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EDITORIAL

Focus on recent, present and future Arctic and boreal productivity and biomass changes

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Abstract

The reduction of cold temperature constraints on photosynthesis in recent decades has led to extended growing seasons and increased plant productivity (greening) in significant parts of Polar, Arctic and Boreal regions, here called northern lands. However, most territories within these regions display stable productivity in recent years. Smaller portions of Arctic and Boreal regions show reduced productivity (browning). Summer drought and wildfires are the best documented drivers causing browning of continental areas. Yet factors like winter warming events dampening the greening effect of more maritime regions have remained elusive, least monitored and least understood. A Norway-US network project called ArcticBiomass was launched in 2013 to further reveal both positive and negative effects of climate change on biomass in Arctic and Boreal regions. This focus collection named *Focus on Recent, Present and Future Arctic and Boreal Productivity and Biomass Changes* includes 24 articles and is an important outcome of this work and addresses recent changes in phenology, biomass and productivity and the mechanisms. These mechanisms include former human interactions (legacies) and drivers that control such changes (both greening and browning), along with consequences for local, regional and global scale processes. We complete our synthesis by stressing remaining challenges and knowledge gaps, and provide an outlook on future needs and research questions in the study of climate and human driven interactions in terrestrial Arctic and Boreal ecosystems.

1. Introduction

Ecosystem responses to Arctic warming have the potential to feedback either positively or negatively to the Earth's climate system depending on latitude, changes in disturbance regime, vegetation distribution and productivity (McGuire *et al* 2009). The lower albedo of shrub and forest vegetation compared with tundra, for example, results in a positive feedback on temperature (Bala *et al* 2007). Global warming presented as a warming rate, e.g. 0.2 °C/decade (ACIA 2004), does not reflect the fact that cold seasons are warming faster than the warm seasons, especially in the Arctic due to positive feedbacks (e.g. albedo-temperature feedback (Meredith *et al* 2019)). The initiation, termination and performance of many biological processes, e.g. plant growth, are tied to threshold temperatures. The trend in timing of these thresholds, and cumulative air temperatures driving

them, may have the effect of enhancing vegetation productivity.

Conversely, increased productivity of Arctic vegetation resulting from warmer temperatures tends to result in increased carbon dioxide (CO_2) uptake by net photosynthesis, providing a negative feedback to rising temperatures (Field *et al* 2007, Speed *et al* 2010). As a result of this trend, between 1982 and 2011, Arctic tundra vegetation increased both in terms of peak productivity, greening and growing season length and this finding is supported by a wide range of field site measurements across the Arctic (ACIA 2004, Walker *et al* 2005, Xu *et al* 2013). Also, in coastal areas of Canada and Alaska (Epstein *et al* 2004) and Arctic islands like Svalbard, there are trends of increased greening (Speed *et al* 2010, Vickers *et al* 2016), with some demonstrated linkages to sea ice (Macias-Fauria *et al* 2017). These dynamics include changes in the composition and density of herbaceous vegetation (Epstein *et al* 2004), increased woody shrub encroachment in tundra areas

(Tape *et al* 2006), increased height of *in situ* erect shrubs (Forbes *et al* 2010, Macias-Fauria *et al* 2012, Bjorkman *et al* 2018), changes in the depth of seasonal thaw (Loranty *et al* 2018), and associated changes in the energy regime (Chapin *et al* 2005). These insights are not obvious from measurements of warming rates alone, and the relative importance of these competing feedbacks. Thus, the cumulative effect of changing Arctic vegetation on the climate system and CO_2 fluxes, is still not very well known, particularly in Svalbard (Speed *et al* 2010), and Fennoscandia (Väisänen *et al* 2014). Drought can modify these feedback effects, decoupling warming and productivity as well as the balance of gross photosynthesis and plant respiration, which varies substantially across plant functional types (Chapin *et al* 1996).

The only effective way to map biomass and plant productivity in such large and remote areas as Alaska and Svalbard, as well as in other territories of the Arctic, is using remote sensing together with necessary *in situ* measurements and observations (Karlsen *et al* 2009).

