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Record-low primary productivity and high plant damage in the Nordic Arctic Region in 2012 caused by multiple weather events and pest outbreaks

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Abstract

The release of cold temperature constraints on photosynthesis has led to increased productivity (greening) in significant parts (32–39%) of the Arctic, but much of the Arctic shows stable (57–64%) or reduced productivity (browning, <4%). Summer drought and wildfires are the best-documented drivers causing browning of continental areas, but factors dampening the greening effect of more maritime regions have remained elusive. Here we show how multiple anomalous weather events severely affected the terrestrial productivity during one water year (October 2011–September 2012) in a maritime region north of the Arctic Circle, the Nordic Arctic Region, and contributed to the lowest mean vegetation greenness (normalized difference vegetation index) recorded this century. Procedures for field data sampling were designed during or shortly after the events in order to assess both the variability in effects and the maximum effects of the stressors. Outbreaks of insect and fungal pests also contributed to low greenness. Vegetation greenness in 2012 was 6.8% lower than the 2000–11 average and 58% lower in the worst affected areas that were under multiple stressors. These results indicate the importance of events (some being mostly neglected in climate change effect studies and monitoring) for primary productivity in a high-latitude maritime region, and highlight the importance of monitoring plant damage in the field and including frequencies of stress events in models of carbon economy and ecosystem change in the Arctic. Fourteen weather events and anomalies and 32 hypothesized impacts on plant productivity are summarized as an aid for directing future research.

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Keywords: anomalous weather events, disturbance, extreme events, NDVI, long-term monitoring series, pathogens, plant stress

1. Introduction

The recent greening trend, viz. increasing vegetation productivity, due to the release of cold temperature constraints on photosynthesis of high northern lands (Angert *et al* 2005), is currently not a pan-Arctic trend (Beck and Goetz 2011, Xu *et al* 2013), despite most northern lands becoming progressively warmer in all seasons (Walsh *et al* 2011). Whilst the 1982–2011 greening trend for the Arctic is most pronounced at very high latitudes in continental tundra regions such as Central Siberia (Russia), northern Alaska (USA), and northern parts of Yukon and the Northwest Territories (Canada), maritime (oceanic) regions show no or weak trends (Beck and Goetz 2011, Xu *et al* 2013). The Nordic Arctic Region (NAR), here defined as the regions of Norway (excl. Svalbard), Sweden and Finland north of the Arctic Circle, is an example of a northern maritime region where productivity has been mostly stable during recent decades, as documented using a satellite-based proxy for vegetation productivity, namely the normalized difference vegetation index, NDVI (Beck and Goetz 2011, de Jong *et al* 2012, Xu *et al* 2013). Examples of other such maritime regions are the Pacific coasts of Alaska, the Atlantic coast of Canada and the Barents Region of Russia. The stable productivity of the NAR and other maritime regions stands in stark contrast to climate trends, which for most of the regions show a significant increase in summer and spring temperatures (Førland *et al* 2010, Walsh *et al* 2011). Understanding the physical and biological processes leading to the decoupling of these two trends is considered one of the grand challenges for global change scientists (Williams *et al* 2011) and is crucial for making firm projections of the state of the Arctic in relation to both future carbon storage potentials and ecosystem resilience (D'Arrigo *et al* 2008, Williams *et al* 2011, Callaghan *et al* 2013, Pearson *et al* 2013, Larsen *et al* 2014).

The NAR is unique in having a mild oceanic to moderately continental climate which facilitates one of the world's northernmost deciduous forests, reaching as far north as 71°N (Hofgaard *et al* 2013). Several recent anomalous events of biogenic, physical and anthropogenic origin have been documented from the NAR. Increasing precipitation rates, and accordingly paludification, have been suggested as drivers of vegetation change in maritime regions (Crawford 2000). Events of long-distance dispersed air pollution from sources in Central Europe have shown to reduce ecosystem health within the NAR recently (Potter *et al* 2007, Karlsson *et al* 2013). There are also sites within the NAR that are under a more permanent pollution stress (Myking *et al* 2009). Climate change-induced expansions in outbreak ranges of canopy-defoliating insects have caused major stress leading to long-term reductions in productivity and vegetation shifts at local and regional scales (Jepsen *et al* 2008, 2011). As the climate change-induced warming is most pronounced in winter (Xu *et al* 2013, Walsh *et al* 2011), snow and ice

conditions and the state of overwintering organisms are potentially strongly affected. Warm spells in midwinter have recently caused full or partial snowmelt and warmed vegetation that has been killed or damaged upon return to normal winter conditions (Bokhorst *et al* 2009, 2012a, 2012b). Overall, these reports indicate that the NAR has recently been subject to stress events that resulted in short- or longer-lasting reductions in productivity at local or regional scales. However, the synergistic effects of stress events of various origins on vegetation greenness and productivity in the NAR have so far not been elucidated in detail. As stress events are erratic, it is challenging to assess the synergistic effects of multiple stresses in nature. However, ecologically relevant extreme events are predicted to increase in frequency (Jentsch *et al* 2007, Smith 2011, Stocker *et al* 2013), thereby making it more likely that a specific region will be hit by multiple stress events simultaneously. This happened to be the case in the NAR during the water year from October 2011 to September 2012, when multiple events were observed and received much attention in national media. Here, we present a combined analysis of field and remote sensing data on the multiple weather events and pest outbreaks that were detected in the NAR during this water year. We assess the relative impacts of these events on vegetation greenness during the 2012 growing season, as compared to mean greenness of preceding years, and discuss how frequent these types of weather events are, and their potential role in impeding pan-Arctic primary productivity.

2. Materials and methods

Due to length limits of the main text, many details on materials and methods used and associated results and discussions are placed in the appendix. Not all figures in the appendix are cited in the main text.

2.1. Study area

The planning of this study started when multiple extreme weather events occurred in the NAR starting in November 2011, and accelerated when considerable plant damage was detected during our preliminary field surveys in winter and later during the growing season. We selected a study area that we know well and could easily reach during the growing season in order to be able to document plant responses in the field. We therefore focused on the two northernmost counties of Norway, but added also some field sites in northern Sweden and Finland. We selected a similar area for remote sensing data retrieval, ranging southwards to the Arctic Circle and eastwards to the longitude of the NAR's northernmost point at Magerøya, Finnmark, i.e. 25°40' E, thereby including parts of Norway, Sweden, and Finland (figure 1). This covers a typical maritime region, but also includes more continental, interior areas.

