Legacies of historical exploitation of natural resources is more important than summer warming for recent biomass increases in a boreal-arctic transition region

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Norwegian Institute for Nature Research

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Submission of a manuscript to Ecosystems

Dear Editors,

We hereby submit the revised manuscript "Legacies of historical exploitation of natural resources is more important than summer warming for recent biomass increases in a boreal-arctic transition region" written by Hans Tømmervik, Jarle W. Bjerke, Taejin Park, Frank Hanssen and Ranga B. Myneni for eventual publication in Ecosystems.

We thank the Editor and Reviewers for a comprehensive review of our manuscript. We have revised the manuscript according to the textual remarks by reviewer 2 + a minor error we found in the caption of table 3, and hope this will suffice for publication in Ecosystems.

Sincerely,

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Legacies of historical exploitation of natural resources is more important than summer warming for recent biomass increases in a boreal-arctic transition region

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Abstract

Eurasian forest cover at high northern latitudes (>67 °N) has increased in recent decades due to stimulatory effects of global warming, but other factors may be important. The objective of this study is to compare the importance of historical human exploitation and climate change. Periodic information on forest and tundra resources along with human and domestic animal population and forest harvesting were collected from sources like official statistics and maps and compiled for joint analysis. Our results show that the northernmost birch and Scots pine forests of the World often presumed as pristine, were repeatedly exploited by logging, agriculture and grazing the last century. In addition, repeated moth outbreaks have also had regulatory impacts on birch forest development. Despite, these disturbances, forested area quadrupled during the period, largely because of reduced human activities in recent decades. Linear modelling confirms that the most important predictors for the variation in Scots pine and birch biomass and area were logging, grazing and farming activity, and not climatic changes. The dynamics in the forest cover over the last century seem to follow the 'repeated human perturbation' scenario. This study's application of legacy data, historical and long-term data and evaluation of how the different drivers impacted some of the northernmost forests is essential to understand if the greening of the boreal and arctic regions is a result of recent climate change or a recovery from earlier human impacts.

Key-words: northernmost forests, Scots pine, downy birch, historical data, biomass, NDVI, remote sensing, grazing, harvesting, Second World War.

Manuscript highlights

- **Historical land use data may contribute to distinguish between impacts of recent climatic change and prevailing impacts of historical exploitation.**
- **Historical exploitation of wood resources and farming, including grazing, over the last century was confirmed to be more important than climatic change for current forest area and biomass.**
- **The area of forests quadrupled during the last century, due to reduced human activities in recent decades.**

Introduction

Land plant cover at high northern latitudes (> 67 °N) is subject to rapid change. Much of the change is a direct consequence of the stimulatory effects of a longer and warmer growing season, concomitant with thawing permafrost. Temperature is a principal climate variable in the framework of global warming and the largest temperature increase is projected at high northern latitudes (IPCC 2013). Recent climate warming has led to increased biomass in large parts of the Arctic, a process known as "the greening of the Arctic" (Xu and others 2013; Park and others 2016). This greening trend is largely due to increased establishment and growth of tall shrub communities and sub-Arctic birch forests onto former non-shrub tundra (Tape and others 2006; Tømmervik and others 2009) which then replaces the low-statured tundra dominated by lichens, bryophytes, small herbs and graminoids. These types of tundra may therefore be under threat by climate change impacts in concert with grazing and herbivory (Tømmervik and others,2004; Jepsen and others 2009; Callaghan and others 2013; Fauchald and others 2017).

Indirect effects of climate change also drive vegetation changes, but not necessarily towards increasing biomass. It is known that the increased frequency of drought and wildfires has led to reduced growth of biomass in the boreal and continental areas on both the North-American and Eurasian continents (Goetz and others 2007, Williams and others 2011; Abatzoglou and Williams 2016; Abis and Brovkin 2017). Still, greening has been significantly greater than browning in the same regions during the last three decades (Park and others 2016).

The expansion of invertebrate pests has also led to reduced biomass at both continents (de Beurs and Townsend 2008, Jepsen and others 2009). Extreme climatic events can also cause damage to vegetation and induce plant cover change. Examples of such events are extreme winter warming (Bokhorst and others 2009; Bokhorst and others 2012a; Bjerke and others 2014; Bjerke and others 2017), extreme rainstorms and floods (Bjerke and others 2014;

Bjerke and others 2015; Komatsu and others 2016), and frost in the growing season (Bjerke and others 2014; Friesen and others 2014).

Direct and indirect effects of climate change are not the only drivers of arctic plant cover change. Increasing land use, intensified forestry practices, industrialization, and air pollution have locally caused massive reduction of plant biomass in some northern regions (Odasz-Albrigtsen and others 2000; Tømmervik and others 2003; Kibsgaard 2011). Unsustainable exploitation of resources is not a new behaviour, though. For example, already in 1685, the government of Denmark-Norway commanded the local governors and sheriffs in northern Norway to manage the forests in a sustainable way, and this included conservation measures: one of the World's northernmost Scots pine (*Pinus sylvestris*) forests (Alta, Finnmark) was protected this same year (Kibsgaard 2011).

Exploitation of natural resources for herding of semi-domesticated reindeer is another example of land use that may induce environmental change in boreal-arctic transition areas. Tømmervik and others (2004, 2009) reported that the birch forest area in the continental parts of Finnmark (Finnmarksvidda) in the Norwegian Arctic doubled from 1957 to 2006, hence transforming the former tundra into shrub tundra or forest. This change was largely driven by a technical revolution in reindeer husbandry, allowing for a more extensive use of Finnmarksvidda as grazing area, as herders could access the more remote areas by means of snowmobiles and helicopters (Riseth and others 2017), which resulted in excessive use of the lichen tundra and increased establishment of vascular plants through the removal of the so-called lichen barrier which hampers plant seeds to reach the soil layer (Tømmervik and others 2004). Increased mobility and increased pressures towards commercialization have led to increasing reindeer herds in Fennoscandia (Tømmervik and others 2012). Overabundance of reindeer puts considerable pressure on primary productivity and causes reversible vegetation changes (Hofgaard and others 2013; Tømmervik and others 2012). Domestic livestock like cattle, goat and sheep may also reduce the cover of forest in boreal-arctic transition regions (Hofgaard and others 2013).

The importance of legacy effects of human land use were prominently emphasized through the papers of Fuller and others (1998), Foster and others (1998) and recently by Bürgi and others (2017). Past events such as climate fluctuations, natural disturbances, or human activities can cause disequilibrium dynamics (Normand and others 2017) that may induce either transient or persistent vegetation changes (Svenning and others 2015). Disequilibrium might occur either when the vegetation is too slow to respond to a perturbation, or if it lags behind a directional change in the environment caused by a change in the climate or continued human activity (Bürgi and others 2017). Evidence of human legacies and impacts on arctic environments, both on temporal and spatial scale, is sparse (Kuuluvainen and others 2017, Normand and others 2017). Hence, to understand and predict ongoing vegetation changes in arctic and boreal regions, the legacies of historical human impacts and activities need to be revealed and assessed (Kuuluvainen and others 2017).

Remotely-sensed temporal studies of circumpolar and circumboreal changes in biomass generally have low spatial resolution and do not focus much on regional change in cases where it deviates from the larger-scale trends (Xu and others 2013; Epstein and others 2012; Park and others 2016). To better understand the trends, this study focused on one region which enabled multiple long-term datasets on environmental impacts to be coupled to time series on forest and tundra biomass. Specifically, our objectives were to evaluate how the forest extent and biomass varied over a 100-year period and to identify potential drivers of any vegetation change.

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Study area

The study area comprises the whole of Finnmark County in northern Norway, situated between 68°38' and 71°11' N, an area that covers 48,631 km^2 including freshwater (Figure 1). The landscape of Finnmark is mountainous and comprises non-forested coastal heaths, sheltered fjord areas and river valleys, arctic tundra, and sparsely forested upland plateaus (Oksanen and Virtanen 1995; Moen 1999; Hofgaard and others 2013, Bjørklund and others 2015; Virtanen and others 2016). The county has, for these latitudes, a very mild, maritime-buffered climate (Moen 1999). Summer drought and wildfires are virtually non-existent due to the oceanic climate. Instead, outbreaks of leaf-defoliating moths and winter warming events currently drive the vegetation change in the area (Jepsen and others 2009; Bokhorst and others 2009; Bjerke and others 2014). The annual temperature varies from 1.5 °C in coastal areas to 2.5 °C in inland areas with an overall increase of 1–2 °C during the last 100 years (Førland and others 2013). Annual precipitation increased ca. 2–3% per decade over the same period and varied between 300 and 500 mm (1961–1990; Førland and others 2013).

The dominating tree species in the study area is downy birch (*Betula pubescens*), while Scots pine (*Pinus sylvestris*) forests grow at lower elevations across the inner part of the county. The World's northernmost Scots pine forests and some of the World's northernmost birch forests are situated in Finnmark (Wielgolaski and Sonesson 2001). The altitudinal limit of the tree and forest line of both species is mostly located below 100 m alt. (Wielgolaski 2005). All parts of the county are utilized as rangelands for semi-domesticated reindeer, domestic sheep, wild moose and rodents. Wood resources in Finnmark have been exploited since the stone age (Sjögren and Damm 2018). It was documented that as early as the beginning of the 17th century, Finnmark's birch and pine forests were extensively logged and utilized for fuelwood and construction wood (Kibsgaard 2011) and outfield clearing for extension of grazing land. In 1743, restrictions on logging in Finnmark were implemented due to rapidly decreasing stocks of standing timber (Kibsgaard 2011). After a period with reduced forestry, logging activity escalated during the Second World War when large forests were exploited by the German troops, especially near infrastructure, settlements and towns (Kibsgaard 2011). In addition, in periods of approximate 10-y cycles, the birch forests are attacked by leaf-defoliating larvae of geometrid moths, and ca. 25 % of the forest was damaged during the large 2002-2006 outbreak (Tenow and others 2007; Jepsen and others 2009; Tomter 2012). Severe outbreaks were also recorded in the 1920s, 1930s and 1960s (Tenow 1972). Forest fires in Finnmark are rare and only two fires with some extent have been reported (Øyen 1998), one in Karasjok in 1884 which burned down 20 km^2 of pine forests and 100 km^2 shrub and lichen tundra (Figure 2) and one forest fire with an extent of 20 km^2 in Pasvik (Kirkenes) in 1945. According to Øyen (1998), the total burned forested area in the period 1949 to 1987 was 13.6 km^2 which is less than the reported burned forest area of 33.5 km^2 in the period 1870-1900.