The aim of our synthesis is to provide an overview of the studies in this focus issue and to place their findings within the broader context of ecosystem–climate dynamics. Our overview is organized into four sections that focus on studies that were primarily relevant to: (1) Changes in the physical environment over high latitude regions and associated ecological and phenological changes in Arctic/Boreal vegetation, including vegetation-mediated responses and climate feedbacks; (2) Actual and potential biomass change influenced by (local) climate, natural disturbances, human impacts (e.g. resource extraction and legacies) and impacts on humans; (3) Transformation of open tundra vegetation to tall shrub tundra or forests, due to warming and other processes, influencing local and global climate, albedo and climate feedback mechanisms; and (4) Integration of *in situ* observations and manipulation experiments including remote sensing and other data sources to advance methodological approaches for measuring and monitoring.

We then discuss the key collective advances made in each of these areas by the studies within this focus issue, as well as opportunities for future research.

2. Northern lands (45⁰N)

The synthesis comprise studies conducted north of 45°N comprising both the Boreal and Arctic zones and in figure 1 we can see the areas that were covered by the different studies. In order to define both regions, the latest version of the MODIS International Geosphere-Biosphere Programme (IGBP) land cover map (WWW-MCD12Q1) and the Circumpolar Arctic Vegetation Map (CAVM) (Walker *et al* 2005, WWW-CAVM) is used. Arctic (8.16 million km²) is defined as the vegetated area north of 65°N, excluding

agricultural land and forests, but including the tundra south of 65°N. Boreal region (17.86 million km²) is defined as the vegetated area between 45°N and 65°N, excluding agricultural land, tundra and nemoral forests.
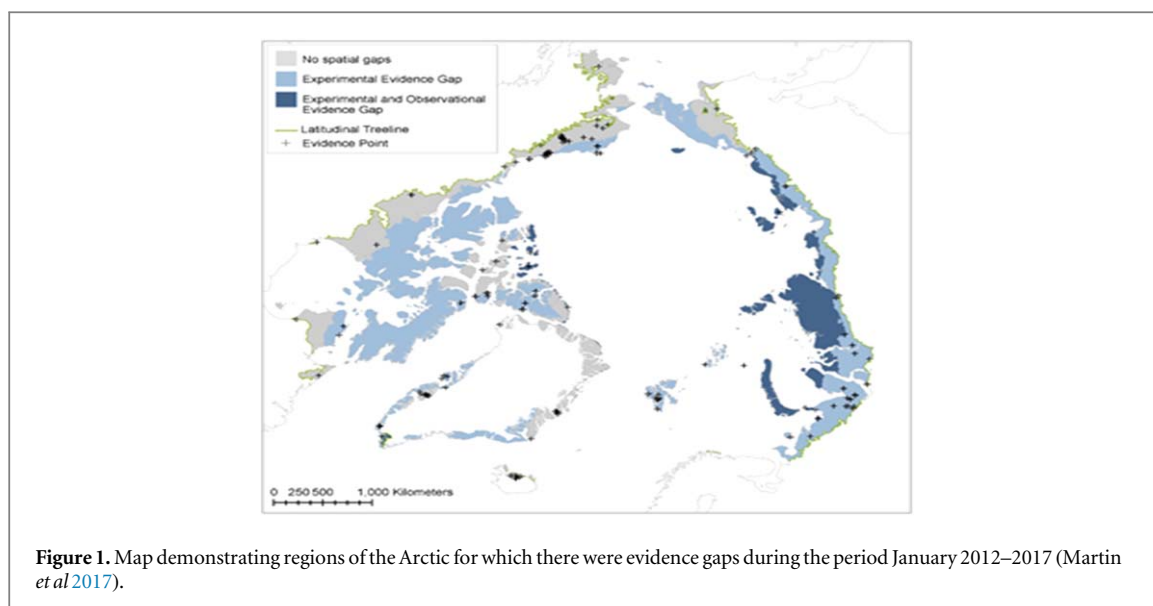
3. Overview synthesis

3.1. Changes in the physical environment over high latitude regions and associated ecological and phenological changes in Arctic/Boreal vegetation, including vegetation-mediated responses and climate feedbacks

