on previous summer and autumn N uptake for the following spring green-up, unlike shrub species. Finally, non-growing-season (NGS) nutrient uptake is important for arctic plants, but particularly vascular plants (Jonasson and Michelsen, 1996), and differences between plant communities ability to utilise NGS nutrients may determine future tundra plant composition (Riley et al., 2021).

Soil Nitrogen (N) is available to Arctic plants through litter decomposition and mineralization by microbes, which should accelerate in warmer soils (Brown et al., 2004; Oelbermann et al., 2008), but nitrogen can also be made available from deepening of the active layer (thawing permafrost), releasing previously frozen-in nutrients (Pedersen et al., 2020). This deeper nitrogen source is accessible to plants with deeper rooting systems (e.g. shrubs); although most species preferred top-soil N, all plants were able to access permafrost-front (just above the permafrost layer) N in both the autumn and the following growing season in a high Arctic Greenland site (Pedersen et al., 2020). Increases in soil nitrogen are advantageous to shrubs, and especially deeper-rooting plants that can access any thawing permafrost front nutrients. However, as examples of varying results: no change in root phenology was found in sub-Arctic heath and meadow sites in Northern Sweden in an autumn warming experiment (Schwieger et al., 2018), but significant increase in root growth was identified during September in experimental warming in west Greenland (D'Imperio et al., 2018). The European sites in our study range from moss dominant to mixed plant types; increases in NDVI driven only by increased vascular plant root growth cannot easily explain the link between Svalbard NDVI and previous autumn temperature (where our peat areas have low coverage of vascular plants).

Mosses rely less on soil nitrogen than vascular plants as they do not have rooting systems, but studies do show that soil nitrogen is accessible to bryophytes/mosses (e.g. Gordon et al., 2001; Ayres et al., 2006) mediated by

Table 2

R^2 values, errors and F statistic (with *p*-value) for each MLR in Fig. 8.

All datapoints	R^2	Adjusted R^2	RSE	F stat	*p*-Value	Datapoints count
All sites mosaic	0.2813	0.2605	0.8714	13.57	0.0000	107
All sites peat	0.3094	0.2780	0.8335	9.86	0.0000	115
Lapland mosaic	0.5019	0.4223	0.7767	6.30	0.0012	29
Lapland peat	0.2299	0.1846	0.8443	5.08	0.0118	36
Svalbard mosaic	0.4286	0.3828	0.7915	9.37	0.0000	54
Svalbard peat	0.4079	0.3716	0.8095	11.25	0.0000	52
Salluit mosaic	0.8788	0.8250	0.4187	16.32	0.0004	13
Salluit peat	0.9700	0.9221	0.2271	20.24	0.0021	13
Bylot mosaic	0.8375	0.7834	0.5277	15.46	0.0043	8
Bylot peat	0.8358	0.7994	0.5139	22.91	0.0003	11

2+ datapoints per year	R^2	Adjusted R^2	RSE	F stat	*p*-Value	Datapoints count
All sites mosaic	0.3601	0.3225	0.8553	9.57	0.0000	90
All sites peat	0.3990	0.3663	0.7877	12.22	0.0000	97
Lapland mosaic	0.5779	0.4021	0.8044	3.29	0.0424	17
Lapland peat	0.6279	0.5286	0.6199	6.33	0.0034	19
Svalbard mosaic	0.4506	0.3945	0.7840	8.04	0.0000	54
Svalbard peat	0.4079	0.3716	0.8095	11.25	0.0000	52
Salluit mosaic	0.8227	0.7045	0.6309	6.96	0.0193	10
Salluit peat	0.9700	0.9221	0.2381	20.24	0.0021	13
Bylot mosaic	0.8490	0.7735	0.6021	11.25	0.0228	6
Bylot peat	0.9020	0.8366	0.4614	13.80	0.0035	10

