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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

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4 provide an outlook on future needs and research questions in the study of climate and
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6 human driven interactions in terrestrial Arctic and Boreal ecosystems.
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10 **1 Introduction**

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12 Ecosystem responses to Arctic warming have the potential to feedback either
13
14 positively or negatively to the earth's climate system depending on latitude, changes in
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16 disturbance regime, vegetation distribution and productivity (McGuire et al. 2009).
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19 The lower albedo of shrub and forest vegetation compared with tundra, for example,
20
21 results in a positive feedback on temperature (Bala et al. 2007, Lorantý et al. 2011).
22
23 Global warming presented as a warming rate, e.g. 0.2 °C/decade (ACIA 2004), does
24
25 not reflect the fact that cold seasons are warming faster than the warm seasons,
26
27 especially in the Arctic due to positive feedbacks (e.g. albedo-temperature feedback
28
29 (Meredith et al. 2019). The initiation, termination and performance of many biological
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31 processes, e.g. plant growth, are tied to threshold temperatures. The trend in timing of
32
33 these thresholds, and cumulative air temperatures driving them, may have the effect of
34
35 enhancing vegetation productivity.
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40 Conversely, increased productivity of Arctic vegetation resulting from warmer
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42 temperatures tends to result in increased carbon dioxide (CO₂) uptake by net
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44 photosynthesis, providing a negative feedback to rising temperatures (Field et al. 2007;
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46 Serreze et al. 2000, Speed et al. 2010). As a result of this trend, between 1982 and
47
48 2011, Arctic tundra vegetation increased both in terms of peak productivity, greening
49
50 and growing season length and this finding is supported by a wide range of field site
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52 measurements across the Arctic (Myneni et al. 1997, ACIA 2004; Serreze et al. 2000;
53
54 Walker et al. 2006, Zu et al. 2013). Also, in coastal areas of Canada and Alaska
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56 (Epstein et al. 2004) and Arctic islands like Svalbard, there are trends of increased
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58 greening (Speed et al. 2010, Vickers et al. 2016), with some demonstrated linkages to
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4 sea ice (Macias-Fauria et al. 2017). These dynamics include changes in the
5
6 composition and density of herbaceous vegetation (Epstein et al. 2004; Shaver et al.
7
8 2007), increased woody shrub encroachment in tundra areas (Sturm et al. 2001; Tape
9
10 et al. 2006, Tømmervik et al. 2009), increased height of in situ erect shrubs (Forbes et
11
12 al. 2010; Macias-Fauria et al. 2012; Bjorkman et al. 2018), changes in the depth of
13
14 seasonal thaw (Goulden et al. 1998; Kimball et al. 2006; Schuur et al. 2009; Loranty et
15
16 al. 2018), and associated changes in the energy regime (Chapin et al. 2005; Sturm et al.
17
18 2001). These insights are not obvious from measurements of warming rates alone, and
19
20 the relative importance of these competing feedbacks. Thus, the cumulative effect of
21
22 changing Arctic vegetation on the climate system and CO₂ fluxes, is still not very well
23
24 known, particularly in Svalbard (Speed et al. 2010; Johansen et al. 2012, Johansen &
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26 Tømmervik 2014), parts of Alaska (references?), and Fennoscandia (Väisänen et al.
27
28 2014). Drought can modify these feedback effects, decoupling warming and
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30 productivity as well as the balance of gross photosynthesis and plant respiration, which
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32 varies substantially across plant functional types (Chapin et al. 1996; Goetz and Prince
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34 1999).

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43 The only effective way to map biomass and plant productivity in such large and remote
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45 areas as Alaska and Svalbard, as well as in other territories of the Arctic, is using
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47 remote sensing together with necessary *in situ* measurements and observations
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49 (Myneni et al 1997, Karlsen et al. 2009, Beck et al. 2011).

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54 The aim of our synthesis is to provide an overview of the studies in this focus issue
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56 and to place their findings within the broader context of ecosystem– climate dynamics.