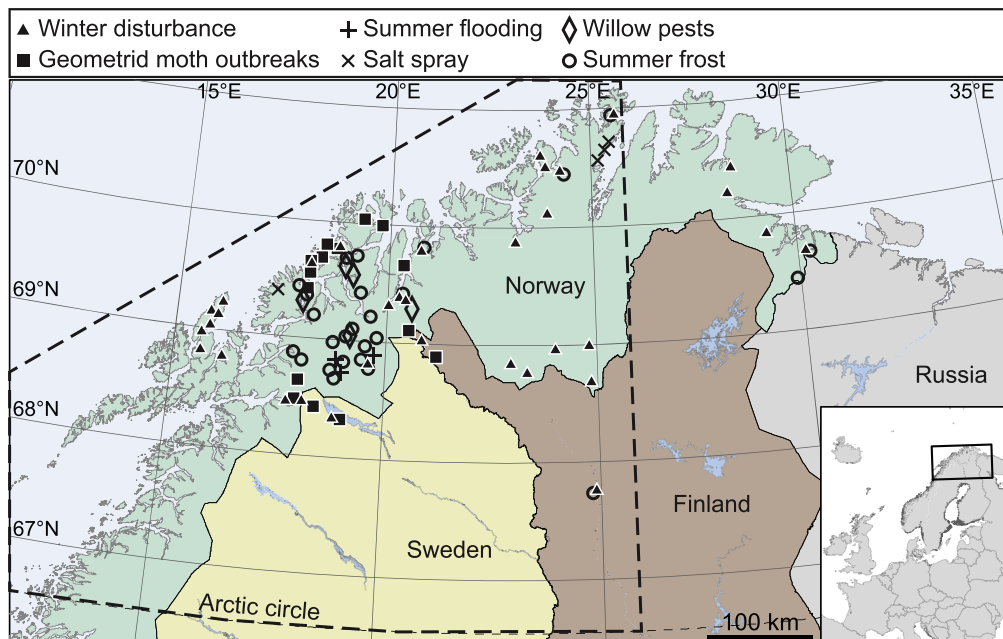


Figure 1. Map of the Nordic Arctic Region (NAR). Country borders are shown in black. The stippled line indicates the focal area from which trends in NDVI and snow cover fractions were retrieved.

2.2. Moderate Resolution Imaging Spectroradiometer (MODIS)-NDVI

The reflectance products from the MODIS Terra satellite are an estimate of the surface spectral reflectance for each band, as it would be measured at ground level with no atmospheric scattering or absorption (NASA 2014). We extracted NDVI data from the MOD09Q1 250 m eight days reflectance data product in order to have both the best time and spatial resolution for our study. We also used the MOD09A1 product with surface reflectance values for bands 1–7 at 500 m resolution to extract additional information on cloud cover. Both datasets were processed for the 2000–12 period, and re-projected to the UTM Zone 35N projection. The extensive calibration process included several steps for cloud removal. Product quality assessment (QA) and validation are integral parts of the MODIS Land product generation process (NASA 2014). The QA flags in the MOD09A1 product give information about different types of atmospheric noise, and for each eight day period we undertook a visual quality control in ArcGIS of which of the different State QA values best detected the cloud cover. In most cases, one of the State QA values or a combination of the State QA values detected the clouds in the data covering the NAR. However, this was not always the case, as it depended on the cloud type, time of the season, and type of land cover. In particular, the detections of cloud shadows and clouds over sparsely vegetated areas failed. Therefore, we also calculated additional cloud detection algorithms based on the 7-band MOD09A1 product, where the algorithm (band 2 (NIR) < 30%) of the 2000–12 median value indicated shadows of the clouds over vegetated areas during summer. In a few cases, none of the State QA values or our own cloud algorithms were able to detect noise in the data. In such cases, we manually masked out the noise

by drawing polygons around the cloudy parts. Altogether, we had 16 different combinations using State QA values, our own algorithms and/or manual masking for cloud detection. For each of these combinations we developed a python script to remove the clouds. Hence, after visually evaluating each eight day composite we chose one of the scripts for each eight day composite, which then automatically removed the noisy part of the composite. This was a rather time-consuming procedure, but was done only once and ensured that most of the noise in the datasets was removed and that most of the noise-free clear-sky data was kept. With the clear-sky time-series of NDVI data we calculated mean NDVI values for the period from 10 June to 20 August each year. We masked out water bodies and areas with mean NDVI values below 0.12, as these areas are almost without vegetation. The NDVI values reflect the photosynthetic activity and change during the summer, hence, to some degree the annual mean values could be affected by clouds and noise. There are some effects of missing clear-sky data due to long periods with clouds. However, due to the size of the study area, which includes a strong coast-inland gradient, these cloudy periods only occur locally during some periods in some years. Hence, since we calculate the average values for the whole study area over a two month period, these local effects are on a scale much lower than the actual differences in average NDVI values for the whole study area between the years. The MODIS sensor degradation on the Terra satellite is in a scale well below the differences in mean NDVI between years (Wang *et al* 2012), especially the exceptionally low NDVI values for 2012. For studies of specific localities known to have been affected by one or several of the stressors described here, we manually excluded data points affected by clouds.

2.3. Meteorological data

We downloaded data from the E-OBS dataset, which is a European land-only daily high-resolution gridded data set for precipitation, and minimum, maximum and mean surface temperatures for the period 1950–2013 (ECA&D 2013, Haylock *et al* 2008). Data applied in this study have 0.25° spatial resolution on a regular latitude-longitude grid, and we resampled the daily E-OBS data to a spatial resolution of 8 km × 8 km in UTM projection, Zone 33 N and datum WGS84, as described in Høgda *et al* (2013).

As a supplement to E-OBS, we used Collection 5 MODIS/Aqua Land Surface Temperature (LST) Level 3 products (USGS 2014). These data products provide per-pixel temperature values in a sequence of swath-based grid in the Sinusoidal projection. The data used are acquired during night between 02:11 AM and 04:30 AM local time at 1 km spatial resolution (Wan 2006), meaning that the observations for this region were taken in the coolest time of the night.

Meteorological observations from Norwegian weather stations were retrieved from the database Eklima (Norwegian Meteorological Institute 2014). Data on summer flooding were retrieved from the Norwegian Water Resources and Energy Directorate (2013).

2.4. MODIS snow cover data

We calculated the fraction of total land area covered by snow ('snow cover fraction', SCF) for the study area using the NASA MOD10A1 time series (Hall *et al* 2002). For every day in the period from 2000 to 2012 we calculated SCF maps for the study area by linear interpolation between cloud-free pixels in the time series (Malnes *et al* 2010, Nilsen *et al* 2013). Subsequently we calculated the total SCF, the daily minima and maxima, and the mean for each day. We then compared the daily means from the period 2000–11 with the SCF of 2012.

2.5. Field surveys of vegetation damage and pest outbreaks

During the growing season of 2012, we arranged field campaigns to various parts of the study area to assess vegetation damage caused by the observed disturbance events, spending most time in areas known to have been hit by one or more events. Further, we included sites along damage gradients, from modest to severe damage. In the field, wilting or browning of leaves was assessed on individual or plot scales using relative values as compared to green leaves, as detailed in the appendix A1.B. Field observations were used to categorize sites as low- or high-damage sites, based on damage ratios of the dominant species.

During the growing season of 2012, the effects of the leaf defoliation became very striking at the landscape level. Affected sites seen during field surveys in various parts of the NAR were georeferenced and photographed. Two areas were given particular attention, a coastal area in Troms County, Norway, where monitoring of moth densities is on-going (Jepsen *et al* 2008, 2011), and an upland area in Sweden.

Due to length limits of the main text, the field surveys are described in further detail in the appendix A1.B–C.

2.6. Statistical analyses

Significance analyses, model selection and linear trend analyses were undertaken using SPSS Statistics 21 (IBM, NY, USA) and R (R Core Team 2012). Standard tests for checking departures from normality and homogeneity were performed prior to analyses of variance (ANOVA). One-sample *t*-tests were used to compare 2012-values with the average for the years 2000–11. This test is robust to departures from normality. Hence, normality was not emphasized when performing this test.