Methods

Digitization of historical forest maps

The National Forest Map for Norway from 1914 (The General Director for Forestry in Norway 1914) includes information on the spatial extent of agricultural land, coniferous forest, deciduous forest and non-forested land. Using this map, we estimated the early 20th century forest and land cover (Table 1). A digital version of this map for Finnmark was produced in the UTM 33 North (WGS84) base map projection (Figure 2) by using ArcGIS 9.3 (see methods in Hofgaard and others 2013). For further information of historical maps see Methods S1 in the Supplementary Information.

Digital topographic and vegetation maps for the period 1990-2012

Digital topographical maps with land cover information were used to represent the second half of the 20^{th} century (Table 1). A vegetation map for Finnmark based on the satellite images acquired during 1998-2003 (Johansen 2009) was used for estimating biomass and area extent for the year 2003 (Table 1). The overall accuracy of this vegetation map was estimated to be between 75 and 85 %, depending on vegetation type (Tømmervik and others 2009).

Monitoring of forests and biomass

Analyses of longer-term changes are based on forest surveys (Table 1). The most commonly used methodology is the resurvey of field plots from previous decades (Tomter 2012, Bjørklund and others 2015). Investigation of aerial photographs is useful tool for studying longer-term changes (Hofgaard and others 2013). On the basis of the different forest and land

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cover maps and sources listed in Table 1, forest and land cover statistics were calculated using ArcGIS 10 (ESRI®ArcMap™ 10.0) and by the image processing software ENVI 5.4 (Exilis Visual Information Solutions - Harris). Additional forest and land cover statistics from Statistics Norway and Norwegian Institute of Bioeconomy Research were used (Table 1). These statistics were applied along with the map-based statistics to assess the dynamics of the vegetation in the study area for the period 1907-2012. In order, to estimate the live above ground biomass, we used different sources and methods described in Supplementary Information (Tables S1-S2).

Monitoring using earth observation

To capture inter-annual vegetation change and eventual rate of growth in the study area over the last three decades (from 1982 to 2015), we used the Global Inventory Modelling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) dataset obtained from the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard the NOAA satellite (series 7 to 19). NDVI is a global vegetation indicator combining the red and near-infrared (NIR) reflectance and has been broadly applied as a proxy of vegetation leaf area, biomass and physiological functioning (Tucker 1979). The latest version of GIMMS NDVI3g provides the longest, continuous, and consistent global vegetation records which span 1981–2015 with a native resolution of 1/12° at bimonthly temporal resolution (Pinzon and Tucker 2014). The Growing Season Integrated NDVI (GSINDVI) has been shown to be a good proxy for vegetation gross primary productivity (Goward and others 1985; Wang and others 2004; Park and others 2016). In this study, we derived long-term GSINDVI from 1982 to 2015 using the fixed growing season period (i.e. June to August), as well as the maximum annual NDVI (MaxNDVI), which is known as a good proxy of plant biomass in high-latitude

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environments (Epstein and others 2012). From 2000 to 2015, we also extracted the same parameters from the latest version (Collection 6) of the Moderate Resolution Imaging Spectroradiometer (MODIS) product suite (Didan 2015). Prior to deriving the parameters from both GIMMS and MODIS, we performed the pre-processing steps to maintain distinct seasonal vegetation trajectory and minimize spurious signals (e.g., cloud and snow) in the NDVI time series (Park and others 2016).

Statistical analyses and potential factors/drivers

Potential factors and drivers of forest dynamics were analysed and assessed using statistical analysis. This includes statistics of time series on the number of farms, forest harvests, fire wood consumption per farm, number of domestic livestock, number of semi-domestic reindeer and climatic data (temperature and precipitation), published by the Central Bureau of Statistics of Norway (now Statistics Norway), the Norwegian Mapping Authority and the Norwegian Meteorological Institute (Table 1). Considering uncertainties in the forest area statistics (see Supplementary Information), other statistics, like number of farms, livestock numbers and forest harvest have been reported to Statistics of Norway once per decade back in time (Central bureau of Statistics of Norway – Statistics Norway 1960), and it is the status of each parameter in the end of the year that counts, except for the semi-domestic reindeer that are counted before calving on 31st March each year (Norwegian Agriculture Agency 2017). Uncertainties in the different statistics may exist and were at the highest during the Second World War and the following 3 years, since most of the human population was evacuated from Finnmark and most of the livestock was slaughtered. To assess which factor/driver had the greatest influence on the forest biomass, we correlated the above-mentioned factors (predictors and response variables) using automatic linear modelling (Yang

2013). Model selection and linear trend analyses were undertaken using SPSS Statistics 25 (IBM Corp., NY, USA). We used Pearson Correlation Coefficient for the analyses of the different parameters/factors. For predictors (pressures or drivers) assumed to have an impact on response variables, we use 10-y averages in the correlation estimations and linear modelling, this to emphasize that a given response variable is not mostly affected by the current-year value, but the levels in the recent historic past. Since we do not have data from every single year, we decided to use 10-y averages. Thus, as an example, the 10-y average value for tree harvest in 1959 is the mean of the values from 1949 and 1959 (no values available for the years 1950-1958). The trend analyses of GIMMS and MODIS data were calculated using Vogelsang's t-PS_T test (Vogelsang 1998). Percent trend is calculated with respect to mean values of 1982-2015.

Results

The conversion of non-forested areas to birch forest from 1914 to 2012 is shown in Figure 2. The figure shows that large areas in the southern and inner part of Finnmark were converted to birch forests during this period. However, the extent of forests varied considerably during the period from 1893 to 2012 (Figure 3). Forest cover in 1893 was estimated to be 3634 km^2. The first forest map, published in 1914, estimated the pine and birch forest cover to be 1250 and 6255 km^2, respectively, viz. a total of 7505 km^2, with a standing biomass of 14.21 mill. metric tonnes (Table 2). At the end of the Second World War, the areas of pine and birch forests were estimated to be around 700 km^2 and 6300 km^2, respectively, with a standing biomass of 9.55 mill. tonnes (Table 2). After a slight increase from 1949 to 1959, both forest types were again reduced, and in 1969, covered 758 and 5924 km^2, respectively, hence a total area of 6682 km^2 and a standing biomass of 11.3 mill. tonnes (Table 2). During the last four to five decades, the forest has expanded, it currently (i.e. 2012) covers 15357 km^2, of which 1347 km^2 are Scots pine forests and 14007 km^2 are birch forests. However, a reduction of almost 2500 km^2 of the birch forest was reported from 2003 to 2009 (Table 2). The standing forest biomass in 2012 was estimated at 24.55 mill. tons (Table 2). The tundra biomass decreased substantially from 1914 to 2012 (Table 2).

Factors influencing the dynamics of the forest and tundra systems

The number of farms increased by 42 % from 1907 to 1939, with a subsequent decrease by 95 % from 1939 to 2012. The number of domestic livestock (horse, cattle, goat and sheep) increased by 124 % from 1907 to 1939 and subsequently was reduced by 40 % from 1939 to 2012 (Table 2). The number of reindeer decreased by 43 % from 1907 to 1949 with a subsequent increase of 310 % from 1949 to 2012 (Table 2). The forest harvest (roundwood cut) and fuelwood extraction by the farms and the Finnmark Estate Agency (a state-owned company) increased by 81 % from 1907 to the end of the Second World War (1944), largely due to an extreme exploitation of forest resources by the German army (Figure 3). After the Second World War and until 2012, harvesting of timber and wood decreased by 77 % (Table 2). The mean growing season temperature (JJA) varied significantly during this period but shows an overall increase of 1.1 °C from 1894 to 2015 (Figure 4). The mean growing season precipitation increased from 130 mm to 150 mm, a near-significant increase ($r = 0.165$, $P = 0.069$; data not shown).

Relationships between forest biomass and explanatory factors

In Table S3, we present a correlation matrix for the period 1914 to 2012 including the parameters of highest importance from the linear modelling, with 10-y averages for all predictor variables. Mean JJA 10-year temperature and Mean JJA precipitation 10 year were correlated with year ($r = 0.62$, $P = 0.024$ and $r = 0.85$, $P < 0.000$). Mean JJA 10-year temperature and Mean JJA precipitation 10 year were not significantly correlated with the birch forest area ($r = 0.38$, $P = 0.195$, and $r = 0.29$, $P = 0.332$ but inclusion of the years 1900 and 1907 in the analysis showed that, the JJA 10-year temperature was significantly correlated with the area of birch forests ($r = 0.59$, $P = 0.025$). Birch and pine forest areas were significantly correlated with the biomass for the same forests ($r = 0.98$, $P < 0.000$ and $r = 1.0$, $P = 0.000$). Birch forest area was strongly correlated with the 10-y averages of reindeer numbers ($r = 0.83$, $P < 0.000$) and negatively correlated with the 10-y averages of number of farms ($r = –0.71$, $P = 0.006$) and total forest harvest ($r = -0.76$, $P = 0.002$). Pine forest area was significantly correlated with most of the same factors as birch forest area (Table S3). For example, it was negatively correlated to 10-y averages of number of farms ($r = -0.74$, $P = 0.004$) and 10-y averages of pine forest harvest ($r = -0.86$, $P < 0.000$).

Best linear models for forest and tundra development

The best linear models for the area and biomass of forest and tundra have high accuracies (>79 %) and show some consistent patterns (Table 3). The extent and biomass of birch forest, total forest and tundra were largely explained by 10-y average reindeer numbers. This predictor explains between 43 % and 84 % of the best models for these response variables. While birch and total forest are positively related to reindeer numbers, tundra is negatively related. The most important predictor for variation in Scots pine biomass and area is 10-y average logging activity of Scots pine which explains 60 % of the variation. Five additional predictors were included in the best models for forest and tundra trends, explaining between 9 and 40 % of the variation in response variables. The number of farms is included in the best models for birch and total forested area (positive coefficient) and tundra areas (negative coefficient). Number of farms is the second-most important predictor for birch area and total forested area, and this has a positive coefficient while the farm number is negatively correlated with birch area ($r = -0.61$, $P = 0.026$) and total forested area ($r = -0.63$, $P = 0.021$). However, both farm numbers and birch area increase during the interwar period (r for 1907-1939 = 0.57). Fuelwood demand is included in the best models for Scots pine biomass and area (positive) and tundra biomass (negative). Fuelwood demands came out as the third-most important predictor for Scots pine, but with a positive coefficient, despite these factors being negatively correlated for the whole study period ($r = -0.78$, $P = 0.002$). Domestic livestock is included in the best models for Scots pine area and biomass (negative) and birch (positive). Finally, birch logging is in the best model for birch biomass and total tree biomass (both positive). We also elucidated causes for variation of forest harvesting activities over time. Farm numbers largely explain birch harvest volumes, total forest harvest volumes and fuelwood demands, explaining between 28 and 100 % of the variation (Table 3). Population number is the second-most important variable, explaining 69 % of the Scots pine harvest and

62 % of fuelwood demands. Domestic livestock and JJA temperature are also included in best models for some variables, but with low importance as compared to farm and population numbers

Remotely-sensed monitoring of forest change (1982-2015)

The growing-season integrated NDVI (GSINDVI) based on GIMMS increased by 8% from 1982 to 2000 (Figure 5, Table S4). Index values were stable from 2000 to 2010, while the period from 2010 to 2015 showed an increasing trend, albeit with one deviating year (2012). The GSINDVI trend (Figure 6) was positive for the period (1982-2015) as a whole ($r = 0.46$, $P = 0.007$) and shows a positive correlation ($r = 0.61$, $P < 0.001$) with JJA temperature. The MODIS-based GSINDVI (Figure 7) did not show any significant temporal change from 2000 to 2015 ($r = 0.41$, $P = 0.113$) and was not correlated with JJA temperature ($r = 0. 41$, $P = 0.114$). Trends were stronger for GIMMS than for MODIS MaxNDVI for both periods 1982-2015 and 2000-2005 (Figures S1-S2). The correlation between GIMMS and MODIS (2000-2015) is weak (Figure S3, Table S5).