microbes (Schmidt et al., 2002; Kostka et al., 2016). Mosses also access nutrients directly from the atmosphere or from water, and due to their slow rate of decay and their water absorption capacity, they are able to outcompete vascular plants by creating low nutrient soil conditions (Malmer et al., 2003). They also control the below-ground environment; a deep moss layer can insulate soils against changes (e.g. warming) in atmospheric temperature (Gornall et al., 2007), potentially reducing nutrient release from permafrost by reducing thaw rates. Bryophytes are also more productive than vascular plants at the start (Street et al., 2012) and end of growing seasons, before full leaf maturity and after senescence happens in deciduous plants; and even year-round growth is possible if conditions are favourable (Küttim et al., 2020). But drying, rather than warming alone, seems to reduce mosses capacity to maintain their advantage over vascular plants and shrubs (Radu and Duval, 2018; Sim et al., 2019; Malhotra et al., 2020). Desiccation tolerance in mosses was developed in late autumn in hummock and aquatic species likely as a response to frost (Hájek and Vicherová, 2014), but *Sphagnum* protonema failed to develop desiccation tolerance in an experimental study (Hájek and Vicherová, 2014). This suggests that desiccation may limit *Sphagnum* establishment in drier habitats; conversely a longer growing season (warmer autumn) with sufficient water availability may be advantageous for *Sphagnum* expansion. In the Svalbard moss dominant peat areas, both autumn temperature and precipitation has increased between 1985 and 2020, suggesting that long term drying would not be happening here, so possibly maintaining moss-dominance and driving increases in extent.

If higher autumn temperatures result in increased soil nitrogen availability, through increased metabolic rates of soil microbes and possible thawing of permafrost, as well as the lengthening of the season for these below-ground processes to take place, this may explain why autumn temperature is a driver for the following year peak-NDVI. At different sites, the in-situ plant-specific drivers of NDVI may be different, but all plants may be responding to increased nutrient availability in the autumn; vascular plants by increased root stock leading to increased following-summer growth, and mosses (or grasses) by increased extent/increased productivity/increased density.

Another possibility for autumn as a controller on the following years NDVI is the effect of freeze-thaw cycling, where these short-frequency cycles may impact plant processes, and soil thermal regimes (e.g. Barrere et al., 2018). A warm event in autumn may thaw an overlying snow layer, increasing soil wetness; if this is followed by a sustained freeze, the lack of snow insulation could result in damage to leaves and roots affecting the following years productivity-potential. A warmer autumn per se does not describe the variability of temperature in the autumn season, but perhaps pushing the date of the onset of freeze-thaw events later is advantageous for phenological processes. Differences in cold season temperatures

