Eurasian Arctic greening reveals teleconnections and the potential for novel ecosystems

Marc Macias-Fauria, Bruce C. Forbes, Pentti Zetterberg and Timo Kumpula

Arctic warming has been linked to observed increases in tundra shrub cover and growth in recent decades on the basis of significant relationships between deciduous shrub growth/biomass and temperature. These vegetation trends have been linked to Arctic sea ice decline and thus to the sea ice/albedo feedback known as Arctic amplification. However, the interactions between climate, sea ice and tundra vegetation remain poorly understood. Here we reveal a 50-year growth response over a >100,000 km² area to a rise in summer temperature for alder (Alnus) and willow (Salix), the most abundant shrub genera respectively at and north of the continental treeline. We demonstrate that whereas plant productivity is related to sea ice in late spring, the growing season peak responds to persistent synoptic-scale air masses over West Siberia associated with Fennoscandian weather systems through the Rossby wave train. Substrate is important for biomass accumulation, yet a strong correlation between growth and temperature encompasses all observed soil types. Vegetation is especially responsive to temperature in early summer. These results have significant implications for modelling present and future Low Arctic vegetation responses to climate change, and emphasize the potential for structurally novel ecosystems to emerge from within the tundra zone.

Within the Arctic, northwestern Eurasian tundra (NWET) is unique in being one of the warmest regions, as measured by the summer warmth index (that is, growing season temperature), and in having highly variable sea ice, lower overall than other Arctic seas, owing to the direct influence of atmosphere and ocean heat transport through the North Atlantic storm track. The normalized difference vegetation index (NDVI), a decadal satellite-based proxy for vegetation productivity, highlights most of NWET as extremely productive, with a sharp productivity drop in the geologically distinct Yamal, Gydan and Taz peninsulas (Fig. 1). Tree-sized, tall (>2 m) deciduous shrubs (mainly Salix) have developed in recent decades within the region, demonstrating an in situ change of the Low Arctic tundra structure that is quantifiable but has also been observed in detail by indigenous Nenets reindeer herders both west and east of the Polar Ural Mountains. NWET is thus now experiencing environmental and ecological conditions likely to soon develop across other Arctic regions if the ongoing warming trend continues, and can be seen in this respect as a bellwether of the tundra biome. Extensive oil and gas development amidst huge herds of reindeer (Rangifer tarandus L.) that heavily exploit willow-dominated shrub tundra for summer, and autumn forage further reinforces the vision of the region as an example of the likely future in the Arctic. For all of these reasons, NWET is an optimal area to: investigate large-scale responses to decadal warming through in situ phenotypic changes in plant individuals representing different areas, substrates and species; and partition among and characterize the respective intra-seasonal drivers of these vegetation changes.

To address these questions, we conducted an extensive study encompassing remote sensing, climate and sea ice data, ring-width chronologies of tall individuals from two abundant and nearly circumnporal deciduous shrub species in the Low Arctic (Salix lanata L. and Alnus fruticosa Rupr.), and intensive ground truthing through three sites across the Low Arctic of NWET (Fig. 1). Our results strongly suggest that recent sea ice retreat has had a limited influence on tundra productivity in the region, and that the growth of tall shrubs is ultimately related to the position of continental air masses in July. For the period 1982–2005, NWET greenness (as measured by NDVI at 8 km resolution) was related to sea ice cover only in late spring (May and early June), when NDVI values in NWET were still low (<0.3 in all cases; Fig. 2a). Spatiotemporal relationships between temperature and the Barents and Kara seas ice area reflected a similar pattern, with a strong effect of sea ice on adjacent land in spring followed by no effect during the summer months (Fig. 2b). Tall shrub growth was highly correlated to July NDVI (<0.01, r² ranging regionally from 0.4 to 0.75; Fig. 3 and Supplementary Fig. S1). Shrub dendrochronologies, well chronologies of tall individuals from two abundant and nearly circumnporal deciduous shrub species in the Low Arctic (Salix lanata L. and Alnus fruticosa Rupr.), and intensive ground truthing through three sites across the Low Arctic of NWET (Fig. 1). Our results strongly suggest that recent sea ice retreat has had a limited influence on tundra productivity in the region, and that the growth of tall shrubs is ultimately related to the position of continental air masses in July. For the period 1982–2005, NWET greenness (as measured by NDVI at 8 km resolution) was related to sea ice cover only in late spring (May and early June), when NDVI values in NWET were still low (<0.3 in all cases; Fig. 2a). Spatiotemporal relationships between temperature and the Barents and Kara seas ice area reflected a similar pattern, with a strong effect of sea ice on adjacent land in spring followed by no effect during the summer months (Fig. 2b). Tall shrub growth was highly correlated to July NDVI (<0.01, r² ranging regionally from 0.4 to 0.75; Fig. 3 and Supplementary Fig. S1). Shrub dendrochronologies, well