3. Results

3.1. Anomalous weather events

We here treat the observed anomalous weather events in chronological order. The water year started with a record-warm autumn (figure 2(a), A.1). October was unusually warm and wet. November had the highest mean monthly temperature ever recorded for Norway as a whole, and for North Norway, and was warm in Sweden. December was also much warmer than the norm, especially in the Norwegian–Swedish–Finnish border area where monthly mean temperature was 8–10 °C above normal (appendix A2.A). The turn from autumn to winter was associated with the storm 'Dagmar' which was one of the strongest storms in Norway during the last 30 years (Norwegian Meteorological Institute 2013). Mid-winter was extreme in the unusual combination of shallow snow depths and extreme fluctuations in temperature from record-low to unusually warm over short time periods preceded and followed by numerous freeze-thaw cycles (figure 2(b)). The shallow snow depth led to exposure of many plants that under normal snow conditions would be covered by snow and thereby sheltered from ambient temperature extremes.

The NAR had the coldest mean monthly May temperature recorded by E-OBS (figure 2(c)). This led to delayed snowmelt, the proportion of land areas covered by snow in mid-May being extremely high (figures A.2, A.3). By summer solstice, snow cover was more than double the norm (figure 2(e)) and by 1 July snowmelt was 14 days delayed respective to normal snowmelt (figure A.3). Cool weather continued in July (figure 2(c)). In addition to being generally cool, some extreme minimum temperatures were also measured related to five midsummer frost events (i.e. from 15 June to 31 July; figure 2(d)). Extreme rainfall in mid-July caused flooding in several rivers, in particular affecting one of the largest drainage basins in the NAR, where the event was larger than a 50-year flood (figure 2(f)). Furthermore, anomalously heavy storms raged along the coast in mid-season (appendix A2.A).

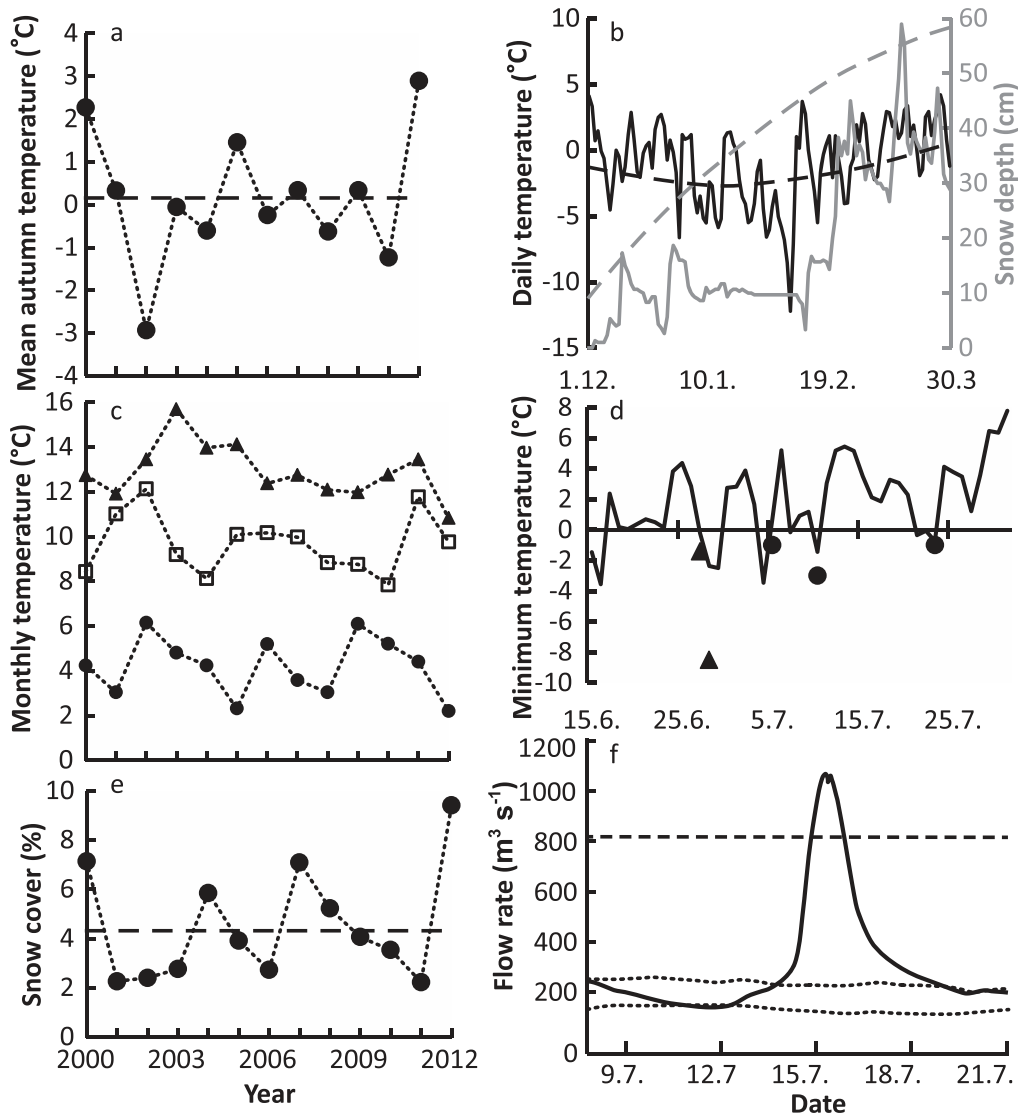


Figure 2. Physical observations of anomalous weather events during the water year from October 2011 to September 2012. (a) Warm autumn temperatures (filled circles; dashed line: average temperature). (b) Fluctuation of winter temperature and snow cover (black: temperature, grey: snow depth; dashed: average, solid: 2011/12). (c) Anomalously low growing season temperatures (filled circles: May, open squares: June, filled triangles: July). (d) Midsummer frost events (line: minimum E-OBS temperatures within the NAR; triangles: LST observations; circles: weather station observations). (e) Remaining snow on summer solstice. (f) July flood (solid line; stippled line: level for 50-year flood; dotted lines: 25th and 75th percentiles). These observations are further described in the appendix.

3.2. Plant responses to anomalous weather events

We recorded vegetation damage, delayed phenology, and reduced productivity caused by these weather events. The growing season of 2012 had the lowest mean NDVI ever recorded for the MODIS period from 2000 to 2012, being 6.8% lower than the 2000–11 average (figure 3(a); $t = 11.1$, $p < 0.001$). Growing season temperature explains little (16.8%, $p = 0.09$) of the year-to-year variation in mean NDVI (figure 3(b)), though cool June and July temperatures may have contributed to the record-low NDVI of 2012. However, areas that we know were affected by stress events show much higher reductions in NDVI as compared to the average decline, suggesting that these events contributed strongly to the decline in NDVI for 2012. The most extreme reduction of 58% from 2000–11 was in an area exposed to multiple

disturbance events (figure 4(d)). 43.3% of the land area showed a reduction in NDVI in 2012 compared with the 2000–11 average (figure 3(c)). 60% of this area had a decrease higher than 0.1 NDVI units (dark blue areas in figure 3(c)). 50.4% of the land area had an NDVI in 2012 that was similar to the 2000–11 average (yellow), while 6.4% of the area had NDVI values higher than the average (red). Most of this area is in the more continental, eastern parts of the studied area.