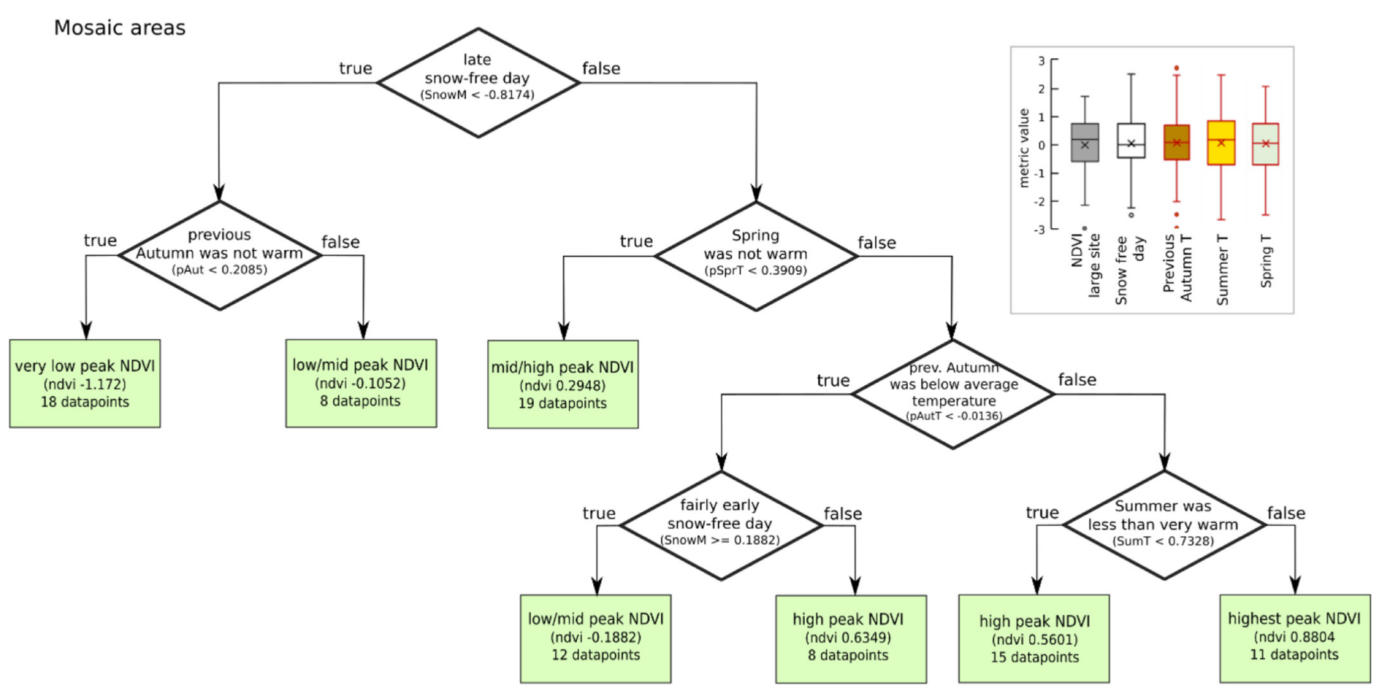

Fig. 9. Pruned regression tree for climate parameters with statistically significant correlations to NDVI data for the large mosaic area all sites (both High Arctic and Low Arctic, for years with 2 or more NDVI datapoints). Inset is the distribution of standardised values for parameters named in the regression tree for the years 1985 to 2020. All NDVI values are standardised NDVI (see Fig. S10 for standardised data plots for NDVI and climate parameters).

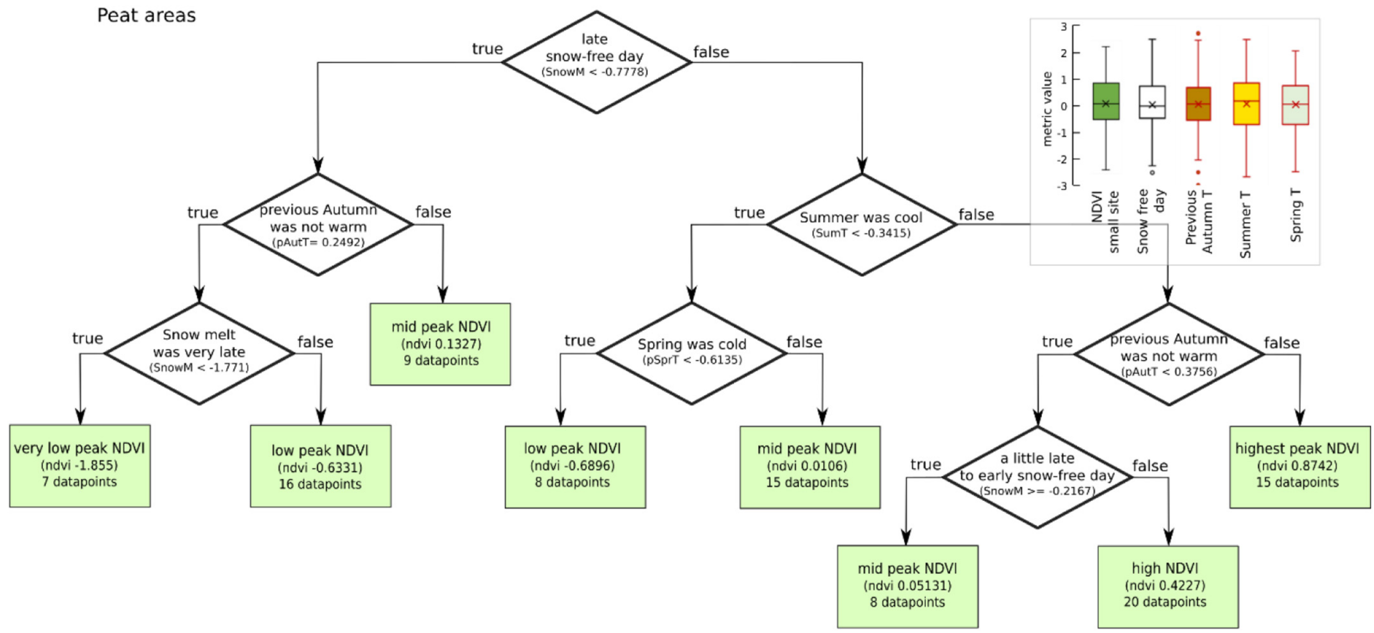

Fig. 10. Pruned regression tree for climate parameters with statistically significant correlations to NDVI data for the small peat area at all sites (both High Arctic and Low Arctic, for years with 2 or more NDVI datapoints). Inset is the distribution of standardised values for parameters named in the regression tree for the years 1985 to 2020. All NDVI values are standardised NDVI (see Fig. S10 for standardised data plots for NDVI and climate parameters).

may also be playing a role in the differences seen in European sites versus Canadian sites regarding autumn freeze-thaw conditions, making the milder-winter sites more sensitive to autumn conditions.