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1. Long-term Ecology Laboratory, Biodiversity Institute, Department of Zoology, University of Oxford, Tinbergen Building, South Parks Road, Oxford, OX1 3PS, UK. 2. Arctic Centre, University of Lapland, Box 122, FI-96101 Rovaniemi, Finland. 3. Laboratory of Dendrochronology, Department of Forest Sciences, University of Eastern Finland, FI-80101 Joensuu, Finland. 4. Department of Geographical and Historical Studies, University of Eastern Finland, Yliopistonkatu 7, FI-80101 Joensuu, Finland. *e-mail: bforbes@ualaplnd.fi.

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Figure 1 | Map of NWET. Sites where dendrochronologies were extracted are shown with a filled black triangle and two letters: VR, Varandei; LB, Laborovaya; YR, Yunbei River. Meteorological stations <400 km away from the sites used in the computation of response functions are shown with a black rhomboid symbol and three letters: NAR, Naryan Mar; PEC, Pechora; SAL, Salekhard; UST, Ust Kara; MAR, Marre Sale; NAD: Nadym. Major landscape units and depositional origins are depicted for the tundra\(^2\): 1,2: foothills, 1: glacial and glaciofluvial, 2: marine; 3–5: high plains and plateaux, 3: erosional-denudational, 4: glacial and glaciofluvial, 5: tablelands; 6–8: low plains, 6: fluvial, lacustrine, 7: glacial and glaciofluvial, 8: marine and ice-rich marine; 9,10: mountains, 9: erosional-denudational, 10: table mountains, mountain ranges; 11: ice caps and glaciers. Upper-right inset: circumpolar high, 12–14: lowlands with marine sediments and continuous, often ice-rich permafrost east of them\(^19\) (lower NDVI; Fig. 1). Within Yamal (east of the Urals), productive areas, that is shrubbery and with higher NDVI, correspond to regions with topographically dissected valleys and extensive landslide activity\(^18\). Regardless of overall biomass accumulation due to differences in substrate, all ring-width chronologies and overall NDVI variability were found to be strongly linked to summer temperature (Fig. 4a and Supplementary Figs S2, S3 and S5c). Nevertheless, the most productive areas were more inter-correlated (Fig. 3 and Supplementary Fig. S1). Both regional (250 m resolution, 50 × 50 km) and local (1 m resolution, ∼25–40 km\(^2\)) land cover classifications revealed greater tall shrub cover west of the Urals. The tall shrub fraction ranged between 13% (west) and 6–8% (east), whereas overall deciduous shrub cover was large everywhere and did not follow a west–east gradient (76–94%, not taking into account water bodies; Supplementary Fig. S6a). Biweekly NDVI data revealed high variability in the early growing season and a synchronous growth cessation (Supplementary Fig. S8a). This pattern of variability has been reported for northern high-latitude vegetation\(^20\) and does not correspond to differences in climatic variability between autumn and spring (Supplementary Fig. S8b). In cold-adapted tree species, the initiation of growth in spring occurs from buds when genetically determined winter chilling and spring heat sums are met, whereas bud set and height growth cessation occur when a genetically determined critical day length is experienced\(^21\). Photoperiod rather than temperature most likely limits vegetation growth at the end of the season. This suggests that an in situ response of tundra vegetation to climate warming might be restricted to the early growing season, whereas an autumn-extended growing season would depend...
on the northward migration of southern individuals and would therefore occur much slower.