Changes and variation over time in the physical environment across northern high latitude regions have been demonstrated to be large. Malnes *et al* (2016) report on the duration of snow season using snow cover area fraction data based on satellite data (daily 500 m standard snow product—MOD10A1 from MODIS) from the northernmost Norway. The first and last snow-free days for the study area were extracted from satellite data and compared to *in situ* met-station measurements. The start of the snow-free periods was up to 30 d later in spring 2000 and 2005 (DOY 135) compared with spring 2002 and 2006, which had an early start (DOY 105). The end of autumn/start of winter had a very late start in the years 2000 and 2007 (DOY 290) compared with 2009, whereas the first snow fall was 20 d earlier (270). In spring, the correlation between the first snow-free day mapped by MODIS data and snow data from 36 of 40 meteorological stations was highly significant ($p < 0.05$), with a of bias of less than 10 d for 34 of the stations. In autumn, 31 of 40 stations show highly significant ($p < 0.05$) correlation with MODIS data, and the bias was less than 10 d for 27 of the stations.

Park *et al* (2016) analyzed satellite observations during 33 years in order to assess changes in growing season metrics (onset: SOS, end: EOS and length: LOS) and seasonal total gross primary productivity using the growing season summed NDVI (GSSNDVI). They found that LOS had lengthened by 2.60 d dec⁻¹ ($p < 0.05$) due to an earlier onset of SOS (-1.61 d dec⁻¹, $p < 0.05$) and a delayed EOS (0.67 d dec⁻¹, $p < 0.1$) the past three decades. The changes in growing season metrics were stronger in Eurasia (EA) and in boreal regions compared to North America (NA) and the arctic regions.

Reports on tundra greening are numerous and varied, and include increases in summer, spring, and autumn temperatures, as well as growing season length (Macias-Fauria *et al* 2012, Zeng *et al* 2013, Bhatt *et al* 2017, Vickers *et al* 2016). The paper by Vickers *et al* (2016) made use of 30 years of a 1 km spatial resolution dataset (AVHRR) from 1986 to 2015 to calculate annual maximum NDVI over parts of Svalbard, and they found positive trends in maximum NDVI (+29%) and average summer temperature (+59%),

Figure 1. Map demonstrating regions of the Arctic for which there were evidence gaps during the period January 2012–2017 (Martin *et al* 2017).

which were significantly positively correlated with each other. On the same high arctic island, Karlsen *et al* (2018) found a a non-significant increase of 15% for the integrated MODIS NDVI defined as OP NDVI (onset to peak NDVI) for the period 2000–2014. At both local and regional scales, the latter NDVI-measure was found to predict biomass.

However, an increasing number of northern regions currently show declining productivity (browning). Such trends are evident both in North America and Eurasia, and factors assumed to contribute to this decline include recent reductions in summer moisture (see Verbyla 2015). Browning has also been attributed to mire and pond formation from increasing precipitation in some regions (Miles and Esau 2016), increasing moisture stress in other regions (Verbyla 2015), thermokarst development (Raynolds and Walker 2016), wildfire disturbance (Chu *et al* 2016), forest insect outbreaks (Bjerke *et al* 2015), increasing plant stress from winter warming and reduced snow protection (Bjerke *et al* 2017), fungal infestations and moose damage on young pine forests in the Nordic region (Normark 2019), spring freeze damage after bud swelling (Chamberlain *et al* 2019) and increasing industrial development (Hofgaard *et al* 2010, Miles and Esau 2016) and finally general forest change, which may lead to temporal browning including browning due to logging of forests (White *et al* 2017).

te Beest *et al* (2016) found that when reindeer reduce shrub abundance/cover and height, summer albedo increases in both *Betula nana*-dominated heath vegetation and *Salix glauca*-dominated shrub tundra. Model results reveal associated lower net radiation, together with latent and sensible heat fluxes in heavily-grazed areas in all shrub-dominated vegetation types. Hence reindeer have a potential cooling effect on climate by increasing summer albedo and decreasing net radiation. Herbivory may have long-term

consequences in warmed and ambient high Arctic tundra according to the study by Little *et al* (2017). They found that significantly more dead vascular plant material was found within warmed open-top chambers during a 12 year period compared to ambient plots, regardless of grazing history, but in contrast to many short-term experiments no difference in the amount of living material was found.