We observed spring-like development of plants from November to January during and shortly after the record-warm autumn; goat willow (*Salix caprea*) produced catkins, coltsfoot (*Tussilago farfara*) flowered, and new primrose (*Primula verna*) leaves developed. Naturally, these new organs died during the following frost. In areas that

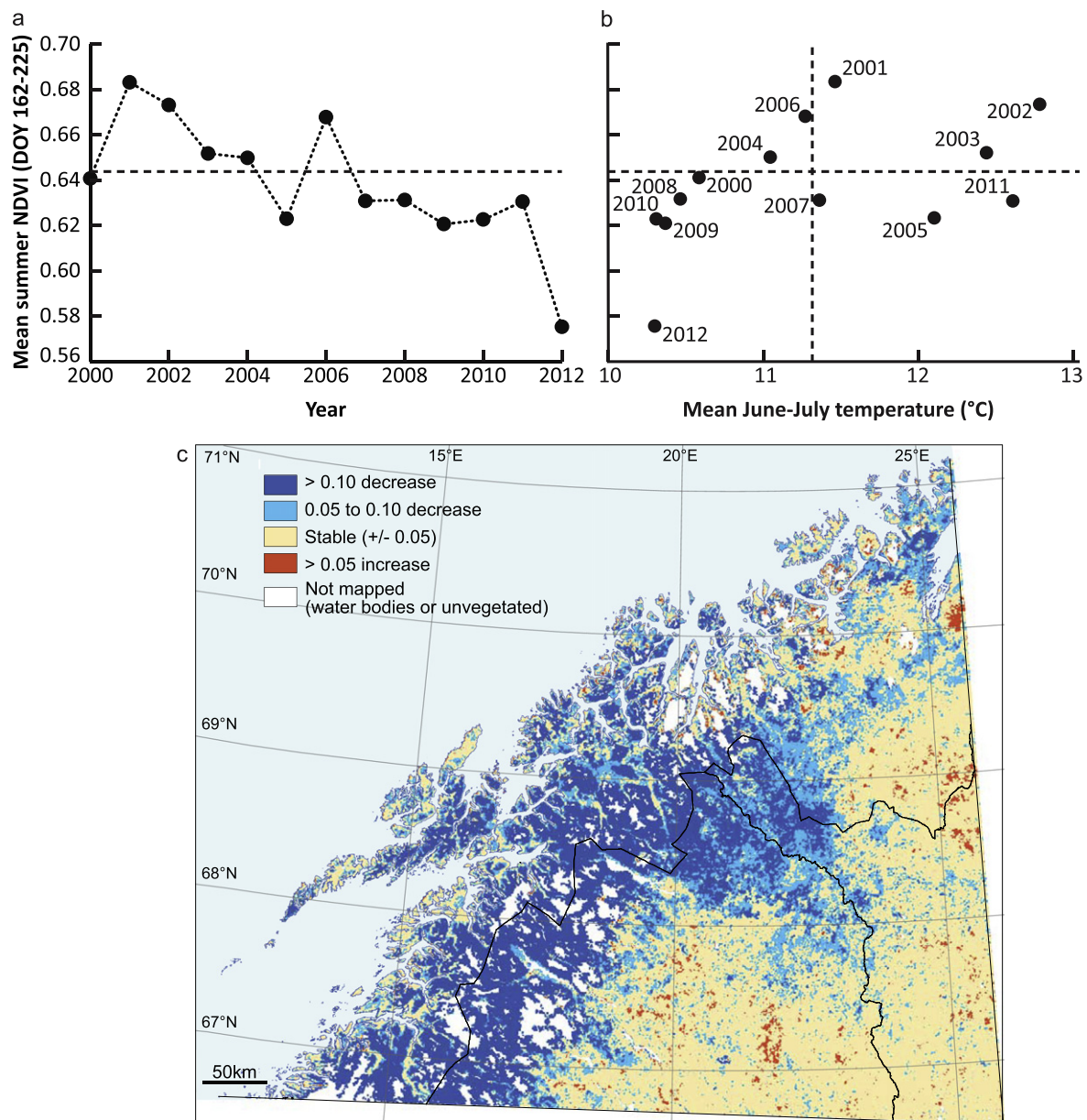


Figure 3. NDVI of the NAR. (a) Year-to-year variation in mean NDVI. (b) Correlation between mean NDVI and summer temperature. Stippled lines: 2000–11 average. DOY: day of year. (c) NDVI map showing areas with NDVI values in 2012 lower (blue colours) and higher (red) than the 2000–11 average. Scale shows changes in NDVI units.

experienced midwinter warming events followed by extreme cold and shallow snow depths, damage to evergreen plants was high. Within the area most strongly affected by this disturbance, 38% of evergreen plants browned, most prominently crowberry (*Empetrum nigrum*; 50%) and juniper (*Juniperus communis*; 37%; figure 4(a), A.6). As crowberry is a dominant plant in the understory vegetation, this browning trend was very striking on a landscape scale (figure A.5a). NDVI at the studied sites with much visible damage was reduced by 34% compared to the 2000–11 average (figure 4(b); period (i.e. 2012-value versus 2000–11 average): $F = 36.6$, $p < 0.001$; period \times damage category: $F = 9.5$, $p = 0.004$). Onset of the growing season was delayed

by seven days due to the cool spring and long-lying snow (figure 4(c)).

Midsummer frost of the severity of late June 2012 is very unusual in the NAR (appendix A2.A). Most strongly affected were ferns, shrubs and herbs with thin leaves (figure 5(a), A.5c, A.8–10). The minimum ground temperature recorded was $-8.5\text{ }^{\circ}\text{C}$ in interior valleys (figure 2(d)), and in the bottoms of these valleys 99% of fronds of the dominant ferns were wilting (figure 5(a); two-way ANOVA results with bioclimatic position (1–4 in figure 5(a)) and position in valley (i.e. valley bottom versus valley slope) as fixed factors: bioclimatic position: $F = 5.8$, $p = 0.001$; position in valley: $F = 2.1$, $p = 0.145$; interaction:

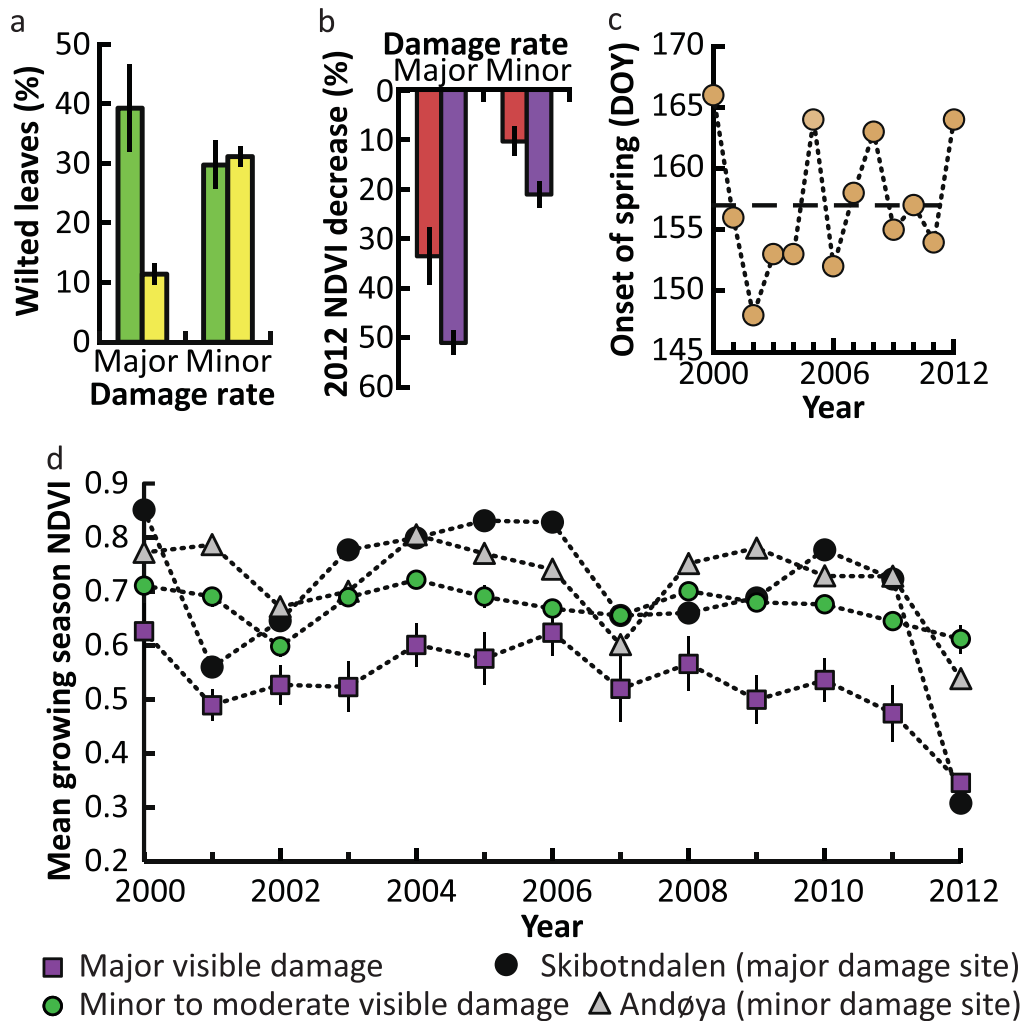


Figure 4. Vegetation productivity responses to anomalous winter and spring weather. (a) Winter disturbance damage in evergreen plants at 46 winter disturbance sites, 36 with minor to moderate visible damage ('Minor'), and 10 with major visible damage ('Major'). Green bars: dominant evergreen species; yellow bars: low-occurring evergreen species. (b) Decrease of NDVI at the same 36 + 10 winter disturbance sites. Red bars: 2012 NDVI versus average 2000–11 NDVI; violet bars: 2012 NDVI versus maximum 2000–11 NDVI. (c) Phenological development during early growing season (stippled line: 2000–11 average; DOY: Day of Year). (d) Growing season NDVI of two selected sites and the average of the 36 + 10 sites with minor to moderate or major visible damage in 2012. The two selected sites are Skibotndalen, Troms County, an area with high damage to dominant evergreen plants and also much summer frost damage to herbs and biogenic stress, and Rambergaksla, Andøy, Nordland County, an area with low damage to evergreen plants and little damage due to other disturbance events. These two sites had a significant 58% and 27% reduction in NDVI compared to the average for 2000–11 (Skibotndalen: $t = 16.1, p < 0.001$; Rambergaksla: $t = 12.1, p < 0.001$). Error bars are ± 1 s.e.m.

$F = 4.8, p = 0.003$). NDVI in mid-July of sites with major and minor to moderate visible damage from summer frost were 24% and 11% lower than the 2000–11 average (figure 5(b)). The difference between NDVI in 2012 and the 2000–11 average was highly significant (one-sample t -test with 0 as test sample: $t = -10.6, p < 0.001$). Furthermore, the reduction was significantly higher in sites with major visible damage compared to sites with minor to moderate visible damage (one-way ANOVA: $F = 9.5, p = 0.004$). Intra-season NDVI development clearly shows that NDVI started to decline shortly after the late June frost event (figure A.11). The selected sites are open areas were ferns dominate among scattered trees. Thus, much of the reduced NDVI at these sites is due to the wilting of ferns, but other plants may also have contributed to this reduction.

Swamp woodland and farmland along flooded rivers were bent or completely damaged (figures 6(a), A.5g). NDVI of the flooded area was reduced by 56% compared to right before the flood (figure 6(b); $t = 5.4, p = 0.032$). NDVI in the same area normally does not change during this period of the summer ($t = -0.9, p = 0.472$). NDVI was reduced by 49% compared to average late-July NDVI (figure 6(b); $t = 4.9, p < 0.001$). The claims settlements paid to affected farmers were the second highest recorded (figure A.17).

Leaf injury due to sea salt spray was highest at low altitudes (figure A.14; $F = 35.4, p = 0.008$). NDVI declined by 37% from before the storm event until ca. two weeks after the event (figure A.15). NDVI for the period 28 July–4 August was 43% lower than the 2000–11 average for this eight-day period (figure A.16; $t = 7.6, p < 0.001$).

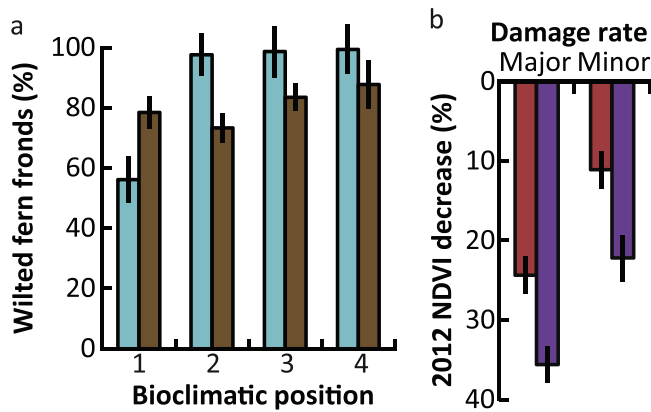


Figure 5. Vegetation productivity responses to summer frost events. (a) Summer frost damage in ferns at four sites along a coast-inland gradient. Turquoise bars: valley bottom; brown bars: valley slopes; Bioclimatic position: 1: oceanic; 2: intermediate; 3: inland; 4: continental. (b) Decrease of NDVI at 28 sites with major visible damage ('Major') and 7 sites with minor to moderate visible damage ('Minor'). Red bars: 2012 NDVI versus average 2000–11 NDVI; violet bars: 2012 NDVI versus maximum 2000–11 NDVI. Error bars are ± 1 s.e.m.