Our data show that vegetation response to climate warming is not restricted to Arctic processes such as snow albedo and sea-ice-related amplification mechanisms but extends also to climatic patterns linked to the position of mid-troposphere air masses over Eurasia (Fig. 4 and Supplementary Fig. S3). Whereas late-spring tundra productivity and temperatures are still largely linked to declining sea ice extent in seas adjacent to NWET (Fig. 2), vegetation growth at the peak of the growing season is decoupled from sea ice and responds strongly to the position of synoptic weather systems with clear links to lower latitudes. Significantly, secondary growth of woody vegetation, which is responsible for the size of the individuals and thus for potential transitions from low erect shrubs to tall tree-sized growth forms, takes place during this latter period, thus not being dependent on what occurs in the Arctic Ocean and adjacent seas. Although such decoupling might be so far unique to NWET owing to the low sea ice cover in the Barents Sea, it has the potential to become a prevailing pattern of vegetation/climate relationships in a warmer Arctic as the position of sea ice continues to recede earlier in the spring and its ability to influence peak growing season temperatures decreases.

Whereas annual shrub growth is controlled by summer temperature, the spatial distribution of tall shrubs in NWET is topographically restricted to sheltered locations where snow depth in winter provides protection from abrasion and desiccation. Large increases in the number of days with deep snow cover (2–6 cm per decade; ref. 22) and trends towards earlier spring snowmelt have been reported since 1966/7 (ref. 23) in NWET, whereas late-twenty-first-century climatic projections predict a continuation of such trends in the Barents region, with an 18% increase in precipitation anticipated for the period 2080–2099 relative to 1981–2000, largest in winter. Moreover, tall shrubs trap snow, enhancing snow depth and reducing winter snow loss due to sublimation. Sheltered, tall shrub-favourable locations result from erosive processes operating over different spatial and temporal scales, such as fluvial valleys and cryogenic landslides. Whereas fluvial landscapes are dominant west of the Urals, cryogenic landslides are the leading landscape-forming process in the continuous permafrost zone of northwestern Siberia. Cryogenic landslides are controlled by the depth of summer thaw (hence, temperature) and water content, which within substrates of comparable texture depends on precipitation and rate of thaw. Ongoing climatic trends and predictions suggest an increase and a northward displacement of permafrost-related landslide activity, potentially favouring the expansion of willows.

Regardless of whether climate change eventually results in a spatial expansion of tall shrub thickets, as has been observed at lower latitudes in our study region and over a range of locations in other regions within the Low Arctic, contemporary tall shrub individuals are already tree-sized, free of grazing pressure and cover 6–13% of the Low Arctic of NWET. These alone represent a significant ecosystem transformation already underway. The processes we report here for NWET suggest a large-scale shift towards a structurally novel ecosystem absent for millennia, which shares many characteristics with that described for Beringia in the early Holocene epoch. This structurally complex mosaic of open woodland characterized by thickets of tree-sized (>2 m) individuals of deciduous broad-leaved taxa has the potential of significantly altering abiotic and biotic conditions within the Low Arctic, and is already modifying reindeer herd management practices.

Low Arctic tundra is dominated by woody taxa with wide growth-form variability partly due to phenotypic variation. Observed changes in northern Eurasia agree with predictions of potential in situ rapid shifts from low to high shrubs or trees and the appearance of structurally novel biomes under a warming scenario. This process occurs over decades, whereas...
Figure 3 | Monthly Pearson correlation coefficients ($r$) between NDVI (ref. 11) and Laborovaya (S. lanata) shrub ring-width chronology. Red triangle shows the location of the Laborovaya site. Period is 1982–2005, for which there is NDVI data. Only significant ($p < 0.05$) correlations are shown. Field significance, accounting for multiplicity,$^{26}$ is shown in the upper part of each panel as: $\ast \ast$: $p < 0.01$; NS, not significant. Note: the short period over which correlations are widespread (July); and the correlation between the ring-width chronology and distant highly productive areas to the north and west is higher than that to proximal sandy low-productivity areas to the east. Biweekly correlations, not shown here for brevity, show even higher values for the second half of June and the first half of July. Calculations for the remaining chronologies show the same pattern and are available in Supplementary Fig. S1.

Methods

Climatic data. In NWET, climatic data north of the treeline is patchy, spatially and temporally, and distances between stations can be great. Monthly precipitation and temperature data from Russian Arctic stations located near our study sites (that is, <400 km; Fig. 1) were available for 1961–2005 at the National Snow and Ice Data Centre at Boulder, Colorado. We also used mean monthly surface temperature from a 2.5° latitude per 2.5° longitude regional grid covering the period 1949–2005 from the NCEP Reanalysis database, provided by the NOAA-CIRES Climate Diagnostics Centre, Boulder, Colorado (http://www.cdc.noaa.gov/). Monthly indices of the SCA were obtained from the Climate Prediction Centre of the National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov/data/), covering the period 1950–2005.