Belowground plant biomass allocation in tundra ecosystems and its relationship with temperature is of importance for modelling and analysis of climate change (Wang *et al* 2016). They found that plant community biomass–temperature relationships were significantly different between above and belowground biomass. Tundra ecosystems through altered litter input and distribution in the soil, as well as possible changes in root turnover.

The timing and duration of different pheno-phases within a plant's life cycle are critical for plant performance and growth. In the High Arctic, the start of many of these phenological phases is determined by the start of snowmelt, which can change in a changing climate (Semenchuk *et al* 2016). In order to assess any change in these phases, Semenchuk *et al* (2016) tested if snowmelt data control the timing and duration of phenological periods in Svalbard using a timing gradient from natural to experimentally altered snow depths. All pheno-phases followed irrespective of timing of occurrence, vegetative or reproductive nature, and three of the four phenological periods were fixed for most species such as the indigenous, hence the last was aperiodic. Semenchuk *et al* (2016) concluded that periodic species like the dwarf shrubs *Dryas octopetala* and *Cassiope tetragona* and the grass species *Luzula arcuata* are likely to be limited in their ability to adapt to changing snowmelt dates, and thus may be disadvantaged compared to some of the invading species on Svalbard such as the herb *Rumex longifolius* the grass *Deschampsia cespitosa*. Gillespie *et al* (2016)

studied the plant-pollinator interactions in High Arctic (Svalbard) and in their study they altered the timing of flowering phenology, using snow fences and open-top chambers. As expected, deep snow plots delay snow melt timing and this in turn delay the first and peak flowering dates of the plants, hence shortened the prefloration period overall. The OTCs, however, counteracted the delay in first and peak flowering to some extent. There was no effect of treatment on length of flowering season, although for all variables there were species-specific responses. The insect flower-visitor community was species poor, and although evidence of disruption to phenological overlaps was not found, reduced insect-flower visitation rates to flowers in plots with deep snow may have occurred, due to limited observation methods.

3.2. Actual and potential biomass change and productivity influenced by (local) climate, natural disturbances, human impacts (e.g. resource extraction and legacies) and impacts on humans

Bjerke *et al* (2015) detail the effects of above ground ice accumulation on meadow productivity by using ground observation and remotely sensed data (GIMMS NDVI3g data). Five contrasting snow season types were identified; snow-rich season with no soil frost or no ground-ice through low snow and considerable soil frost and ground-ice. Conditions of shallow snow depth and shallow soil frost or above-ground ice formation which may be a result of more frequent warming events, are rare at present but are predicted to become the dominant snow season type in Low Arctic and the Boreal lowlands. Agricultural productivity was lowest after winters with high accumulation of plant-damaging, hermetic above-ground ice formation Deep soil frost by itself did not reduce primary productivity. Loranty *et al* (2016) quantified the distribution of vegetation productivity trends, wildfire, and near-surface soil carbon, according to vegetation type, across the continuous and discontinuous permafrost. Zones. They observed positive trends in vegetation productivity in areas of continuous permafrost, whereas areas underlain by discontinuous permafrost have proportionally less positive productivity trends.

3.3. Transformation of open tundra vegetation to shrub tundra or forests, due to warming and other processes, influencing local and global climate, albedo and climate feedback mechanisms.

In recent decades, woody shrubs have either increased in biomass/height and/or expanded into new areas throughout the Pan-Arctic tundra biome (Martin *et al* 2017, see also Forbes *et al* 2010, Macias-Fauria *et al* 2012). The same authors created a protocol for (a) identification of an operational suite of controls on shrub growth and expansion, and (b) characterization of an evidence base for controls on Arctic shrub

growth and expansion. Evidence for a suite of 23 proximal controls that operate directly on shrub growth and expansion was found, while the evidence base was only focused on just four controls like air temperature, snow dynamics, soil moisture and herbivory. In particular, 65% of the evidence was generated within the warmest tundra climes (i.e. Low Arctic), while 24% of the evidence was from only one of 28 floristic sectors, indicating huge gaps (Martin *et al* 2017) in the available evidence (figure 1) in, so not comprehensive enough to answer key questions concerning Pan-Arctic shrub change.