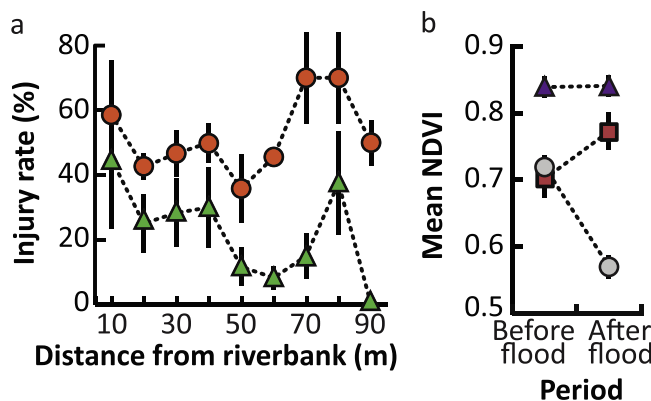


Figure 6. Vegetation productivity responses to summer flooding. (a) Flooding damage in swamp forests at four sites along the major watercourse that was flooded in 2012 (circles: willow; triangles: grey alder). (b) Mean NDVI of three polygons along the same watercourse, in total comprising 37 km². Squares: average 2000–11 NDVI; triangles: maximum 2000–11 NDVI; circles: 2012 NDVI. Values are mean NDVI for the growing season periods before and after the date of the 2012 flood. Error bars are ± 1 s.e.m.

3.3. Outbreaks of plant pests and effects on plants

During the peak growing season outbreaks of leaf-attacking insects caused major leaf defoliation of trees and shrubs (figure 7(a), A.5e), and rust fungi caused premature autumn yellowing of willow trees (figure A.5j).

Areas with high moth larval density experienced a significant 16% reduction in peak NDVI compared to the average for 2000–11 at the coast (figure 7(b)) and a 27% decrease at the upland site (figure 7(c); $t=23.4$, $P<0.001$). At this upland site, hardly any birch leaves were left on the trees, and dwarf shrubs at the forest floor showed considerable browning after the outbreak (figure A.5e), experiencing a 31% reduction in NDVI (as measured by a handheld proximal

sensor) compared to unaffected, green patches nearby (appendix A2.B).

Willow trees (*Salix* spp.) within the NAR were severely attacked by a bud-mining moth, a leaf-defoliating beetle and a pathogenic rust fungus, having infestation rates between 15 and 50% (figure A.12). Infestations of the bud-mining microlepidopteran *Argyresthia retinella* were easily visible as the new leaves wilted and turned dark shortly after bud burst (figures A.5i, A.12). The leaf-defoliating larvae of the beetle *Chrysomela lapponica* reached high population densities and consumed large amounts of dark-leaved willow leaves giving the trees a naked appearance (figures A.5f, A.12). Willow rust had a severe outbreak at least in one area. Infested goat willow trees were completely yellow in mid-July (figures A.5j, A.12).

4. Discussion

Our plot records of plant damage correspond well with declines in NDVI. As the close relationship between these types of plant stress at plot scales and NDVI and/or productivity at larger scales is well established (e.g. Jepsen et al 2008, Bokhorst et al 2009, 2012a, 2012b, Hufkens et al 2012) we find it very likely that the field-observed damage also caused much of the recorded NDVI decline. In Central Sweden, south of the NAR, yearly monitoring of winter desiccation damage to a Scots pine (*Pinus sylvestris*) population is undertaken (Kullman 2014a). We do not know of any monitoring programmes that cover the types of plant stress reported here from the NAR. A few reports with descriptions of single events exist, but these are far too few to give a clear indication of the frequency of these types of plant stress. Our review of the literature from 2000 to 2011 shows that events causing reduced vegetation greenness occur almost every year (table A.1), and some of these are known to have caused massive reductions of NDVI at local or regional scales (e.g. Jepsen et al 2009, Bokhorst et al 2012a, Olofsson et al 2012). Due to the lack of long time series, it is challenging to directly assess the frequency and severity of the types of plant stress reported here. However, the MODIS NDVI time series at local and regional scales and our analyses of the frequency of weather events (e.g. of the frequency of summer frost events; appendix A2.A) clearly suggest that 2012 was unprecedented, at least within the time interval we have focused on here. This is also supported by monitoring data from a Swedish alpine site south of the NAR, which documented a dramatic floristic regression in 2012 (Kullman 2014b). Although we do not have monitoring data, we can also rely partly on our own (qualitative) observations made during many field campaigns every year since the 1980s. Our impression is that winter-related damage to evergreen shrubs has increased in frequency during the last 8–12 years (Bokhorst et al 2009, 2012a, 2012b, and unpublished observations). Similarly, recent outbreaks of leaf-defoliating moths have been of historically unprecedented severity (Jepsen et al 2008, 2009, 2011). Moreover, we have previously not seen summer frost, salt spray and flood

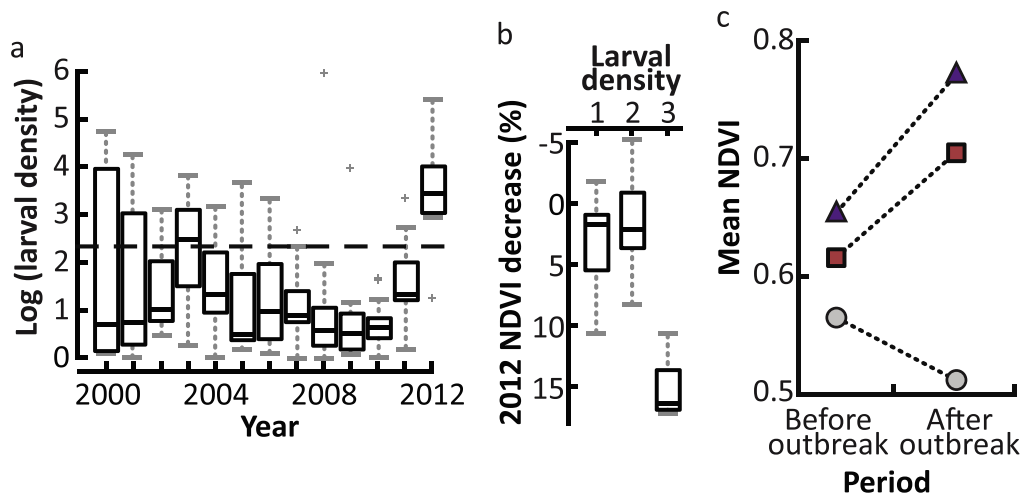


Figure 7. Vegetation productivity responses to geometrid moth outbreaks. (a) Densities of larvae of geometrid moths from 2000 to 2012 at 15 monitoring sites in coastal birch forest (stippled line: 2000–11 average). (b) Decrease of NDVI in coastal birch forest with variable densities of geometrid moths (1: low density; 2: intermediate; 3: high). (c) Mean NDVI of mountain birch forest attacked by geometrid moths. Squares: average 2000–11 NDVI; triangles: maximum 2000–11 NDVI; circles: 2012 NDVI). Error bars (± 1 s.e.m) are smaller than symbols in c. ‘Period’ in c refers to period before and after the 2012 outbreak event.

damage to the extent and of the severity as we report here for 2012.

The growing season of 2012 had the lowest mean summer temperature since 2000, and one could easily conclude that summer temperature constraints were the major factor for the observed decline in NDVI. However, the fact that the highest reductions in NDVI in 2012 were found in areas exposed to one or multiple stresses (figure 4), up to 8.5 times higher than the average reduction for the NAR (figure 4(d)), and that the NDVI of the NAR is not significantly correlated with growing season temperature (figure 3(b)) clearly suggest that the events reported here have contributed greatly to the observed decline in NDVI.