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59 Our overview is organized into four sections that focus on studies that were primarily
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4 relevant to: (1) Changes in the physical environment over high latitude regions and
5 associated ecological and phenological changes in Arctic/Boreal vegetation, including
6 vegetation-mediated responses and climate feedbacks; (2) Actual and potential
7 biomass change influenced by (local) climate, natural disturbances, human impacts
8 (e.g. resource extraction and legacies) and impacts on humans; (3) Transformation of
9 open tundra vegetation to tall shrub tundra or forests, due to warming and other
10 processes, influencing local and global climate, albedo and climate feedback
11 mechanisms; and (4) Integration of *in situ* observations and manipulation experiments
12 including remote sensing and other data sources to advance methodological
13 approaches for measuring and monitoring.
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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 (45° N)

40 The synthesis comprise studies conducted north of 45°N comprising
41 both the Boreal and Arctic zones and in Fig. 1 and Table 1 we can see the areas that
42 were covered by the different studies. In order to define both regions, the latest version
43 of the MODIS International Geosphere-Biosphere Programme (IGBP) land cover map
44 (Friedl et al 2010, WWW-MCD12Q1) and the Circumpolar Arctic Vegetation Map
45 (CAVM) (Walker et al 2005, WWW-CAVM) is used. Arctic (8.16 million km²) is
46 defined as the vegetated area north of 65°N, excluding agricultural land and forests,
47 but including the tundra south of 65°N. Boreal region (17.86 million km²) is defined as
48 the vegetated area between 45°N and 65°N, excluding agricultural land, tundra and
49 nemoral forests.
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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. (2017) 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 days 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 days 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 days 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 days 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

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4 (GSSNDVI). They found that LOS had lengthened by 2.60 d dec⁻¹ ($p < 0.05$) due to
5
6 an earlier onset of SOS (-1.61 d dec⁻¹, $p < 0.05$) and a delayed EOS (0.67 d dec⁻¹, p
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8 < 0.1) the past three decades. The changes in growing season metrics were stronger in
9
10 Eurasia (EA) and in boreal regions compared to North America (NA) and the arctic
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12 regions.
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18 Reports on tundra greening are numerous and varied, and include increases in summer,
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20 spring, and autumn temperatures, as well as growing season length (Macias-Fauria et
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22 al. 2012; Zeng et al. 2013; Bhatt et al., 2017; Vickers et al., 2017). The paper by
23
24 Vickers et al. (2016) made use of 30 years of a 1 km spatial resolution dataset
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26 (AVHRR) from 1986 to 2015 to calculate annual maximum NDVI over parts of
27
28 Svalbard, and they found positive trends in maximum NDVI (+29%) and average
29
30 summer temperature (+59%), which were significantly positively correlated with each
31
32 other. On the same high arctic island, Karlsen et al. (2017) found a a non-significant
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34 increase of 15% for the integrated MODIS NDVI defined as OP NDVI (onset to peak
35
36 NDVI) for the period 2000-2014. At both local and regional scales, the latter NDVI-
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38 measure was found to predict biomass.
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46 However, an increasing number of northern regions currently show declining
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48 productivity (browning). Such trends are evident both in North America and Eurasia,
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50 and factors assumed to contribute to this decline include recent reductions in summer
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52 moisture (cf. Verbyla 2015). Browning has also been attributed to mire and pond
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54 formation from increasing precipitation in some regions (Miles & Esau 2016, Lara et
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56 al. 2018), increasing moisture stress in other regions (Verbyla 2015, Sulla-Menashe et
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58 al. 2018), thermokarst development (Raynolds & Walker 2016), wildfire disturbance
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4 (Chu et al. 2016), forest insect outbreaks (Bjerke et al. 2014, Sweet et al. 2015),
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6 increasing plant stress from winter warming and reduced snow protection (Bjerke et al.
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8 2017, Treharne et al. 2018), fungal infestations and moose damage on young pine
9
10 forests in the Nordic region (Marntell 2019), spring freeze damage after bud swelling
11
12 (Chamberlain et al. 2019) and increasing industrial development (Hofgaard et al. 2010,
13
14 Miles & Esau 2016) and finally general forest change, which may lead to temporal
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16 browning including browning due to logging of forests (White et al. 2017).
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22
23 te Beest et al. (2016) found that when reindeer reduce shrub abundance/cover and
24
25 height, summer albedo increases in both *Betula nana*-dominated heath vegetation and
26
27 *Salix glauca*-dominated shrub tundra. Model results reveal associated lower net
28
29 radiation, together with latent and sensible heat fluxes in heavily-grazed areas in all
30
31 shrub-dominated vegetation types. Hence reindeer have a potential cooling effect on
32
33 climate by increasing summer albedo and decreasing net radiation. Herbivory may
34
35 have long-term consequences in warmed and ambient high Arctic tundra according to
36
37 the study by Little et al (2017). They found that significantly more dead vascular plant
38
39 material was found within warmed open-top chambers during a 12-year period
40
41 compared to ambient plots, regardless of grazing history, but in contrast to many short-
42
43 term experiments no difference in the amount of living material was found.
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50 Belowground plant biomass allocation in tundra ecosystems and its relationship with
51
52 temperature is of importance for modelling and analysis of climate change (Wang et al.
53
54 2016). They found that plant community biomass–temperature relationships were
55
56 significantly different between above and belowground biomass. Tundra ecosystems
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4 through altered litter input and distribution in the soil, as well as possible changes in
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6 root turnover.
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11 The timing and duration of different pheno-phases within a plant's life cycle are critical
12
13 for plant performance and growth. In the High Arctic, the start of many of these
14
15 phenological phases is determined by the start of snowmelt, which can change in a
16
17 changing climate (Semenchuk et al. 2016). In order to assess any change in these
18
19 phases, Semenchuk et al. (2016) tested if snowmelt data control the timing and
20
21 duration of phenological periods in Svalbard using a timing gradient from natural to
22
23 experimentally altered snow depths. All pheno-phases followed irrespective of timing
24
25 of occurrence, vegetative or reproductive nature, and three of the four phenological
26
27 periods were fixed for most species such as the indigenous, hence the last was
28
29 aperiodic. Semenchuk et al. (2016) concluded that periodic species like the dwarf
30
31 shrubs *Dryas octopetala* and *Cassiope tetragona* and the grass species *Luzula arcuata*
32
33 are likely to be limited in their ability to adapt to changing snowmelt dates, and thus
34
35 may be disadvantaged compared to some of the invading species on Svalbard such as
36
37 the herb *Rumex longifolius* the grass *Deschampsia cespitosa*. Gillespie et al (2016)
38
39 studied the plant-pollinator interactions in High Arctic (Svalbard) and in their study
40
41 they altered the timing of flowering phenology, using snow fences and open-top
42
43 chambers. As expected, deep snow plots delay snow melt timing and this in turn delay
44
45 the first and peak flowering dates of the plants, hence shortened the prefloration period
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47 overall. The OTCs, however, counteracted the delay in first and peak flowering to
48
49 some extent. There was no effect of treatment on length of flowering season, although
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51 for all variables there were species-specific responses. The insect flower-visitor
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53 community was species poor, and although evidence of disruption to phenological
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4 overlaps was not found, reduced insect-flower visitation rates to flowers in plots with
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6 deep snow may have occurred, due to limited observation methods.
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10 11 12 **3.2 Actual and potential biomass change and productivity influenced by (local)** 13 **climate, natural disturbances, human impacts (e.g. resource extraction and** 14 **legacies) and impacts on humans** 15