Significant expansion of shrubs has been observed within Arctic and Boreal regions during recent decades and in eastern sub-arctic Canada, where dendrochronological studies have demonstrated that the majority of shrub stands sampled were young, since the dominant stems were developed after 1990 (Paradis *et al* 2016) which seem to be in accordance with Park *et al* (2016). Stratified sampling of shrubs revealed that woody biomass was maximal within the lower canopy stratum, whereas foliar biomass tracked the development of the respective stands' vertical structure. Shrub height as a parameter explained snow depth, winter ground level temperature and summed freezing-degree days, while woody biomass best explained summer ground level temperature. Hence, shrub canopy structure will exert significant control on the abiotic environment in subarctic ecosystems (Paradis *et al* 2016).

Shrub expansion is more likely to occur in areas with high soil moisture and nutrient availability, conditions typically found in sub-surface water channels called water tracks. Curasi *et al* (2016) quantified the distribution of water tracks and their contribution CO_2 dynamics during the growing season for a Siberian tundra landscape using field measurements, satellite observations and meteorological data. They found that water tracks occupied 7.4% of the study area, and account for a slightly larger proportion of growing season carbon uptake relative to surrounding tundra and also larger relative to graminoids within the same water tracks. Water tracks are an important component of this landscape and they will influence ecosystem structural and functional responses to climate, and is therefore of importance for modeling.

Increased wetness confounded Landsat-derived NDVI trends central Alaska North Slope region (Raynolds and Walker 2016) during 1985–2011. Regional trends showed decreases in NDVI for most vegetation types, but increases in tasseled-cap greenness, greatest for shrub dominated vegetation, and tasseled-cap wetness. This was consistent with thawing of polygon ice wedges. Increasing cover of water may be masking increases in vegetation when summarized using the more water-sensitive NDVI. This is also consistent with reduced NDVI due to melting of tundra as well as mire and pond formation from increasing precipitation in some regions of Northwest Siberia (Miles and

Esau [2016]), which show that care should be taken when relying solely on NDVI data (Raynolds and Walker [2016]).

Disturbances can have particularly large effects on Arctic ecosystems when ecosystem structure and function are controlled by strong feedbacks between soil conditions, vegetation moisture, and sub-surface thermal regime (Cameron and Lantz [2016]). An example of such disturbance includes e.g. road construction and maintenance on vegetation structure and biomass along the Dempster Highway. Using field data and very high-resolution remotely sensed data, Cameron and Lantz ([2016]) found that increased shrub proliferation adjacent to the road was caused by greater soil moisture.

3.4. Integration of *in situ* observations and manipulation experiments including remote sensing and other data sources to advance methodological approaches for measuring and monitoring.

Buchhorn *et al* ([2016]) showed that satellites provide the only practical source of data for estimating biomass of large and remote areas of the Arctic. Researchers have found that the normalized difference vegetation index (NDVI) correlates well with biomass sampled on the ground. However, errors in NDVI and biomass estimates due to bidirectional reflectance distribution function (BRDF) effects are not well reported. Finally, they found that studies that only sampling a narrow range of biomass and NDVI may produce equations that are more difficult to correct for BRDF effects.

Brazhnik and Shugart ([2015]) applied the new spatially-explicit gap-dynamics model SIBBORK towards a better understanding of how transition zones, namely treelines or forest lines, which are under-sampled and difficult to model, may change in the near future. They found that a 2 °C change in annual average air temperature will significantly alter the structure, composition, and productivity of boreal forest stands both at the northern treeline by 2040, and at the southern treeline by 2050.