4.2.3. Water availability

Seasonal precipitation in spring and summer is not increasing to match temperature increase at the Svalbard sites, but spring and summer precipitation do not show up as controllers of peak NDVI here. Experimental changes in rainfall frequencies were shown to affect moss, sedge and shrub communities differently (Radu and Duval, 2018), with less frequent but larger rain events being detrimental to moss species, and advantageous to vascular plants. As we consider only the seasonal means, our data does not capture any changes in rainfall frequency and the effect that may have. The two more southern Svalbard sites (Colesdalen and Sassendalen) in our study are both in (post) glacial valleys, meaning that periods of low rainfall in summer may not be limiting here, where glacier melt may continue to provide water during any low-rainfall episodes. In contrast, Blomstrand and Stuphallet may be more susceptible to periods of lower rainfall, with Stuphallet not downstream from a glacier and Blomstrand a small island but both also see a stronger summer-warming trend (so increasing evapotranspiration). If summer rainfall or its frequency is affecting peak NDVI in Blomstrand and Stuphallet, this may explain why we see no significant greening trend here, and also why the edges of the Blomstrand peat area (Fig. 5) do not show increased NDVI like the centre (which may possibly be less susceptible to drying). As we have grouped all the Svalbard sites together for the regional MLR (Fig. 8) we may also be missing detail in site-specific hydrological differences.

At all our Lapland sites, summer precipitation is probably increasing (at the 90 % confidence level) along with increasing summer temperature, which may explain why summer precipitation does not come out as a controller on Lapland sites peak NDVI, i.e. this region is not water limited in summer.

As we have far fewer datapoints for the Canada locations, it is not possible to draw conclusions on regional patterns, but both sites appear to show some dependency on precipitation in the MLR analysis. Only the Bylot peat site does not have precipitation in the linked climate parameters, although this site is down-valley from large glaciers.

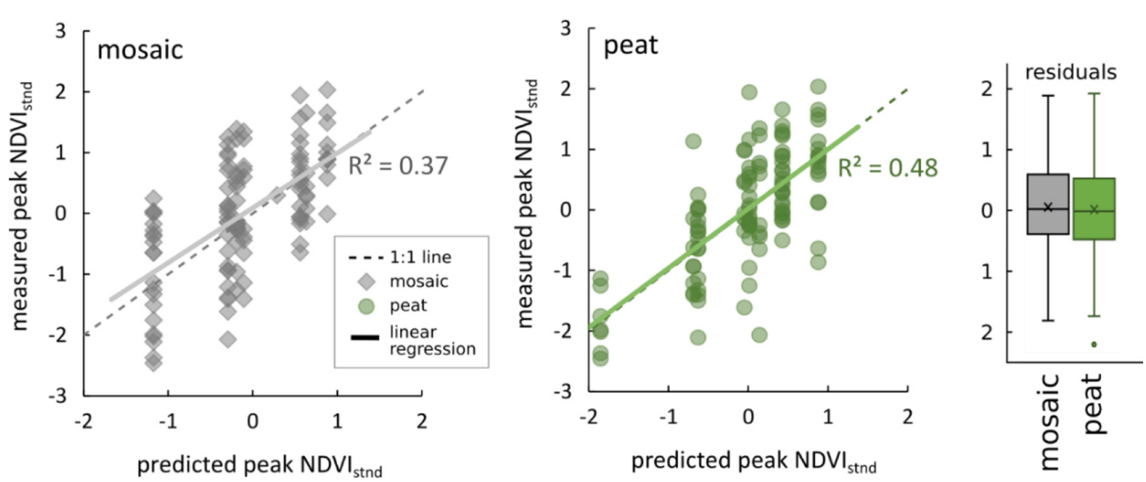

Fig. 11. Cross plots of standardised climate-NDVI model and satellite measured standardised NDVI metric for the large mosaic (grey diamonds) and small peat (green circles) areas, dashed line is the 1:1 relationship (the closer the point is to this line, the better the model).