Estimations of the relative effect of each event, including cool summer temperatures, on the NDVI value for the NAR in 2012 are constrained by many uncertainties. First, many of the events are correlated in space and time; for example, summer frost events are associated with the generally cool summer weather, and sensitivity to winter freeze damage is related to autumn temperatures in complex ways. Since cold autumn temperatures stimulate frost hardening in plants (Sakai and Larcher 1987), the extremely warm autumn probably led to incomplete hardening, thereby making these species more vulnerable to winter damage. Second, the exact area affected by each of the events is unknown, and third, the severity of each event is not evenly distributed. However, based on the frequency and abundance of the vegetation types affected, we may infer that winter freeze damage is the event with potentially the largest negative impact, as vegetation types dominated by evergreen shrubs are abundant in all parts of the NAR (Haapasaari 1988, Oksanen and Virtanen 1995). Indeed, there have been major declines in primary productivity of dwarf shrub heaths in recent years due to winter disturbance (Bokhorst *et al* 2009, 2012a, 2012b).

Outbreaks of leaf-defoliating insects may also have large impacts, as birch is the dominant tree in large parts of the

NAR (Jepsen *et al* 2008, 2009). Although leaf defoliation of birch indeed affects the mean growing season NDVI (figure 7(b)), it does not necessarily have any strong effects on maximum NDVI (figure A.13). This is probably because the understory vegetation, which becomes more visible to the satellite sensors after leaf defoliation, has NDVI values that are similar to, or higher than, those of an intact birch canopy (van Wijk and Williams 2005, Bokhorst *et al* 2012b). Moreover, increasing light penetration and manuring from larval faeces stimulate the primary productivity of the understory vegetation during the same growing season (Karlsen *et al* 2013). Leaf defoliation most strongly affects NDVI in areas where moth larvae also defoliate understory plants, as we observed in the upland site in 2012 (figure A.5f), but even there, NDVI at the end of the growing season reached normal levels (figure A.13).

Summer frost occurred in all parts of the NAR (figure A.4). Thus, it may have caused reduction in NDVI in all ecosystems. However, visible damage to plants caused by summer frost was most striking in lowland valleys where thin-leaved plants are abundant (figure 5, A5c). These have very low freezing resistance, many not surviving frost of only -3 °C (Sato 1982). Plants with thicker leaves, which have higher freezing resistance (Sato 1982, Sakai and Larcher 1987), dominate upland sites and interior valleys. This may be the reason for less visible damage to these sites. However, even in such sites, we noticed that some plants, for example graminoids and deciduous dwarf shrubs, turned pale green or partly reddish (premature autumn colouring; figure A.10), and this decolouration was probably a frost response. Frost in the growing season has recently been shown to be a strong regulator of distribution ranges of broad-leaved trees in Europe (Kollas *et al* 2014). Most of the species that were visibly damaged by summer frost in 2012 have a coastal or lowland distribution in the NAR (Hultén and Fries 1986, Tigerschiöld 2000), avoiding areas that are more prone to

Table 1. Weather events and anomalies with relevance for the Nordic Arctic Region and their hypothesized effects on the physical environment of the biosphere and on plant productivity. Arrows indicate the predicted frequency change of the effects during the next 10–50 years. Hypothesized effects and predictions are based on literature cited in the main text and the appendix.

Weather anomalies/ events	Potential effects on the phytosphere environment	Potential effects on plant productivity	Prediction
		(1) Autumn-winter-spring	
(a) Autumn much warmer than normal	Snow-free ground, non-frozen soil	(I) Respiratory loss during low-light conditions. (II) Successful seed ripening and dispersal, and development of flower buds for next summer, which may enhance recruitment in coming years. (III) Reduced winter hardening, which makes plants more susceptible to cold injury.	↑ ↑ ↑
(b) Snow accumulation on unfrozen soil	Long-lasting snow cover. Insulation of understory vegetation and soil from ambient air. Soil-snow interface with temperatures close to 0 °C.	(IV) Reduced soil frost during winter, which reduces the risk for root injury. (V) Increased snow mould growth and microbial respiration. Snow mould may reduce grazing pressure, as it contains toxins, but may have negative effects on the plants that are overgrown.	↓ ↓
(c) Severe cold spells without or with very little snow	Unstable snow cover (often following thaw events; see (d) and (e)). No insulation of understory vegetation and soil from ambient air. Deep soil frost. Much hoar frost.	(VI) Increased risk for root injury. (VII) Winter desiccation of exposed plants, especially evergreens, and often associated with wind or high solar radiation. (VIII) Increased risk for wildfires due to high amount of dead, dry plant material. (IX) Damaged plants become more susceptible to pest outbreaks. (X) Increased mortality of geometrid moth eggs, which can reduce defoliation the subsequent growing season. Note: while VI–IX are expected to increase in frequency due to shallower snow depths, this effect is expected to decrease, as eggs are laid in canopies that are naturally free of snow.	↑ ↑ ↑ ↓
(d) Rain-on-snow events followed by refreezing	Snow becoming hard-packed, often with ice accumulating on the ground. Soil freeze deeper.	(XI) Anoxia damage in late winter when the ground-ice acts as a greenhouse, warming up the plants underneath the ice, most commonly occurring in agricultural fields. (XII) High mortality of large herbivores (e.g. reindeer) due to blocking of access to forage resources on the ground and small herbivores (e.g. lemmings) due to destruction of sub-nivean cavities, reducing grazing pressure. See also VI–IX and XIII.	↑ ↑
(e) Long-lasting warming events	Full or partial snowmelt. Increase of ground temperature. Thawing of soil.	(XIII) Instigation of spring development, involving deacclimation, of exposed ground vegetation and trees, which can result in major dieback upon return to freezing temperatures. See also VII–IX.	↑
(f) Heavy snowfall	Deep snow on the ground and in canopies, with or without soil frost (hence, differing from b).	(XIV) Breakage of trunks and branches of trees and shrubs. (XV) Force reindeer to graze in wind-exposed sites, thereby reducing the grazing pressure on leeward sites.	↓ ↓

Table 1. (Continued.)

Weather anomalies/ events	Potential effects on the phytosphere environment	Potential effects on plant productivity	Prediction
		(XVI) Flooding of watercourses during snow-melt, which can lead to major damage to floodplain vegetation. Mostly expected to decrease, but locally there may be increases. See also VIII–IX and XIX.	↓
(g) Storm activity	Removal of snow from canopies, exposing windward sites and packing snow on the ground in leeward sites	(XVII) Breakage of trees.	↑
		(XVIII) Salt spray damage to evergreen trees and shrubs when storms bring seawater to the terrestrial environment. See also VII–IX.	↑
(h) Spring colder than normal	Delayed snow and soil thaw.	(XIX) Delayed onset of growing season.	↓
		(XX) Increased mortality of newborn reindeer calves, especially when calving is associated with blizzards, eventually leading to reduced grazing pressure in the subsequent summer.	↓
		(2) Growing season	
(i) Frost in the growing season	Freezing temperatures on the ground, especially during clear sky nights	(XXI) Damage to leaves, especially newly developed leaves on plants with low freezing resistance such as thin-leaved herbs and ferns, and damage to floral organs. May increase in frequency with increasing length of growing season. See also VIII–IX.	↑
(j) Summer colder than normal	Low ground and canopy temperatures, often associated with much rainfall and occasional frost (see (i) and (k))	(XXII) Slow development, which may cause incomplete seed ripening and leaf development, the latter making the plant more susceptible to cold injury during the subsequent winter.	↓
		(XXIII) When coinciding with geometrid moth outbreaks, this may lead to increased defoliation of the tree canopy due to slow compensatory leaf growth, and extensive defoliation of understory plants due to insufficient amount of forage resources in the canopy. See also IX.	↓
(k) Heavy rainfall	Direct effects of rain force and flooding	(XXIV) Damage to floodplain vegetation.	↑
		(XXV) Physical damage to plants and plant organs, e.g. flattening of grasslands. See also IX.	↑
(l) Storm activity	Direct and indirect effects	(XXVI) Breakage of trunks and branches, and destruction of flowers and fruits.	↑
		(XXVII) See XVIII, but in summer also affecting deciduous plants. See also IX.	↑
(m) Early growing season much warmer than normal	Early snow melt and soil thaw	(XXVIII) Higher probability of increased plant productivity, if avoiding temperature backlashes, see XXI.	↑
		(XIX) Early plant development that may lead to asynchrony with pollinators, thereby reducing reproductive success.	↑
(n) Mid-season much warmer than normal	High temperatures, including extremes. Often associated with reduced rainfall.	(XXX) Higher probability of increased plant productivity, if avoiding drought effects, see XXXI.	↑
		(XXXI) Drought currently not having a strong effect on ecosystems in the NAR, but may occasionally become a problem in the most continental regions of the NAR.	↑
		(XXXII) Increased risk for wildfires.	↑