Juutinen *et al* ([2017]) assessed the spatial variation and seasonal dynamics of leaf-area index (LAI) linking ground observations and very-high-spatial resolution multispectral satellite images (e.g. Worldview-2). They illustrated how the short growing season, rapid development of the LAI, yearly climatic variation, and timing of satellite data should be accounted for in matching imagery and field verification data in the Arctic. Among the main plant functional types, graminoid LAI displayed the largest seasonal amplitudes and was the main cause of varying NDVI spatial patterning.

The utilization of earth observation data in vegetation monitoring is highly dependent on a long heritage of ground-based observations in the Arctic (Walker *et al* [2016]). Several products of the Conservation of

Arctic Flora and Fauna are key to our current understanding (Shuchman *et al* [2015], Christensen *et al* [2013]). They have concluded that there is an urgent need for more consistent standards of plot-based observations and recommend improvements regarding the linkage between plot-based observations biodiversity studies and satellite-based observations of Arctic vegetation.

3.5. New tools

Bratsch *et al* ([2017]) assessed the ability of hyperspectral remote sensing data to estimate low arctic tundra biomass in Alaska. The main result was that the ability to identify unique biomass-spectra relationships within respective vegetation types using hyperspectral sensors was decreased during the peak of the growing season, since shrubs obscure lower-statured, bryophyte-dominated vegetation types. Hence, this study supports previous studies that shrubs control the spectral reflectance in Low Arctic communities (see also Forbes *et al* [2010]).

4. Further work and concluding remarks

Winter warming induced damage (arctic browning), particularly on dwarf-shrub vegetation (e.g. *Cassiope tetragona*) should be followed up via field monitoring and remote sensing (including UAV) in the future. Other vegetation changes in Arctic tundra and boreal regions, including the warming and thawing of permafrost (see Loranty *et al* [2016], [2018]), should be followed up. UAV based sensors and satellite sensors with very high spatial resolution (30–50 cm) may be efficient tools for detection of coastal erosion, human impacts (tourism), changes in tundra vegetation cover/stature, as well as permafrost thaw, and should be followed annually in the future. UAV can also be used as an upscaling tool. Another problem is that there exists huge gaps (Martin *et al* [2017]) in the Arctic and Boreal regions concerning long-term monitoring sites, including large areas that are not monitored at all (figure [1]). These gaps currently afford us insufficient evidence of what is transpiring ecologically within these regions. However, a recent paper published by Virkkala *et al* ([2019]) in ERL provide detailed maps of potential new sampling locations in Arctic and the northern boreal region (the land north of the Arctic Circle (66,5° N)), hence help prioritize future research efforts concerning environmental change in the north.

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References

ACIA 2004 Impacts of a warming Arctic *Arctic Climate Impact Assessment Overview Report* ed S J Hassol (Cambridge: Cambridge University Press)

Bala G *et al* 2007 Combined climate and carbon-cycle effects of large-scale deforestation *Proc. Natl. Acad. Sci. USA.* **104** 6550–5

Bhatt U *et al* 2017 Changing seasonality of Panarctic tundra vegetation in relationship to climatic variables *Environ. Res. Lett.* **12** 055003

Bjerke J W *et al* 2015 Impacts of snow season on ground-ice accumulation, soil frost and primary productivity in .a grassland of sub-Arctic Norway *Environ. Res. Lett.* **10** 095007

Bjerke J W *et al* 2017 Understanding the drivers of extensive plant damage in boreal and Arctic ecosystems: Insights from field surveys in the aftermath of damage *Sci. of Tot. Environ,* **599–600** 1965–76

Bjerke J W, Rune Karlsen S, Arild Høgda K, Malnes E, Jepsen J U, Lovibond S, Vikhamar-Schuler D and Tømmervik H 2014 Record-low primary productivity and high plant damage in the Nordic Arctic Region in 2012 caused by multiple weather events and pest outbreaks *Environ. Res. Lett.* **9** 084006

Bjorkman A D *et al* 2018 Changes in plant functional traits across a warming tundra biome *Nature* **62** 57–62

Bratsch S *et al* 2017 Relationships between hyperspectral data and components of vegetation biomass in Low Arctic tundra communities at Ivotuk, Alaska *Environ. Res. Lett.* **12** 025003