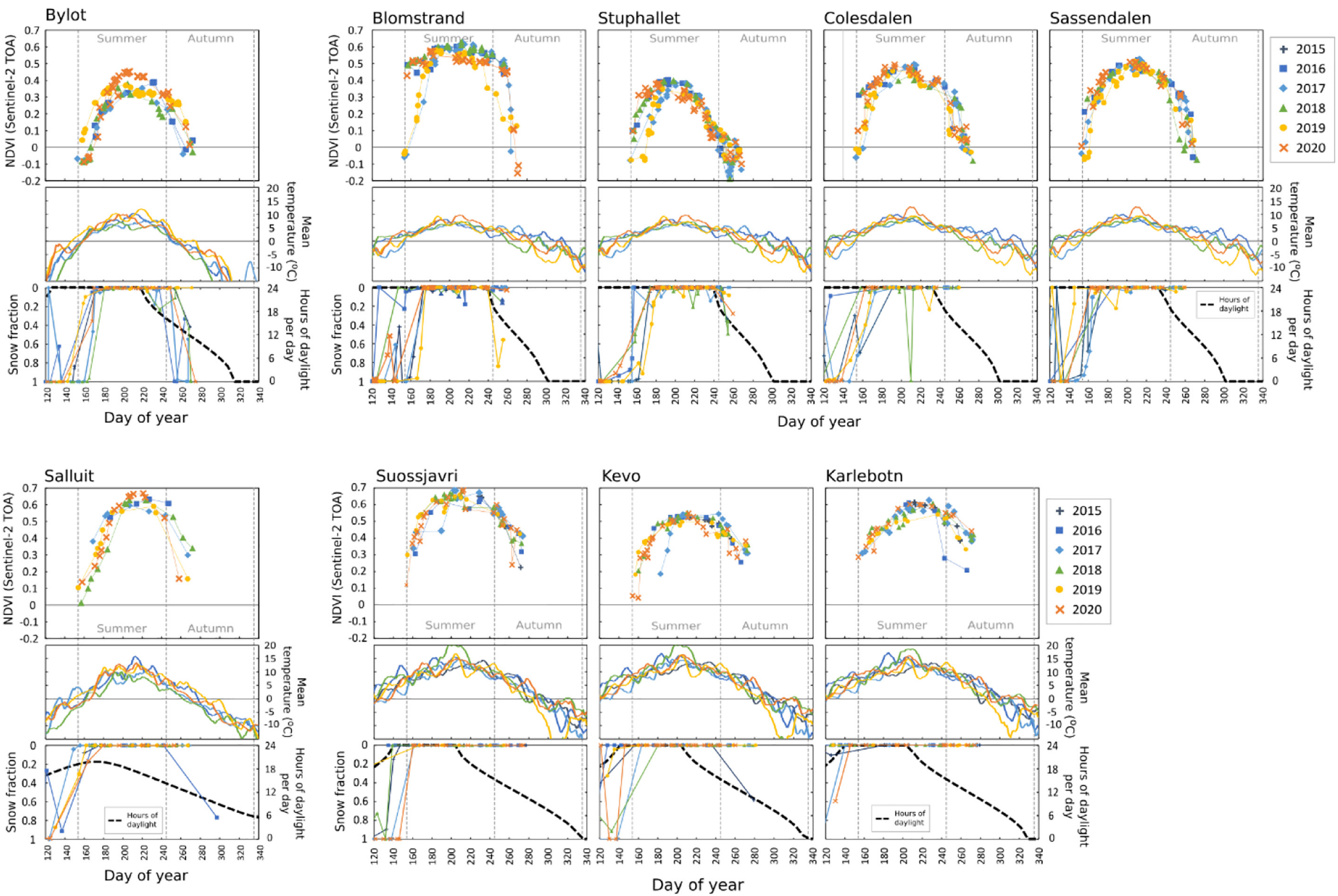

Fig. 12. Seasonal NDVI from Sentinel-2 (TOA) plotted per day of the year for the sites for 2015 to 2020. Temperature is 10-day running mean. Snow fractions are for the peat area only (unlike the snow melt climate metric used in the NDVI climate MLR). Hours of daylight are calculated using Matlab code to find sunrise and sunset time (Droste, 2021).