freezing temperatures in the growing season, for example upland sites or the most continental sites. These distribution patterns therefore suggest that growing season frost events have a similar regulatory role for distribution ranges of thin-leaved plants, such as summer-green ferns and wood stitchwort (*Stellaria nemorum*, figure A.8), as they have for broad-leaved trees (Kollas *et al* 2014). Warmer spring temperatures will lead to earlier onset of the growing season, hence increasing the risk for temperature backlashes and exposure to frost after deacclimation (Hufkens *et al* 2012, Jönsson and Barring 2011). Thus, climate change may reduce the distribution ranges of thin-leaved summer-green plants along with increasing frequency of freezing temperatures after spring deacclimation.

The remaining weather and biogenic events that we have reported here to cause plant stress were on more local scales, but may become more frequent and affect larger areas as climate change progresses. Precipitation rates and storm activity during the growing season are projected to increase over northern latitudes (Beniston *et al* 2007, Hov *et al* 2013, Stocker *et al* 2013), thereby increasing the risk for flood and sea salt damage beyond the extent seen in 2012.

Outbreaks of leaf-defoliating moths have increased in frequency and severity in recent decades, and it is likely that this process will continue (Jepsen *et al* 2008, 2011). There are to our knowledge no earlier reports in the literature of such heavy rust fungal infestations of willow in the NAR, but this is a well-known pest in temperate regions (Pei and Hunter 2000). This may therefore be the first sign of a new pest establishing in the NAR, which may become more frequent along with the prolongation of the growing season. The leaf-defoliating beetle *Chrysomela lapponica* and the bud-mining microlepidopteran *Argyresthia retinella* are also examples of insect pathogens that may become more frequent at high northern latitudes (Tenow *et al* 1999, Zvereva *et al* 1995, Gross *et al* 2007).

Winter climatic change at high northern latitudes causes decreased seasonality and increased oceanicity (Xu *et al* 2013). This implies that continental ecosystems with currently stable winter climate and snow cover and a recent greening trend may be more vulnerable to winter stress in the near future, as the snow cover will become more irregular and expose plants to ambient fluctuations in temperature (Crawford 2000, Liston and Hiemstra 2011, Bokhorst *et al* 2009, 2012a). These areas may also experience increased diversity of pest insects and plant pathogens with increasing growing season length, as reported here for the NAR. Overall, these changes may portend a decoupling between ongoing and predicted growing season warming and vegetation productivity (Xu *et al* 2013). From this perspective, it is highly uncertain whether the ongoing greening trends of high-latitude continental areas in the Arctic will persist, unless the effects of increasing summer temperatures and northward migration of more thermophilous plants with higher leaf area become so strong that this will mask the stress effects of anomalous weather events and pest outbreaks. For warmer continental and oceanic regions north of the Arctic Circle where primary productivity is less dependent on summer

temperatures (Xu *et al* 2013; see also figure 3(b)), the predicted increase in frequency of extreme climatic events (Jentsch *et al* 2007, Smith 2011, Stocker *et al* 2013) may cause a shift from stable to browning trends (Crawford 2000). There is therefore immediate need for more attention to the role of steadily increasing weather events and climate change-induced pest outbreaks in regulating productivity and ecosystem change in the Arctic. Monitoring programmes for the areas north of the Arctic Circle may therefore draw on programmes designed for warmer biomes, where some of these events and outbreaks are implemented (e.g. Lindenmayer *et al* 2010, Peters *et al* 2012). However, to our knowledge, there are no monitoring programmes that satisfactorily cover all the events we have presented here. As a tool to incorporate weather events and anomalies in monitoring programmes, we summarize the events and anomalies considered relevant for the NAR, and probably also for the entire Pan-Arctic region (table 1). Fourteen events and anomalies with 32 potential effects on plant productivity are proposed. Of these effects, we hypothesize that 23 are likely to increase in frequency with increasing climate change. Positive effects that are predicted to increase in frequency are mostly related to increasing average temperatures and include increased seed production due to warmer autumn temperatures, and higher probability of increased plant productivity due to increasing growing season temperatures. Weather events may affect plant productivity positively mostly by reducing population sizes of herbivores. Overall, the large majority of the effects described in table 1 are negative for plant productivity. This further emphasizes the importance of including stress events and their effects in modelling and monitoring.

5. Conclusions

Elucidating the factors causing the weakening of the positive relationship between high-latitude productivity and summer temperature can only be achieved through research campaigns that integrate measurements (both in the field and via remote sensing), manipulative studies, and ecological modelling (Williams *et al* 2011, Callaghan *et al* 2013, Johansson *et al* 2012). Residing at high northern latitudes and able to arrange field campaigns at short notice (and able to compare results with our own qualitative observations over 30 years), we documented the multiple anomalous weather and biogenic events causing plant stress to numerous vegetation types, thereby capturing an excellent example of a water year with anomalously low plant productivity. Many major events of biological and physical origin directly or indirectly caused by climatic change and with negative effects on primary productivity have been reported from the NAR during our focal interval (table A.1), suggesting that such events are common. Hence, the productivity of this region seems to be partly regulated by these events. The total pressure of these events on plant productivity should for some years, such as 2012, be termed extreme (see. Smith 2011). Although the NAR only makes up a small fraction of the land area north of the Arctic Circle, this study shows how multiple stressors may coincide

and interact, and hence the results are valuable for highlighting the potentially large effects of partly understudied processes on Arctic plant productivity. The lack of long time series and programmes for monitoring plant stress impede a detailed evaluation of the frequency of the types of plant damage reported here. As also concluded by the IPCC group for Polar Regions (Larsen *et al* 2014), we see an urgent need to incorporate such monitoring in on-going Arctic monitoring programmes in order to better understand how factors other than average summer temperature, drought and wildfires (Angert *et al* 2005, Goetz *et al* 2007, Groisman *et al* 2007, Zhao and Running 2010, Beck and Goetz 2011, Berner *et al* 2012) affect primary productivity.

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