Brazhnik K and Shugart H H 2015 3D simulation of boreal forests: structure and dynamics in complex terrain and in a changing climate *Environ. Res. Lett.* **10** 105006

Buchhorn M *et al* 2016 Influence of BRDF on NDVI and biomass estimations of Alaska Arctic tundra *Environ. Res. Lett.* **11** 125002

Cameron E A and Lantz T C 2016 Drivers of tall shrub proliferation adjacent to the Dempster Highway, Northwest Territories, Canada *Environ. Res. Lett.* **11** 04500

Chamberlain C J *et al* 2019 Rethinking false spring risk *Glob. Change Biol.* **25** 2209–20

Chapin F S *et al* 1996 Plant functional types as predictors of transient responses of arctic vegetation to global change *J. Veg. Sci.* **7** 347–58

Chapin F S *et al* 2005 Role of land-surface changes in Arctic summer warming *Science* **310** 657–60

Christensen T *et al* 2013 The Arctic terrestrial biodiversity monitoring plan *CAFF Monitoring Series Report Nr.* 7 CAFF International Secretariat. Akureyri, Iceland

Chu T, Guo X and Takeda K 2016 Remote sensing approach to detect post-fire vegetation regrowth in Siberian boreal larch forest *Ecol. Indicat.* **62** 32–46

Curasi S R *et al* 2016 Water track distribution and effects on carbon dioxide flux in an eastern Siberian upland tundra landscape *Environ. Res. Lett.* **11** 045002

Field C B, Lobell D B, Peters H A and Chiariello N R 2007 Feedbacks of terrestrial ecosystems to climate change *Ann. Rev. Environ. Resour.* **32** 1–29

Forbes B C, Fauria M M and Zetterberg P 2010 Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows *Glob. Change Biol.* **16** 1542–54

Epstein H E, Calef M P, Walker M D, Stuart Chapin F and Starfield A M 2004 Detecting changes in arctic tundra plant communities in response to warming over decadal time scales *Glob. Change Biol.* **10** 1325–34

Gillespie M A K *et al* 2016 High Arctic flowering phenology and plant–pollinator interactions in response to delayed snow melt and simulated warming *Environ. Res. Lett.* **11** 115006

Hofgaard *et al* 2010 Role of disturbed vegetation in mapping the boreal zone in northern Eurasia *Appl. Veg. Sci.* **13** 460–72

Juutinen S *et al* 2017 Spatial variation and seasonal dynamics of leaf-area index in the arctic tundra-implications for linking ground observations and satellite images *Environ. Res. Lett.* **12** 095002

Karlsen S R *et al* 2009 Growing-season trends in Fennoscandia 1982–2006, determined from satellite and phenology data *Clim. Res.* **39** 275–86

Karlsen S R, Anderson H B, van der Wal R and Hansen B B 2018 A new NDVI measure that overcomes data sparsity in cloud-covered regions predicts annual variation in ground-based estimates of high arctic plant productivity *Environ. Res. Lett.* **13** 025011

Little C J *et al* 2017 Short-term herbivory has long-term consequences in warmed and ambient high Arctic tundra *Environ. Res. Lett.* **12** 025001

Loranty M M *et al* 2016 Spatial variation in vegetation productivity trends, fire disturbance, and soil carbon across arctic-boreal permafrost ecosystems *Environ. Res. Lett.* **11** 095008

Loranty M M *et al* 2018 Changing ecosystem influences on soil thermal regimes in northern high-latitude permafrost regions *Biogeosciences* **15** 5287–313

Macias-Fauria M, Forbes B C, Zetterberg P and Kumpula T 2012 Eurasian Arctic greening reveals teleconnections and the potential for structurally novel ecosystems *Nat. Clim. Change* **2** 613–8

Macias-Fauria M, Karlsen S R and Forbes B C 2017 Disentangling the coupling between sea ice and tundra productivity in Svalbard *Sci. Rep.* **7** 8586

Malnes E *et al* 2016 Snow season variability in a boreal-Arctic transition area monitored by MODIS data *Environ. Res. Lett.* **11** 125005