Discussion

We revealed a pattern of strong anthropogenically induced forest dynamics in some of the northernmost forests of the world (Wielgolaski and Sonesson 2001), which may be perceived as pristine (Steen Jacobsen and Tømmervik 2016) or last primary forests (Sabatini and others 2018), and often referred to as part of "Europe's last wilderness" (Kuuluvainen and others 2017). The human-induced dynamics reported here were either unknown or rarely reported in the scientific literature. However, reports of overutilization, and subsequent regulation, of the exploitation of the Finnmark forests for fuel and construction wood dates back before 1685 (Kibsgaard 2011). This clearly suggests a long history of over-exploitation of forest resources with persistent legacies in this seemingly pristine part of Fennoscandia (Steen Jacobsen and Tømmervik 2016). In fact, some of the first stone age boats built by inhabitants of Finnmark and depicted as boat figures in ca. 5.000 year old rock art at the UNESCO World Heritage Site at Alta in Finnmark, were most likely hollowed out from local Scots pine trees (Klem 2012), which further emphasizes the very long history of exploitation of a scanty resource.

Following a century with large human and climatic disturbances, the extent of the forests more than doubled during the most recent 70-year period (1945-2015). This is in accordance with the mean northward advance of the birch forests which was significantly greater (8.3 km versus 6.5 km) in the period 1975-2009 than in the period 1914-1975, despite the last period (1975-2009) being shorter (Hofgaard and others 2013). The uphill advance followed the same trend as the northward advance (Tømmervik and others 2004, 2009). There are several reasons for the large fluctuation in forest cover and biomass in Finnmark during the last century. First, the general increase in Finnmark's human population from 1914 to 1940 resulted in increased demand for fuel and construction wood. This was a period when the electricity network was not existing or poorly developed, and electricity was expensive; thus, most private houses had to rely on wood for warming. Every farm had an annual demand of 4-20 m^3 of fuelwood in addition to wood for construction of fences and buildings (Central Bureau of Statistics of Norway 1955). Second, the increased population also gave rise to an increase in the numbers of domestic horses, cattle, sheep and goats, which further contributed to reduction in forest cover and biomass, especially around farms and settlements. Third, severe caterpillar (*Epirrita autumnata*) attacks almost once every decade since 1910, orchestrated by high egg survival during a series of mild winters, killed large areas of birch forest (Ruden 1949, Tenow 1972, Tenow and others 2007, Jepsen and others 2008)

Using the ideas in the roadmap proposed by Normand and others (2017), we analysed the data using linear modelling. This modelling approach provides evidence that the extent and biomass of birch forest, and the total forest and tundra can be largely explained by 10-y average reindeer numbers. This predictor explained between 43 % and 84 % of the best models for these response variables. While birch and total forest were positively related to reindeer numbers, tundra was negatively related. High reindeer densities at the near-coastal summer ranges may halt forest regrowth (Dalen and Hofgaard 2005; te Beest and others 2016; Bråthen and others 2018). However, density generally must exceed 5 reindeer per km^2 to instigate a reduction of shrubs and forests (Bråthen and others 2017). Thus, reduced grazing by domestic livestock along with a reindeer density lower than the threshold level will enable extensive natural regrowth of forests and shrubs, and hence, a return to the forested landscape of the 1960s (den Herder and others 2004; Tømmervik and others 2009; Bråthen and others 2017). A positive relationship between the numbers of reindeer and forest increase in Finnmark was also reported by Tømmervik and others (2004, 2009), but Dalen and Hofgaard (2005) and te Beest and others (2016) found a negative relationship. The most plausible reason for this discrepancy is that the two latter studies were of short duration (3 years) and were restricted to analyses of small reindeer fields close to fenced areas and within migration zones, which are strongly overpopulated during parts of the year, and consequently represent only the most extreme grazing pressures found in Finnmark (Tømmervik and others 2009; Tømmervik and others 2012). Thus, studies on larger regional and temporal scales are imperative to fully understand the impacts of reindeer on vegetation change (Fauchald and others 2017). Another important factor is the more extensive use of remote winter grazing areas following the technological revolution in the reindeer husbandry from ca. 1968 and beyond (Riseth and other 2017). This increased activity resulted in rapid removal of dense landscape-covering reindeer lichen mats, which again allowed for increased germination of birch seeds on soils which until then had been unavailable for birch due to the so-called lichen barrier (Tømmervik and others 2004, 2009).

Previous logging activity was the predictor explaining most of the variation in extent and biomass of Scots pine, while population size explained most of the variation in logging activity of Scots pine. The demands of wood and outfield forage increased considerably with the invasion of German troops, which over the war's 5-year period tripled the human population in Finnmark (Ruef 1984). At the end of the war, 168 000 m^3 of Scots pine was logged annually, which was 114 000 m^3 more than the annual growth (Ruden 1949, Kibsgaard 2011), resulting in a rapid reduction of Scots pine.

Number of farms is the second-most important predictor for birch area and total forested area, with a positive coefficient. This may seem counterintuitive, given that farm number is negatively correlated with birch area and total forested area. However, both farm numbers

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and birch area increase during the interwar period and this may likely be the reason for a positive coefficient in the linear modelling. Hence, in the linear model, reindeer number best explains post-war increase while farm number best explains the early 20th Century increase in birch area. However, the positive relationship between birch area and farm numbers may not need be causative. Instead, it is plausible that the increase of birch from 1907 to 1939 was a lagged response to the early 20th Century warming, which was a period of warmer summers (and winters) after a long, cooling period during the 19th Century (Luterbacher and others 2004). Thus, the likely reason for JJA temperature not being selected in the linear modelling approach is that our birch dataset does not include data from the 19th Century.

During the autumn and winter of 1944-45, almost all settlements and farms in Finnmark were burnt and destroyed by the Nazi German forces retreating from the attacking Soviet Russian army (Ruef 1984; Skogan 1993). After the war, there were massive demands for both construction wood and fuelwood to rebuild settlements (Ruden 1949; Kibsgaard 2011), which accounted for the dramatic decline in extent and biomass of both Scots pine and birch in the post-war period from 1945 to 1967. After 1967, the forest areas and biomass recovered and increased again. Our analysis shows that this increase corresponded with a decline in number of farms and domestic livestock, reduced demand for fuelwood, the latter largely because of fewer farms and a rapid development of electrical power for heating (Central Bureau of Statistics of Norway 1955 and the yearly reports by Statistics Norway). Fuelwood consumption came out positively as the third-most important predictor for Scots pine, despite these factors being negatively correlated for the whole study period. However, from 1949 to 1969, these two factors were positively related, both increasing from 1944 to 1959, then both showing a decline from 1959 to 1969 ($r = 0.305$ for this 25-y period). This may be the reason why fuelwood was selected as a positive factor in the linear modelling, and the relationship is probably not causative, as fuelwood demands were highest in coastal reconstruction fishing hamlets far from any major Scots pine forests (Ruden 1949; Kibsgaard 2011). Thus, despite high fuelwood demands, Scots pine area and biomass could increase from 1944 to 1959. This may also be the main reason why the best linear model shows a positive relationship between birch biomass and birch harvest: increasing availability resulted in increasing harvests from 1907 to 1929 (r = 0.744).

Post-war forest extent remained below pre-war extent until 1979. However, during a 10-y period from 1979 to 1989 the forest extent nearly doubled, and this was largely related to an increase in birch. This rapid increase in forest area biomass may be attributed to several factors. As shown above, reindeer is selected as the most important factor in the best linear models for birch, and this with a positive coefficient. The increase may therefore primarily be a result of the deterioration of lichen tundra during the technological revolution of the reindeer husbandry, which paved the way for increased establishment of birch on previous lichen tundra, as discussed above. In fact, reindeer number is also the most important predictor for tundra area and biomass, and there with a negative coefficient.

The extensive increase in birch from 1979 to 1989 in fact took place during a period of summer cooling (average JJA temperature: 1970-1979: 10.8 °C; 1980-1989: 10.2 °C). This shows that extensive shrubification in arctic environments can take place also during climate cooling. From 1979 to 1989, fuelwood demands declined by 29 %. Still fuelwood was not selected in the best models for birch area and biomass, even if fuelwood demands and birch biomass are strongly inversely correlated (r = –0.746, P = 0.003). The exclusion of fuelwood from the best model may be related to an increase of both factors from 1907 to 1939. Thus, the lagged warming response of early 20th Century of birch growth, as discussed above, was larger than the increasing fuelwood demands in the same period. Instead, fuelwood, with a negative coefficient, is the second-most important factor for tundra biomass, which likely is related to a 9 % decrease in tundra biomass from 1914 to 1944 coinciding with a doubling of fuelwood demands. Again, there may not be a direct causative link between these two trends but be related to birch establishing in tundra regions until 1939 due to a lagged climate warming effect.