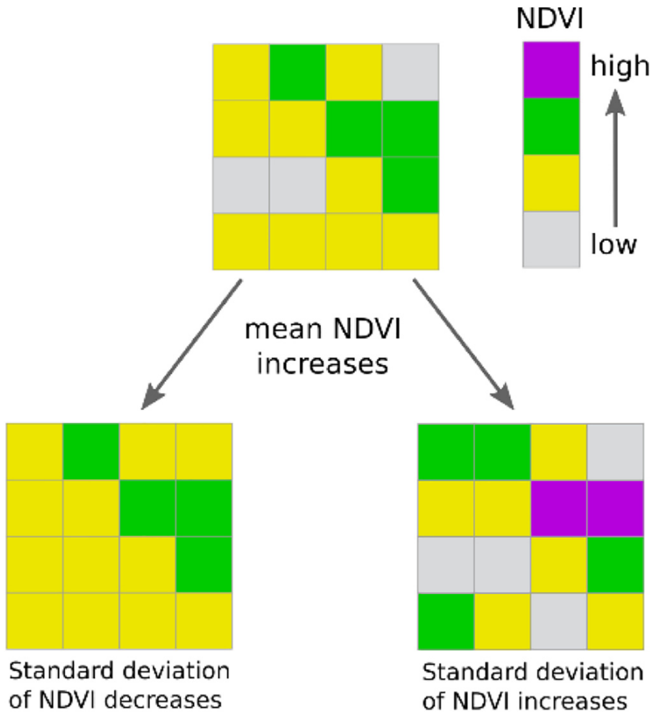

Fig. 13. Changes in standard deviation of NDVI can indicate what the pattern of NDVI rise on the ground represents within our regions of interest. Falling standard deviation indicates a homogenising of pixels, rising is a diversification of pixels.

When we group all the sites together, water supply in the growing season does not emerge as a controller on NDVI (Figs. 8, 9 and 10), but we know water supply is important for arctic plants and especially mosses (Schipperges and Rydin, 1998; Jassey and Signarbieux, 2019). This suggests that effects of water supply are more site-dependent and local than the effects of temperature; local topography and site situation impact water availability in the growing season in these arctic sites (also identified in previous studies, e.g. Campbell et al., 2021).

4.3. Peak season productivity caveats

Due to differences in the timing of green-up and senescence per year, the cumulative seasonal-NDVI sum (interpreted here as a possible measure of total productivity, see Fig. S12) is not exactly proportional to the peak NDVI, which means that peak NDVI may not necessarily well-represent whole-growing-season GPP (gross primary productivity). Green-up and senescence rates have been linked to water regimes (Westergaard-Nielsen et al., 2017), which as we consider only seasonal average climate conditions and peak-growing season NDVI, we do not capture in our analysis. Peak NDVI does not provide information about system respiration, for example Lund et al. (2010) found no significant correlation between GPP and R_{eco} (ecosystem respiration), therefore our timeseries do not capture annual carbon accumulation in the soil either. Further, NDVI in arctic mosses is sensitive to short term changes in soil moisture, that can drive a mismatch between GPP and NDVI on short timescales (May et al., 2018). We do not consider short term changes in soil moisture in drivers of moss-dominated sites' NDVI, which may therefore be affected by soil moisture regimes, and introduce a further source of uncertainty.

5. Conclusion/summary

We found statistically significant rising trends in peak-growing-season NDVI in about half of our Arctic sites between 1985 and 2020, in both peat-dominant areas and in areas with more varied ground cover, but no browning trends. We interpret this as increases in plant biomass (e.g. as leaves or number of plants) or increases in productivity, but this does not necessarily equate to increases in net ecosystem productivity (e.g. as annual carbon accumulation), as we do not consider changes in ecosystem respiration. Differences in the timing of green-up and senescence between years may also affect total growing season productivity, so peak NDVI may not always be a good guide to estimate full growing season GPP. We find that peat dominated areas showed rates of greening similar to the wider mosaic area.

According to our climate-NDVI analysis, in both peat dominant areas and in the wider mosaic areas, NDVI increases are linked to previous-autumn, spring, and summer temperature, and the timing of snow-free conditions. Seasonal precipitation patterns did not come out as controllers of peak season NDVI and precipitation frequency, local site conditions, and topography are likely more important for growing season water availability.

We propose that enhanced nutrient availability from a longer below-ground late growing season may provide an explanation for why previous-autumn temperature can control the following year's peak potential productivity, but further study is needed to investigate these links. The observed increased productivity in Arctic peatlands and their immediate surrounding areas as a result of long term warming trends over the past 35 years suggests that there is potential for increased soil carbon storage over recent decades if decomposition does not increase at the same or faster rate. Future work will focus on determining whether this hypothesis is substantiated by records of recent peat accumulation and peatland extent.

CRediT authorship contribution statement

K.A.C designed the study, Landsat and Sentinel-2 algorithms in GEE, and carried out the analysis with support from K.A and A.G.S. K.A.C produced the manuscript first draft. All authors contributed to and edited the final manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156419.

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