Martin A C *et al* 2017 Shrub growth and expansion in the Arctic tundra: an assessment of controlling factors using an evidence-based approach *Environ. Res. Lett.* **12** 085007

McGuire A D *et al* 2009 Sensitivity of the carbon cycle in the Arctic to climate change *Ecol. Monogr.* **79** 523–5

Meredith M P *et al* 2019 Polar regions *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* ed H O Pörtner *et al* (Geneva: IPCC) (https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/07_SROCC_Ch03_FINAL.pdf)

Miles V V and Esau I 2016 Spatial heterogeneity of greening and browning between and within bioclimatic zones in northern West Siberia *Environ. Res. Lett.* **11** 115002

Normark S 2019 Multiskadad ungskog iVästerbottens-och Norrbottens länMöjliga åtgärder för att mildra problemen *Report* 2019/10 (Härnösand, Sweden: Skogsstyrelsen)

Paradis M *et al* 2016 Greater effect of increasing shrub height on winter versus summer soil temperature *Environ. Res. Lett.* **11** 085005

Park *et al* 2016 Changes in growing season duration and productivity of northern vegetation inferred from long-term remote sensing data *Environ. Res. Lett.* **11** 084001

Raynolds M K and Walker D A 2016 Increased wetness confounds Landsat-derived NDVI trends in the central Alaska North Slope region, 1985–2011 *Environ. Res. Lett.* **11** 085004

Semenchuk P R *et al* 2016 High Arctic plant phenology is determined by snowmelt patterns but duration of phenological periods is fixed: an example of periodicity *Environ. Res. Lett.* **11** 125006

Shuchman R A, Jenkins L and Whitley M A 2015 Arctic land cover change Initiative: MODIS satellite data *CAFF Monitoring Series* 17 Conservation of ArcticFlora and Fauna, Akureyri, Iceland

Speed J D M, Woodin S J, Tømmervik H and van der Wal R 2009 Extrapolating herbivore-induced carbon loss across an arctic landscape *Polar Biol.* **33** 789–97

te Beest M *et al* 2016 Reindeer grazing increases summer albedo by reducing shrub abundance in Arctic tundra *Environ. Res. Lett.* **11** 125013

Tape K, Sturm M and Racine C 2006 The evidence for shrub expansion in Northern Alaska and the Pan-Arctic *Glob. Change Biol.* **12** 686–702

Verbyla D 2015 Remote sensing of interannual boreal forest NDVI in relation to climatic conditions in interior Alaska *Environ. Res. Lett.* **10** 125016

Vickers H *et al* 2016 Changes in greening in the high Arctic: insights from a 30 year AVHRR max NDVI dataset for Svalbard *Environ. Res. Lett.* **11** 105004

Virkkala *et al* 2019 Identifying multidisciplinary research gaps across Arctic terrestrial gradients *Environ. Res. Lett.* **14** 124061

Väisänen M *et al* 2014 Consequences of warming on tundra carbon balance determined by reindeer grazing history *Nat. Clim. Change* **4** 384–8

Walker D A *et al* 2005 The Circumpolar Arctic vegetation map *J. Veg. Sci.* **16** 267–82

Walker D A *et al* 2016 Circumpolar Arctic vegetation: a hierarchic review and roadmap toward an internationally consistent approach to survey, archive and classify tundra plot data *Environ. Res. Lett.* **11** 055005

Wang P *et al* 2016 Belowground plant biomass allocation in tundra ecosystems and its relationship with temperature *Environ. Res. Lett.* **11** 055003

White J C *et al* 2017 Nationwide annual characterization of 25 years of forest disturbance and recovery for Canada using Landsat time series *Remote Sens. Environ.* **194** 303–21

Xu L *et al* 2013 Temperature and vegetation seasonality diminishment over northern lands *Nat. Clim. Change* **3** 581–6

Zeng H, Jia G S and Forbes B C 2013 Response of phenological shifts to climate and anthropogenic factors as detected from multi-satellite data *Environ. Res. Lett.* **8** 035036