The post-1979 continuous increase in forest extent and biomass halted in 2003. From 2003 to 2009, birch forest area declined by 21 % according to our field-based data and reports from the authorities (Finnmark Skogselskap 2010). Birch mortality caused by outbreaks of leaf-defoliating larvae of autumnal moths (Jepsen and others 2009) is the most plausible factor for this decline. Historical data on the extent and severity of moth outbreaks were too scanty to be included as a predictor in our linear modelling approach. However, literature records show that outbreaks have recurred every decade since the 1960s (Jepsen and others 2008). The last major outbreaks were from 2002 to 2008 and from 2013 to 2015 (Jepsen and others 2009, County Governor of Finnmark 2015), and more than 2000 km^2 of the dense birch forests were assumed to be partly or totally damaged during the first of these two outbreak events (Finnmark Skogselskap 2010). Regionally aggregated GSINDVI showed an increasing trend for the whole county from 1982 to 2015, but decreasing trends at local scales were also evident, and this is most strongly visible from 2000 to 2015 (Fig. 6). Declining trends are strongest in areas known to have been severely attacked by moths (Jepsen and others 2009). There are at least five possible reasons for the dominant increasing trends, despite severe damage from leaf-defoliating moths. First, the increasing birch forest area and biomass (Table 1) were superior to the damage caused by the moth outbreaks. Second, sporadic damage and following recovery may mask any possible decline of remotely sensed vegetative signals.

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Third, this could be that significant parts of the forest floor in dense birch forests attacked by the moths were turned into grass-dominated cover (Karlsen and others 2013), thereby quickly regaining high NDVI values (Bjerke and others 2014). Fourth, the Scots pine forest area shows a steady increase since 1979, without any decline in the 2000s, and thereby contributes to the increasing GSINDVI in pine-dominated parts of the county. Fifth, as much as 75 % of Finnmark is non-forested (Bjørklund and others 2015), and since remotely sensed GSINDVI is a composite result of signals from several vegetation types in addition to forest, any positive trends for mires, heaths and tundra will have strong effects on county-level GSINDVI trends.

Since we do not know the exact species composition of the birch and pine forests –especially back in time – it is challenging to assess previous disequilibrium dynamics (Normand and others 2017), a challenge which is intensified by the repeated human impacts in concert with biological pressures and climatic variability. Based on pollen analysis from a lake in the Finnish-Finnmark border area, Miller and others (2008) found a significant reduction of the biomass of Scots pine and birch over the last millennium. This is in accordance with the reported over-utilization of the forests in Finnmark during the 17th century (Kibsgaard 2011), but may also be related to a slow, but prevailing paludification process (Crawford and others 2003, Sjögren and Damm 2018). During the last century, the area and biomass of both species were significantly reduced to a minimum in 1960-70s which was followed by an increase during the last decades (Miller and others 2008). Overall, the equilibrium dynamics for Finnmark seems to follow the ‘repeated human perturbation scenario’ proposed by Normand and others (2017). A recent study by Song and others (2018) concluded that human land-use was the dominant driver of long-term global land-cover change, accounting for 60% of global land change from 1982 to 2017. This conceptually aligns with the argument being made here, which is that human land-use plays a larger role in vegetation change in the northern boreal forests than previously thought. Our study shows that the analyses of long-term data series (>100 years) and assessments of legacy impacts provide a much-improved foundation for the interpretation of the magnitude of current change and their causes (Bürgi and others 2017; Kuuluvainen and others 2017; Normand and others 2017). For our study area, the historical analysis sheds new light on factors influencing the longer-term dynamics of the arctic-boreal ecotone.

Conclusions

While northern-Eurasian forests (> 66°N) currently are gaining biomass, we show here an example of a large northern forest area that, due to variable human impacts and other factors, has undergone large fluctuations in area and biomass since 1900. Our study area may be considered as pristine to an untrained eye due to the lack of major human infrastructure, but we have shown that even this northern region, far from any major urbanized area, has a long history of human influence which continue to have major impacts on the forest and tundra structure. Linear modelling confirmed that the most important predictors were historical land use activities including grazing and not climate change. Overall, we conclude that the application of historical time series is essential for interpreting the importance and magnitude of current trends, for example whether the current greening trend of the boreal and arctic regions is a result of periods of climate warming or a restoration from human legacies or a combination of both, and we now understand that the latter is the case here.

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Data Accessibility

Data are stored internally in the Norwegian Institute for Nature Research Archives' and will be sent for deposition in a proper public repository if the manuscript is published.

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Table 1. Statistics, map and imagery data

Statistical map and image data	Scale	Year	Reference/Sources
Census of forestry and agriculture		1900-1907	Official statistics of Norway V 85, Statistics Norway
Forest map for northern Norway 1914	1:500.000	1910-14	The General Director for Forestryin Norway (1914)
Census of forestry and agriculture		1918	Official statistics of Norway VI 170, Statistics Norway
Census of forestry and agriculture		1917-1920	Official statistics of Norway VIII. 34 Statistics Norway
Census of forestry and agriculture		1920-1929	Official statistics of Norway VIII 134, Statistics Norway
Pine forest map for Finnmark and Troms counties 1925	1:1.430.000	1925	Juul (1925)
Census of Forestry		1930-33	Official statistics of Norway VIII 134, Statistics Norway
Census of forestry and agriculture		1939-1944	Official statistics of Norway X. 99, Statistics Norway
Census of forestry and agriculture		1927-1947	Official statistics of Norway X. 161, Statistics Norway
Census of forestry and agriculture		1949	Official statistics of Norway XI. 40, Statistics Norway
Forest map for northern Norway 1949	1:2.000.000	1949	Ruden (1949), Eidem (1956)
Census of forestry and agriculture		1945-1959	Official statistics of Norway XII. 6, Statistics Norway
Census of forestry and agriculture		1957-1969	Official statistics of Norway XII. 248, Statistics Norway
Census of forestry and agriculture		1957-1969	Official statistics of Norway XII 270, Statistics Norway
Census of forestry and agriculture		1979-1989	Statistics Norway
Land cover map	1:50.000	1990	Norwegian Mapping Authority (1990)
Vegetation map Norway 2003	1:50.000	1998-2003	Johansen (2009)
Yearly County Reports - Finnmark		2008- 2011	County forest administration, Finnmark, yearly reports
Census of forestry2005-2012		2005-2012	NIBIO (2012), Tomter (2012)
Land cover map	1:50.000	2008-2012	Norwegian Mapping Authority (2013)
GIMMS NDVI	8x8km	1982-2015	NOAA and NASA
MODIS C6 NDVI	5x5km	2000-2015	NASA

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Table 2. Statistical and land cover data from 1893 to 2012. The data are extracted from several sources in Table 1. **About the difference between dense and other birch forests, see Methods S1 - Uncertainties in forest statistics.

	Yearly average		Last 10 year average																							
	Temperature	Precipitation	Temperature	Precipitation	Area in km^2				Forest Biomass in tons			Tundra and Mountain Biomass in ton			Population	Domestic animals (#)					Reindeer	Farms	Forest harvest m^3			
Year	Mean JJA °C	Mean JJA mm	Mean JJA °C	Mean JJA mm	Pine	Birch	Forest Tota	Tundra	Pine	Birch	Total	Field layer	Bottom layer	Totalt	People	Horses	Cattle	Sheep	Goats	Total	#	#	Pine	Birch	Total	Firewood
1900	7.7	173.1	9.2	158.2			3634								32800	932	9222	16688	2573	29415	74383	6308				69864
1907	10.1	165.0	9.4	152.5	1250	1540	2790	38375							38065	927	9125	16556	2653	29261	81948	4683		46830	46830	81078
1914	10.2	103.9	9.7	130.8	1250	6255	7505	34527	6251050	7957696	14208746	15850372	20532564	36382937	44190	899	7964	14944	2748	26555	86224	4469	13236	45470	58706	94125
1929	8.8	110.1	10.1	127.8	880	9380	10260	31772	4400000	11933048	16333048	14712712	19058840	33771552	53308	1173	11358	27778	6690	46999	78371	4979	13236	66424	79660	113546
1939	10.9	121.4	11.0	131.7	880	9380	10260	31772	4400000	11933048	16333048	14712712	19058840	33771552	58790	1082	15720	41241	7460	65503	66644	6638	17000	32944	49944	125223
1944	9.8	115.9	10.9	143.3	700	6300	7000	35032	3500000	6048000	9548000	14468629	18742655	33211284	174000	9995	15139	29046	2349	56529	46534	6638	53200	53244	106344	370620
1949	8.7	116.6	10.4	136.9	700	6300	7000	35032	3500000	6048000	9548000	14468629	18742655	33211284	64532	1698	15139	29046	2349	48232	46534	6380	18109	38007	56116	130355
1959	10.8	222.7	10.4	142.6	847	6310	7157	34876	4234000	8027456	12261456	15994334	20719052	36713386	71140	958	12020	40650	533	54161	90907	4756	21329	33197	96379	143703
1969	10.4	114.4	10.2	157.8	758	5924	6682	35351	3790000	7536394	11326394	17070116	22112620	39182736	76538	175	7796	41178	194	49343	68715	3040	23132	18840	68724	76538
1979	11.2	92.5	10.8	144.5	758	5924	6682	35351	3790000	7536394	11326394	17070116	22112620	39182736	78691	104	9390	30650	14	40158	124926	1669	15728	1301	19829	62953
1989	11.4	187.0	10.2	144.2	1092	11262	12354	29678	5459000	14327291	19786291	13847973	17938657	31786630	74034	59	9196	31566	19	40840	180544	1003	13000	4000	19800	44420
1999	10.8	222.2	10.7	146.7	1092	11262	12354	29678	5459000	14327291	19786291	13847973	17938657	31786630	74061	82	9168	28845	183	38278	113538	658	4000	13000	21000	33327
2003	11.6	115.7	11.0	152.8	1197	11719	12916	29117	5985000	14732499	20717499	13615908	17638041	31253948	73514	350	8370	28326	47	37093	147603	464	5981	15000	24193	33081
2009	10.5	142.7	11.3	159.9	1247	9222	10469	31664	6235000	10945920	17180920	14441908	17638041	32079948	72492	378	8206	24176	0	32760	182324	321	4660	10140	14800	32621
2012	9.9	160.1	11.0	155.9	1347	14007	15354	26679	6735000	17819425	24554425	12608890	16333550	28942440	73787	438	7324	24627	19	32408	191012	340	7598	14000	24810	25899

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Table 3. Best linear models for forest and tundra variables for the period 1914-2012. The second column shows the explained variation (accuracy) of the best model in the range from 0 (worst) to 100 (best). First cell value shows the predictor's relative importance (in percentage). Arrows show direction of coefficient (↑ = positive, ↓ = negative). Last value (in italics) shows significance. n.m. = not included in model analysis.