Sea ice data. Data on monthly total ice covered area spanning the SMMR-SSM/I record from October 1978 to the most recent processing date were provided by J. Comiso of the NASA Goddard Space Flight Centre, Oceans and Ice Branch, and from the Bootstrap Sea Ice Concentrations from Nimbus–7 SMMR and DMSI SSM/I data set (http://nsidc.org/data/nsidc-0079.html).

Remote sensing and land cover classification. NDVI data were derived from the NOAA AVHRR meteorological satellites. We obtained biweekly NDVI records from the GIMMS data set, available through the Global Land Cover Facility (http://gfc.umbi.umd.edu/data/gimms/). The data set has been corrected for calibration, view geometry, volcanic aerosols and other effects not related to vegetation change, and covers the period 1981–2005 at 8 km resolution. Moderate-Resolution Imaging Spectroradiometer imagery at 16-day intervals and 250 m resolution was obtained for the period 2000–2011 (http://modis-land.gsfc.nasa.gov/vi.htm) to analyse NDVI patterns along different landscape units for regions defined as the 30 x 30 km area around each site (Supplementary Fig. S6). Finally, 1-m-resolution imagery was acquired for an area ∼40 km around each sampling site: they consisted of VHR images from Quickbird-2 (Varandei, 05/08/2005; Laborovaya, 11/07/2005).
Figure 4 | **a**, Pearson correlation coefficients between surface-gridded temperatures from the Reanalysis project and Laborovaya (S. lanata) ring-width chronology. Correlations are computed between the chronology and the growing season period for which significant response function coefficients were found (June–August). Site location is shown as a white filled square. Temperature correlation fields for the remaining chronologies are similar and shown in Supplementary Fig. S3. **b**, Pearson correlation coefficients between NDVI (ref. 11) and the SCA index (http://www.cpc.ncep.noaa.gov/data/): June Scandinavian index versus second half of June NDVI (left), June Scandinavian index versus first half of July NDVI (right). **c**, Monthly Pearson correlation coefficients between surface-gridded temperatures from the Reanalysis project and the SCA index for June (left) and July (right). Sites are shown as filled white squares. Only significant ($p < 0.05$) correlations are shown. Field significance, accounting for multiplicity, is shown in the upper part of each panel as: $\ast \ast$: $p < 0.01$. Note the clear correspondence between shrub growth versus temperature correlation fields and the Scandinavian index.

**Building of dendrochronologies.** Dendrochronologies were obtained from three separate sites in the Low Arctic of NWET, namely Varandei (68.65° N, 58.38° E), Laborovaya (67.67° N, 68.00° E) and Yuribei River (68.91° N, 70.23° E; Fig. 1). Slices 2–3-cm-thick were collected from 24 to 40 discrete individuals spread across each sample site in the summers of 2006, 2007 and 2010. Care was used in not taking stems from the same copse, thus trying to minimize the effect of sampling clones. A minimum of four slices between the root collar and the upper canopy was taken from each individual to properly account for reaction wood. Wood samples were sanded and measured with a precision of 0.01 mm. Cross-dating of the ring width measurement series was performed following standard dendrochronological procedures. Ring width measurements were detrended using a 32-year smoothing spline. Expressed population signal, which is a function of series replication and mean inter-series correlation, was used to define the reliable part of the chronology (expressed population signal $> 0.85$; ref. 34). Other descriptive statistics were calculated for each chronology to permit comparisons with other dendrochronological data sets (Supplementary Table S1).

**Relationships between environmental variables.** Response functions between the ring-width residual chronologies and monthly climate data (temperature and precipitation) for the four closest climate stations (distance to the site $<400$ km; Fig. 1) were computed using the program DendroClim2002 (ref. 35) for the period 1961–2005, for which full climatic and dendrochronological data were available. Response function coefficients are multivariate estimates from a principal component regression model calculated to avoid colinearity between predictors, commonly found in multivariable sets of meteorological data. Significance and stability of coefficients were assessed by 1,000 bootstrap estimates obtained by...


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Author contributions

M.M.-F. performed the statistical analysis, wrote the manuscript and created the figures. B.C.F. designed and performed the field expeditions and sampling, supervised the project and collaborated in writing the manuscript. P.Z. dated and measured the ring-width chronologies. T.K. performed fieldwork (ground truthing of satellite imagery) and laboratory remote-sensing analyses.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.C.F.