Predictor (right) and response (below) variables	Accu-racy	Reindeer	Scots pine harvest	Farms	Domestic livestock	Birch harvest	Total forest harvest	Fuelwood	Population	Temperature	Precipitation
Birch area	79%	77 ↑ <*.001*		23 ↑ *.002*							
Birch biomass	86%	77 ↑ <*.001*			9 ↑ *.022*	14 ↑ *.008*					
Scots pine area	85%		60 ↓ *.001*		28 ↓ *.010*			12 ↑ *.077*			
Total forested area	82%	78 ↑ <*.001*		22 ↑ *.017*							
Total forest biomass	88%	84 ↑ <*.011*				16 ↑ *.006*					
Tundra area	81%	78 ↓ <*.001*		22 ↓ *.018*							
Tundra biomass	89%	43 ↓ <*.001*	14 ↑ *.002*				3 ↑ *.065*	40 ↓ <*.001*			
Birch harvest	83%		n.m.	77 ↑ <*.001*	19 ↓ *.003*	n.m.	n.m.	n.m.	5 ↑ *.076*		
Scots pine harvest	96%		n.m.	28 ↑ <*.001*		n.m.	n.m.	n.m.	69 ↑ <*.001*	3 ↓ *.053*	
Total forest harvest	69%		n.m.	100 ↑ <*.001*		n.m.	n.m.	n.m.			
Fuelwood	99%		n.m.	30 ↑ <*.001*	4 ↓ <*.001*	n.m.	n.m.	n.m.	62 ↑ <*.001*	1 ↑ *.024*	2 ↓ *.003*
Fuelwood and birch	98%		n.m.	59 ↑ <*.001*	6 <*.001*	n.m.	n.m.	n.m.	35 ↑ <*.001*		

Figures

Figure 1. Map of Finnmark County. International borders are shown in black and county border in grey.

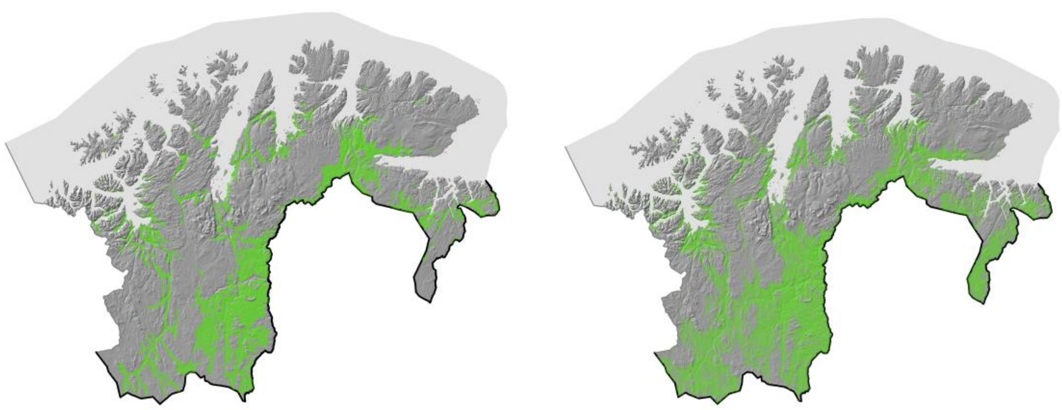

Figure 2. Birch forest change in Finnmark County from 1914 to 2012. The map to the left is based on the forest map produced by the General Director for Forestry in Norway (1914), while the map to the right is the forest cover from State Mapping Authority in Norway from 2012.

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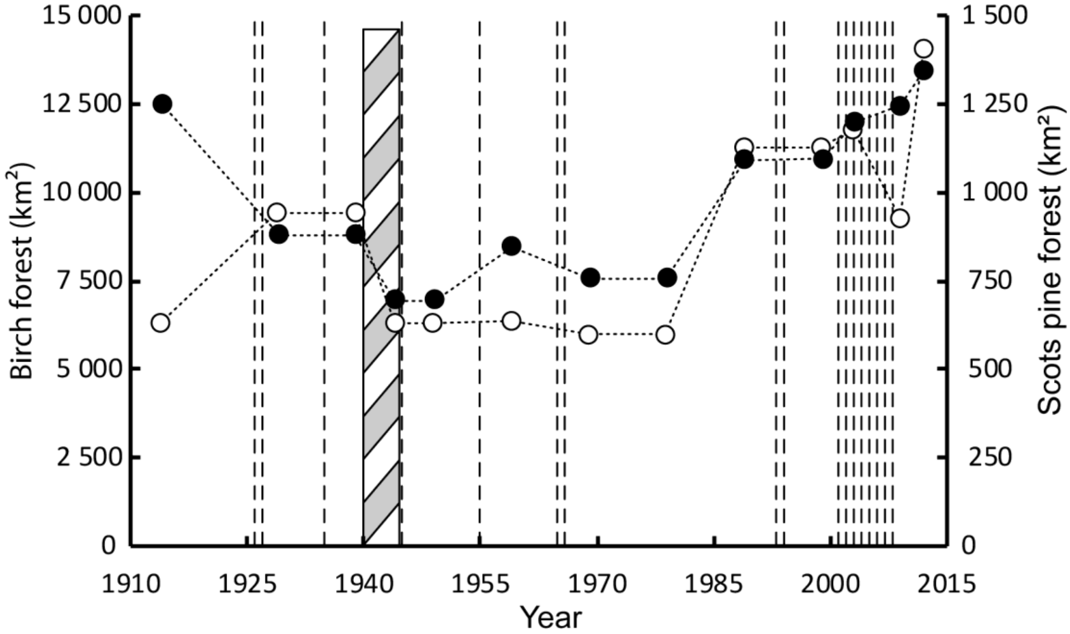

Figure 3. Forest cover changes of forested land in Finnmark County 1914-2012. Area is presented in km^2 for both forest types. Note different scales. Birch forests are presented in white circles and pine forests with black circles. Geometrid attacks are presented as stippled lines and the number of lines indicate the magnitude (number of years) of the attacks. The second world war is represented by a hatched column.

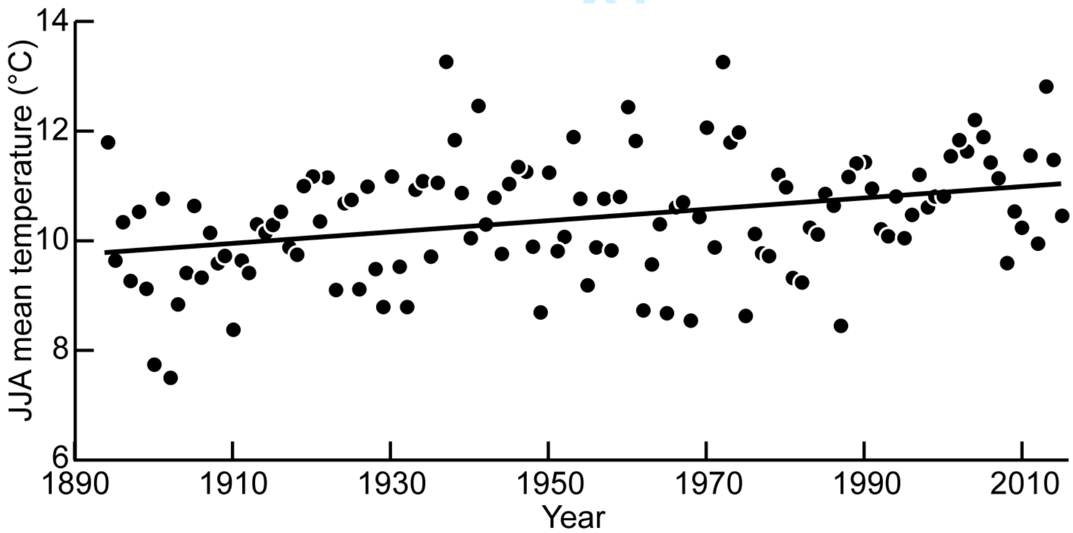

Figure 4. The relationship between year and mean temperature in Finnmark for June-July-August (JJA from 1894 to 2015 *(r = 0.33*, P < 0.000*)*. The time series is based on weather data from the three longest temperature series in Finnmark: Alta (coastal west), Karasjok (interior south), and Vardø (coastal north-east). Values are averages of mean monthly temperatures from the three stations.

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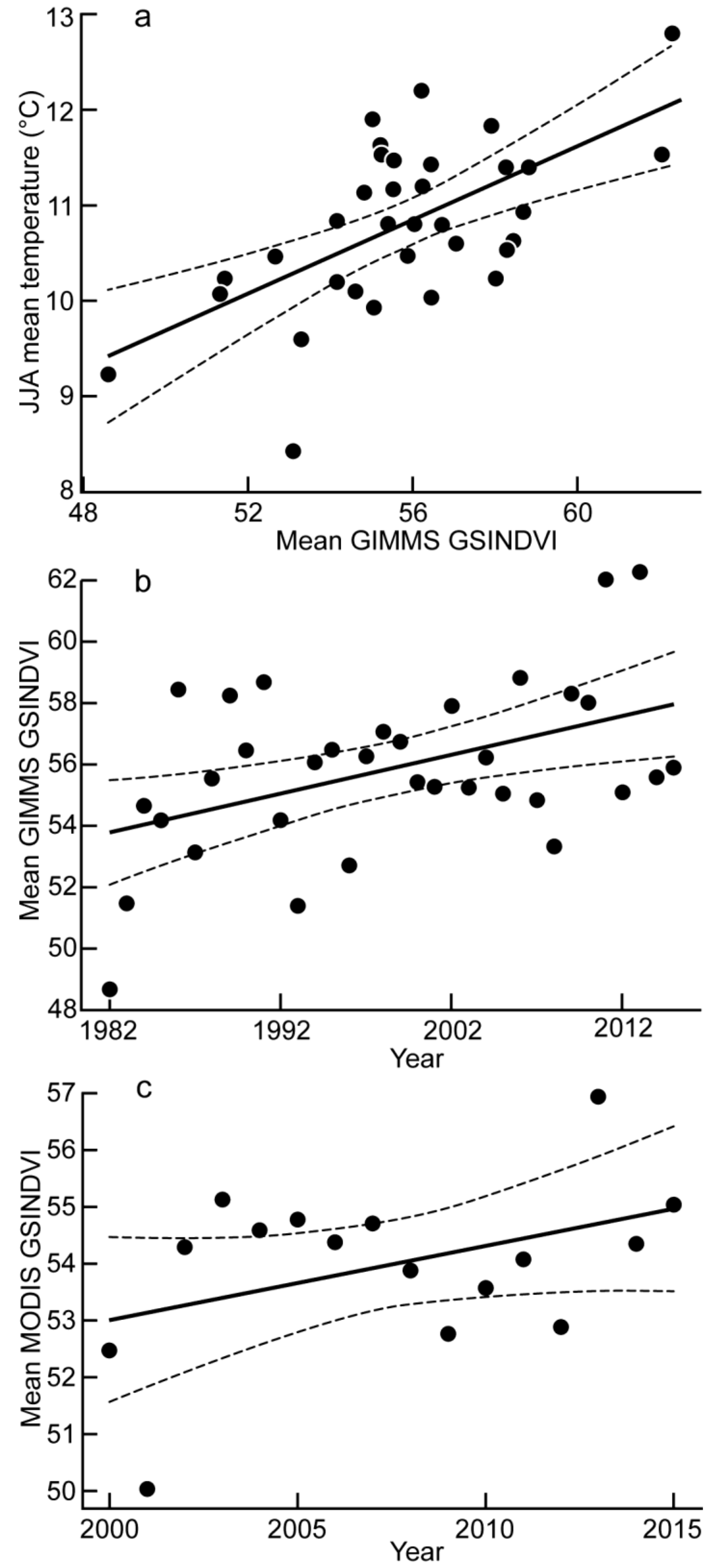

Figure 5. The relationship between the mean GIMMS GSINDVI and the growing season mean temperature (June to August, JJA) for the period 1982-2015 (upper). The time series of GIMMS and MODIS GSINDVI for the period 1982-2015 and 2000-2015 (middle and lower), respectively.

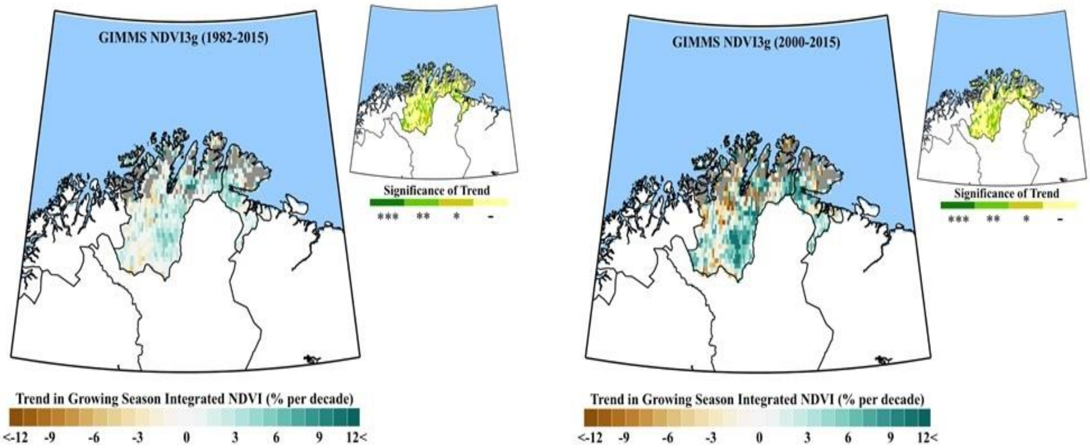

Figure 6. Trend (1982-2015) in NDVI3g based Growing Season Integrated NDVI (GSINDVI), left) and GSINDVI for the period 2000-2015 (right) over Finnmark County in Northern Norway. The trend was calculated using Vogelsang's t-PS_T test and significance is shown in inset figure *(***: P<0.01, **: P<0.05, *: P<0.1,* -: insignificant*)*. Regions suffered from limited valid observations and outside Finnmark County are shown in grey and white, respectively. Percent trend is calculated with respect to mean of 1982-2015.

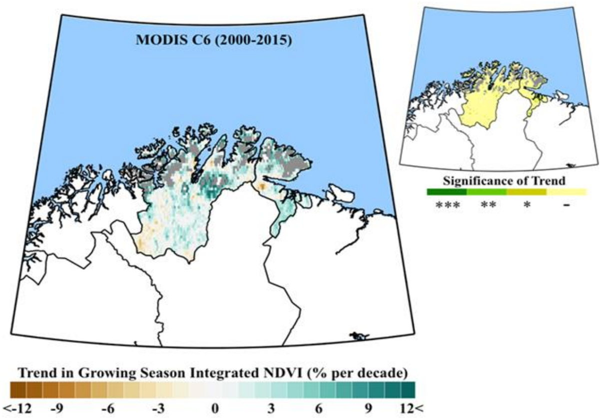

Figure 7. Trend (2000-2015) in MODIS C6 GSINDVI of Finnmark County in Northern Norway. The trend was calculated using Vogelsang's t-PS_T test and significance is shown in inset figure *(***: P<0.01, **: P<0.05, *: P<0.1,* -: insignificant). Regions that suffer from limited valid observations and outside Finnmark County are shown in grey and white, respectively. Percent trend is calculated with respect to mean of 2000-2015. The brown areas at the coast indicate area with autumnal moth attacks.

Supplementary Information

Tømmervik H., Bjerke J.W., Park T., Hanssen F. & Myneni, R.B. Legacies of historical exploitation of natural resources more important than summer warming for recent biomass increases in a boreal-arctic transition region. Submitted to Ecosystems.

Methods S1

Historical maps

The Finnmark part of the National Forest Map of Norway from 1914 (General Director for Forestry in Norway, 1914), including information on the spatial extent of coniferous and deciduous forest, was used to extract forest areas of Scots pine and birch (Table S1). This map was digitized by Hofgaard et al. (2013). Digital land cover maps were used to represent the middle of the second half of the 20th century (Table S1). These maps which were produced from panchromatic aerial photographs acquired mainly in the 1970s depict land cover and the Mapping authority of Norway used a tree canopy cover of more than 30% to delineate forest cover. Vegetation maps for Finnmark based on satellite imagery from 1998 to 2002 (Table S1) were used as late 20th century equivalents of the historical maps. The accuracy of the different historical maps is governed by the georeferencing accuracy of the data sources (e.g. maps) and the accuracy of the definition of the line's position relative to the data source (which in turn will depend on the particular mapping method used). Georeferencing errors in maps are mostly determined by scale, but also by the presence of easily recognized and stable map structures, such as lakes, coastlines, political boundaries and graticules, and probably range from around 50 m for the newer, larger-scale maps to about 1 km for the older, smaller-scale maps. Satellite imagery has georeferencing accuracies of typically 50 to 100 m. The accuracy of the thematic content of the land cover based on satellites and airborne sensors is harder to assess, and possibly also includes species-specific variation. However, vegetation maps based on Landsat data from the eastern part of Finnmark county, were estimated to have an accuracy of 75 % and 83 %, which is a satisfactory result (Tømmervik and others 2003, Tømmervik and others 2009).

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Uncertainties in forest statistics

For the years 1944 and 1949 (Table 3) we have estimated the area of forests by an estimate that a volume of up to 168.000 m^3 of Scots pine was logged annually during the Second World War by the German troops. This was 114000 m^3 more than the annual growth (Ruden 1949, Kibsgaard 2011) and this resulted in a rapid reduction of Scots pine. In addition, birch forests were logged in large quantities during Second World War (Kibsgaard 2011).

The delineation between dense and scattered birch forests have been treated differently during the last Century and this was especially the case in 1969 and 1979, since the focus those years was on a rigid mapping of productive forests only. Hence, the scattered mountain birch forests, which dominate large parts of Finnmark county were either neglected or mapped poorly (Official statistics of Norway XII 6 1959, Tomter 2012). We have therefore added the area of mountain birch forests (5100 km^2) mapped in 1959 to the estimates for 1969 and 1979. In the statics for 1969 and 1979, the forest survey authorities reduced the mountain birch area to be only 2400 km^2 (Official statistics of Norway XII 270 1969) using a strict definition of forests than the definition used before 1969 and after 1979. Since 1979, the forest survey and the mapping authorities have incorporated the mountain birch forests in the definition of forest (Tomter 2012), i.e. similar to the definition used until 1959 (Mork and Heiberg 1937).

Dense birch forests are distinctly separated from other birch forests by a significantly higher number of trees per hectare as well as taller monocormic trees, while the mountain birch forest have fewer number of trees per hectare and is dominated by a low statured polycormic growth form (Bylund and Nordell 2001, Bjørklund and others 2015). Dense forests dominate on rich soils along river valleys and along the coast line.

As the objective of this paper is to consider rates of increase or decrease of forests, we consider the implications of the accuracy concerning their area extents and statistics are to be determined and discussed in light of this information.

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Estimating live aboveground biomass to vegetation cover classes

To estimate trends in forest biomass, we used the forest, land cover and vegetation maps in connection with existing mean biomass estimation tables for different vegetation and forest types (Labrecque et al., 2006). All birch forests were merged together to one class. In Tables S2 and S3, we present the data used to calculate and estimate the different biomass categories.

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Supporting Information S2 (Tables and Figures)

Table S1. Biomass data used for the biomass calculations of the different forest types based on Tømmervik and others (2009).

Area	Forest type	Biomass (tonnes ha^{-1})	Source
Kevo, Finland	Bilberry and meadow types	23.1	Kjelvik and Kärenlampi (1975)
Kevo, Finland	Poor birch forest *(Empetrum)* type	11.0	Kallio and Kärenlampi pers. com. in: Haukioja and Koponen (1975)
Abisko, Sweden,	Mountain birch forests heath *(Empetrum)* type	9.6	Bylund and Nordell (2001)
Northern Finland	Scots pine forest	50	Hari and others (1996)

Table S2 Biomass data used for the biomass calculations of tundra according to Tømmervik and others (2009).

Layer type (mean for all types)	Biomass (tonnes ha^{-1})	Area	Author
Field layer	4.13	Kevo, Finland	Wielgolaski (1981)
Bottom layer (mainly mosses)	2.68	Kevo, Finland	Lyftingsmo (1965)
Bottom layer (mainly mosses and lichens)	5.35	Kevo, Finland	Wielgolaski (1981)

Table S3 Correlation table

	Year	Mean JJA temperature	Mean JJA precipitation mm	Area Scots pine	Area Birch	Total forested area	Area tundra	Biomass Scots pine	Biomass Birch	Total tree biomass	Tundra field layer biomass	Tundra bottom layer biomass	Total tundra biomass	Temperature last 10-year JJA average	Precipitation last 10-year JJA average	Mean human population last 10 y	Mean domestic animal populatoon last 10 y	Mean reindeer population last 10 y	Mean farms last 10 y	Mean pine harvest last 10 y	Mean birch harvest last 10 y	Mean total forest harvest last 10 y
Year	1	0,479	0,415	0,480	,628*	,630*	-,626*	0,479	,608*	,608*	-0,429	-0,479	-0,459	,620*	,848**	0,248	-0,276	,831**	-,867**	-0,545	-,907**	-,768**
Mean JJA temperature	0,479	1	0,285	0,291	0,226	0,236	-0,235	0,291	0,307	0,319	0,087	0,078	0,082	0,281	0,374	-0,131	-0,146	0,416	-0,517	-0,395	-,628*	-0,483
Yearly average Mean JJA mm	0,410	0,285	1	0,252	0,372	0,370	-0,370	0,252	0,389	0,375	-0,319	-0,312	-0,316	0,046	0,213	0,009	-0,069	0,415	-0,285	-0,254	-0,394	-0,321
Area Scots pine	0,480	0,291	0,252	1	,710**	,749**	-,746**	1,000**	,731**	,835**	-,555*	-,597*	-,581*	0,153	0,321	-0,438	-,845**	,809**	-,740**	-,861**	-0,436	-,801**
Area Birch	,628*	0,226	0,372	,710**	1	,998**	-,999**	,710**	,983**	,967**	-,842**	-,827**	-,836**	0,384	0,293	-0,164	-0,492	,834**	-,712**	-,738**	-0,474	-,763**
Total forested area	,630*	0,236	0,370	,749**	,998**	1	-1,000**	,748**	,984**	,978**	-,837**	-,827**	-,834**	0,374	0,301	-0,189	-0,530	,850**	-,729**	-,763**	-0,481	-,782**
Area tundra	-,626*	-0,235	-0,370	-,746**	-,999**	-1,000**	1	-,746**	-,985**	-,977**	,837**	,825**	,833**	-0,370	-0,297	0,189	0,528	-,847**	,726**	,760**	0,479	,779**
Biomass Scots pine	0,479	0,291	0,252	1,000**	,710**	,748**	-,746**	1	,731**	,835**	-,555*	-,597*	-,581*	0,153	0,321	-0,438	-,845**	,809**	-,739**	-,861**	-0,436	-,801**
Biomass Birch	,608*	0,307	0,389	,731**	,983**	,984**	-,985**	,731**	1	,986**	-,739**	-,721**	-,731**	0,311	0,273	-0,303	-,557*	,844**	-,740**	-,802**	-0,486	-,758**
Total tree biomass	,608*	0,319	0,375	,835**	,967**	,978**	-,977**	,835**	,986**	1	-,732**	-,728**	-,732**	0,289	0,299	-0,352	-,657*	,879**	-,779**	-,858**	-0,499	-,808**
Tundra field layer biomass	-0,429	0,087	-0,319	-,555*	-,842**	-,837**	,837**	-,555*	-,739**	-,732**	1	,986**	,995**	-0,403	-0,138	-0,170	0,246	-,586*	0,399	0,410	0,228	,586*
Tundra bottom layer biomass	-0,479	0,078	-0,312	-,597*	-,827**	-,827**	,825**	-,597*	-,721**	-,728**	,986**	1	,997**	-0,469	-0,210	-0,166	0,279	-,623*	0,447	0,458	0,262	,627*
Total tundra biomass	-0,459	0,082	-0,316	-,581*	-,836**	-,834**	,833**	-,581*	-,731**	-,732**	,995**	,997**	1	-0,442	-0,180	-0,168	0,266	-,609*	0,428	0,439	0,249	,612*
Temperature last 10-y JJA average	,620*	0,281	0,046	0,153	0,384	0,374	-0,370	0,153	0,311	0,289	-0,403	-0,469	-0,442	1	0,530	0,398	0,177	0,356	-0,374	-0,238	-0,375	-0,392
Precipitation last 10-y JJA average	,848**	0,374	0,213	0,321	0,293	0,301	-0,297	0,321	0,273	0,299	-0,138	-0,210	-0,180	0,530	1	0,348	-0,109	,581*	-,660*	-0,298	-,744**	-0,446
Mean human population last 10 y	0,248	-0,131	0,009	-0,438	-0,164	-0,189	0,189	-0,438	-0,303	-0,352	-0,170	-0,166	-0,168	0,398	0,348	1	,628*	-0,135	0,146	,614*	-0,203	0,110
Mean domestic animal population last 10 y	-0,276	-0,146	-0,069	-,845**	-0,492	-0,530	0,528	-,845**	-,557*	-,657*	0,246	0,279	0,266	0,177	-0,109	,628*	1	-,669*	,681*	,812**	0,337	,672*
Mean reindeer population last 10 y	,831**	0,416	0,415	,809**	,834**	,850**	-,847**	,809**	,844**	,879**	-,586*	-,623*	-,609*	0,356	,581*	-0,135	-,669*	1	-,951**	-,794**	-,806**	-,934**
Mean farms last 10 y	-,867**	-0,517	-0,285	-,740**	-,712**	-,729**	,726**	-,739**	-,740**	-,779**	0,399	0,447	0,428	-0,374	-,660*	0,146	,681*	-,951**	1	,805**	,867**	,918**
Mean pine harvest last 10 y	-0,545	-0,395	-0,254	-,861**	-,738**	-,763**	,760**	-,861**	-,802**	-,858**	0,410	0,458	0,439	-0,238	-0,298	,614*	,812**	-,794**	,805**	1	0,459	,779**
Mean birch harvest last 10 y	-,907**	-,628*	-0,394	-0,436	-0,474	-0,481	0,479	-0,436	-0,486	-0,499	0,228	0,262	0,249	-0,375	-,744**	-0,203	0,337	-,806**	,867**	0,459	1	,791**
Mean total forest harvest last 10 y	-,768**	-0,483	-0,321	-,801**	-,763**	-,782**	,779**	-,801**	-,758**	-,808**	,586*	,627*	,612*	-0,392	-0,446	0,110	,672*	-,934**	,918**	,779**	,791**	1

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Table S4. Yearly, mean and maximum GSINDVI and MAX for Finnmark County inferred from GIMMS $NDVI_{3g}$ and MODIS C6. We applied area-weighting approach to derive below all quantities.

Year	MeanTemp JJA	MeanPrec JJA	GIMMS GSINDVI Mean	MODIS GSINDVI Mean	GIMMS Maximum	MODIS Maximum
1982	9,23	158,57	48,65		0,68	
1983	10,23	98,37	51,47		0,69	
1984	10,1	176,3	54,63		0,68	
1985	10,83	92,27	54,16		0,72	
1986	10,63	146,4	58,44		0,72	
1987	8,43	138,63	53,12		0,72	
1988	11,17	157,73	55,54		0,72	
1989	11,4	187,03	58,26		0,72	
1990	11,43	102,4	56,45		0,73	
1991	10,93	144,1	58,68		0,73	
1992	10,2	205,07	54,18		0,68	
1993	10,07	132,13	51,37		0,72	
1994	10,8	112	56,05		0,73	
1995	10,03	198,17	56,47		0,72	
1996	10,47	146,27	52,69		0,74	
1997	11,2	70	56,25		0,75	
1998	10,6	134,33	57,06		0,73	
1999	10,8	222,2	56,72		0,72	
2000	10,8	124,7	55,42	52,48	0,78	0,64
2001	11,53	241,27	55,26	50,03	0,7	0,64
2002	11,83	163,8	57,91	54,29	0,69	0,64
2003	11,63	115,67	55,23	55,13	0,69	0,65
2004	12,2	164	56,22	54,59	0,76	0,66
2005	11,9	157,77	55,04	54,78	0,73	0,63
2006	11,4	181,6	58,82	54,38	0,77	0,64
2007	11,13	152,73	54,83	54,71	0,73	0,65
2008	9,6	154,23	53,31	53,88	0,73	0,65
2009	10,53	142,73	58,3	52,77	0,76	0,64
2010	10,23	207,8	58,01	53,57	0,77	0,65
2011	11,53	143,93	62,03	54,08	0,78	0,64
2012	9,93	160,07	55,08	52,89	0,71	0,64
2013	12,8	143,33	62,28	56,94	0,75	0,66
2014	11,47	113,6	55,56	54,35	0,74	0,66
2015	10,47	119	55,89	55,04	0,74	0,65

Table S5. Correlation table of the Growing Season Integrated NDVI (GSINDVI) and the MaxNDVI for GIMMS NDVI3g and MODIS C6 together with the mean temperatures for the period 1982-2015. The significance levels are marked with asterixs: *Correlation is significant at the 0.05 level (2-tailed). **Correlation is significant at the 0.01 level (2-tailed).

Correlations

		Year	MeanTempJJA	GIMMS_GSINDVI_MEAN	MODIS_GSINDVI_MEAN	GIMMS_GSINDVI_TOTAL	MODIS_GSINDVI_TOTAL	GIMMS_MAX	MODIS_MAX
Year	Pearson Correlation	1	,344*	,456**	0,412	,456**	0,412	,559**	0,430
	Sig. (2-tailed)		0,046	0,007	0,113	0,007	0,113	0,001	0,096
	N	34	34	34	16	34	16	34	16
MeanTempJJA	Pearson Correlation	,344*	1	,562**	0,312	,562**	0,312	0,248	0,197
	Sig. (2-tailed)	0,046		0,001	0,239	0,001	0,240	0,157	0,466
	N	34	34	34	16	34	16	34	16
GIMMS_GSINDVI_MEAN	Pearson Correlation	,456**	,562**	1	0,339	1,000**	0,339	,569**	0,090
	Sig. (2-tailed)	0,007	0,001		0,199	0,000	0,199	0,000	0,742
	N	34	34	34	16	34	16	34	16
MODIS_GSINDVI_MEAN	Pearson Correlation	0,412	0,312	0,339	1	0,339	1,000**	0,108	,533*
	Sig. (2-tailed)	0,113	0,239	0,199		0,199	0,000	0,691	0,034
	N	16	16	16	16	16	16	16	16
GIMMS_GSINDVI_TOTAL	Pearson Correlation	,456**	,562**	1,000**	0,339	1	0,339	,569**	0,090
	Sig. (2-tailed)	0,007	0,001	0,000	0,199		0,199	0,000	0,742
	N	34	34	34	16	34	16	34	16
MODIS_GSINDVI_TOTAL	Pearson Correlation	0,412	0,312	0,339	1,000**	0,339	1	0,108	,533*
	Sig. (2-tailed)	0,113	0,240	0,199	0,000	0,199		0,691	0,034
	N	16	16	16	16	16	16	16	16
GIMMS_MAX	Pearson Correlation	,559**	0,248	,569**	0,108	,569**	0,108	1	0,055
	Sig. (2-tailed)	0,001	0,157	0,000	0,691	0,000	0,691		0,841
	N	34	34	34	16	34	16	34	16
MODIS_MAX	Pearson Correlation	0,430	0,197	0,090	,533*	0,090	,533*	0,055	1
	Sig. (2-tailed)	0,096	0,466	0,742	0,034	0,742	0,034	0,841	
	N	16	16	16	16	16	16	16	16

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Supplementary Figures

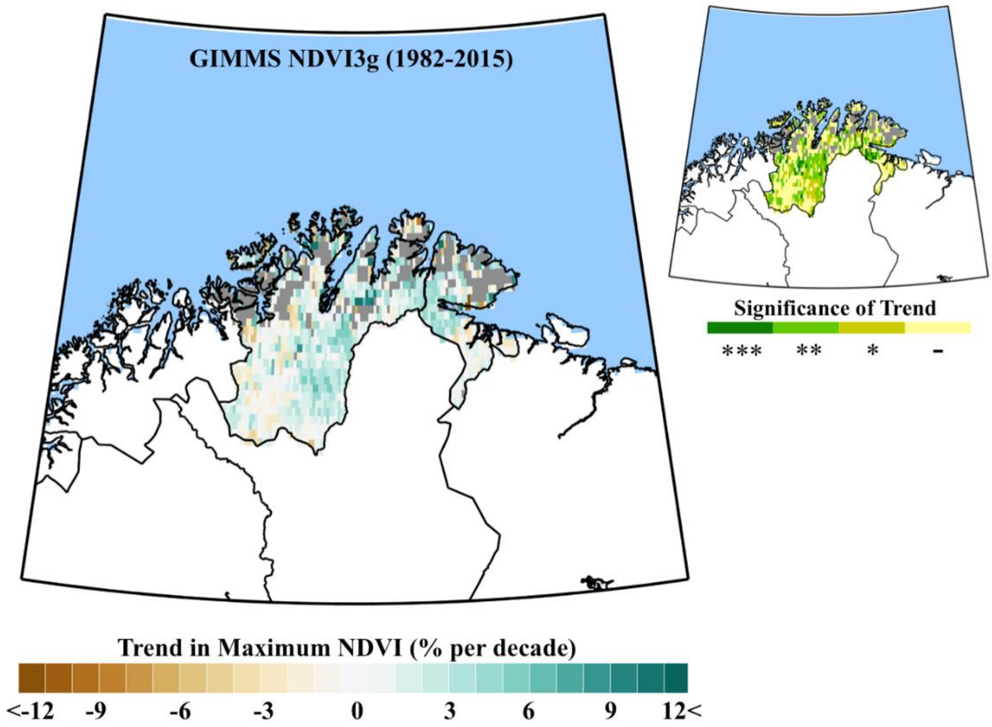

Figure S1. Trend (1982-2015) in $NDVI_{3g}$ based maximum NDVI (MAX) over Finnmark County in Northern Norway. The trend was calculated using Vogelsang's t-PS_T test and significance is shown in inset figure (***: P<0.01, **: P<0.05, *: P<0.1, -: insignificant). Regions suffering from limited valid observations and outside Finnmark County are shown in gray and white, respectively. Percent trend is calculated with respect to mean of 1982-2015.

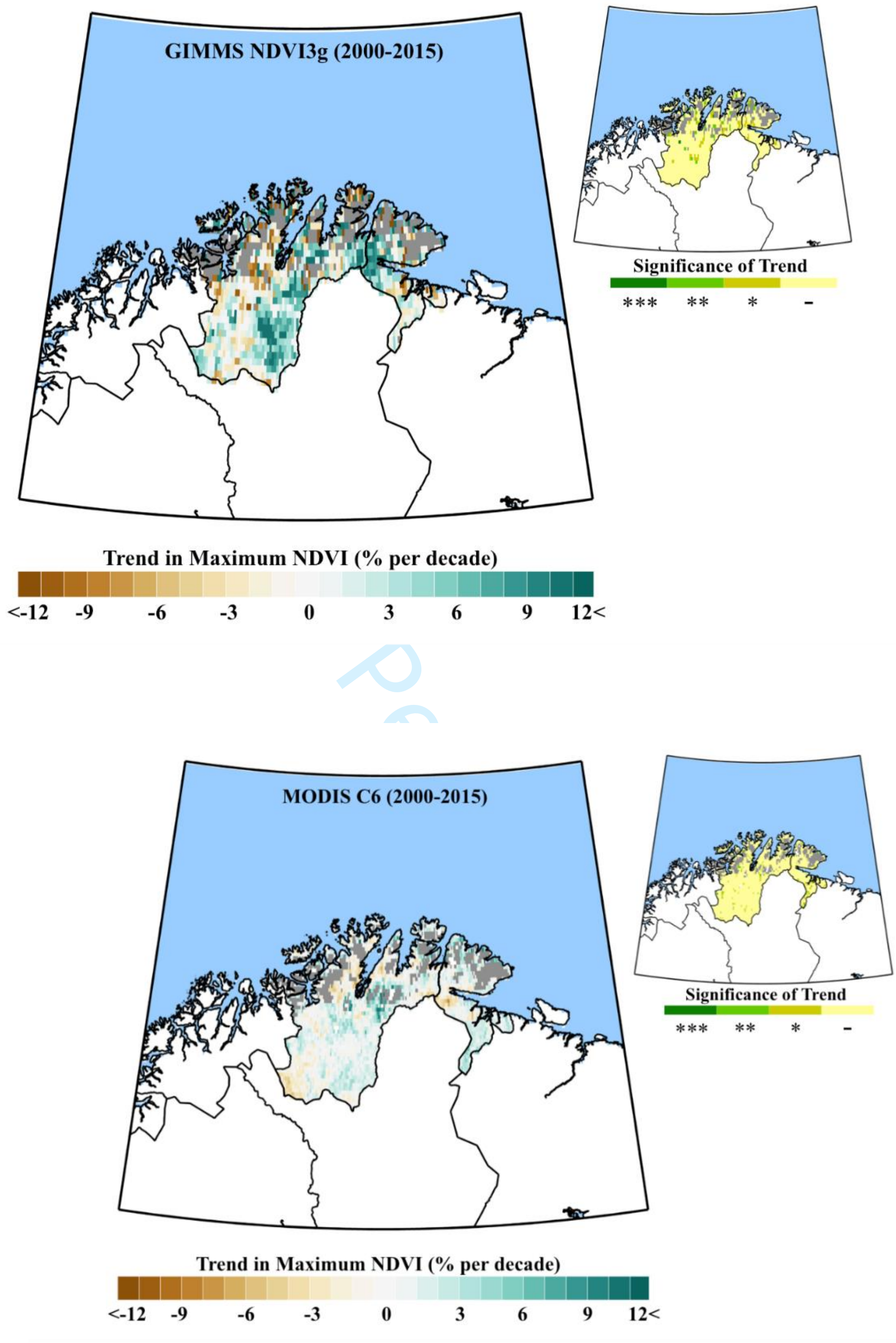

Figure S2. Trend (2000-2015) in $NDVI_{3g}$ based maximum NDVI (MAX, upper panel) and MODIS C6 based maximum NDVI (max, lower panel) over Finnmark County in Northern Norway. The trend was calculated using Vogelsang's t-PS_T test and significance is shown in inset figure (***: P<0.01, **: P<0.05, *: P<0.1, -: insignificant). Regions suffering from limited valid observations and outside Finnmark County are shown in gray and white, respectively. Percent trend is calculated with respect to mean of 1982-2015.

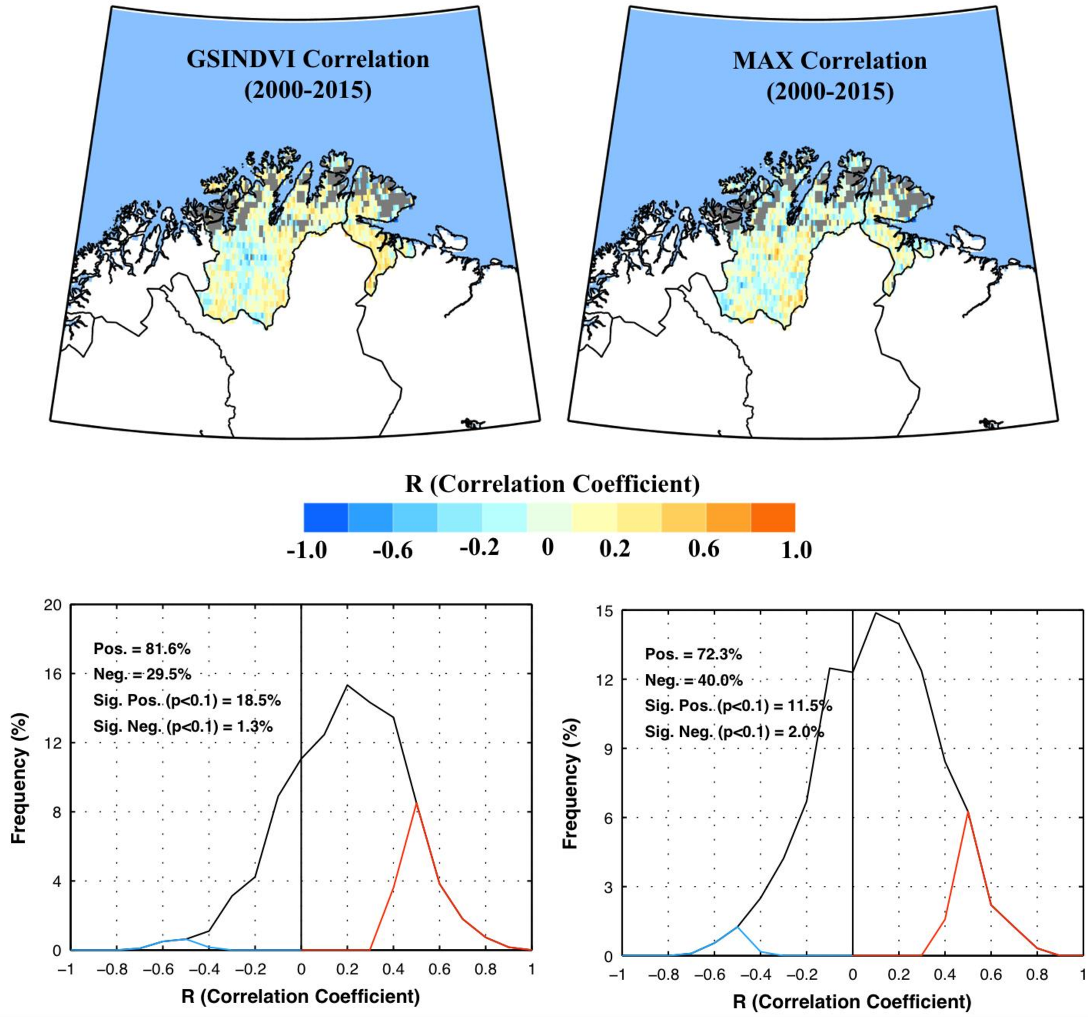

Figure S3. Distribution of correlation coefficient (R, 2000-2015) between NDVI3g and MODIS derivations over Finnmark County. Upper two panels represent geographical distribution of R for GSINDVI (left) and MAX (right). For both, regions suffered from limited valid observations and outside Finnmark County are shown in gray and white, respectively. Lower two panels show histogram of correlation coefficients (black: all cases, blue: negative relation at 10% significance, red: positive relation at 10% significance).

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