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17 Bjerke et al. (2015) detail the effects of above ground ice accumulation on meadow
18
19 productivity by using ground observation and remotely sensed data (GIMMS NDVI3g
20
21 data). Five contrasting snow season types were identified; snow-rich season with no
22
23 soil frost or no ground-ice through low snow and considerable soil frost and ground-
24
25 ice. Conditions of shallow snow depth and shallow soil frost or above-ground ice
26
27 formation which may be a result of more frequent warming events, are rare at present
28
29 but are predicted to become the dominant snow season type in Low Arctic and the
30
31 Boreal lowlands. Agricultural productivity was lowest after winters with high
32
33 accumulation of plant-damaging, hermetic above-ground ice formation Deep soil frost
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35 by itself did not reduce primary productivity. Loranty et al. (2016) quantified the
36
37 distribution of vegetation productivity trends, wildfire, and near-surface soil carbon,
38
39 according to vegetation type, across the continuous and discontinuous permafrost.
40
41 Zones. They observed positive trends in vegetation productivity in areas of continuous
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43 permafrost, whereas areas underlain by discontinuous permafrost have proportionally
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45 less positive productivity trends.
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53 54 **3.3 Transformation of open tundra vegetation to shrub tundra or forests, due to** 55 **warming and other processes, influencing local and global climate, albedo and** 56 **climate feedback mechanisms.** 57

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59 In recent decades, woody shrubs have either increased in biomass/height and/or
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61 expanded into new areas throughout the Pan-Arctic tundra biome (Martin et al. 2017;

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4 see also Forbes et al. 2010; Macias-Fauria et al. 2012). The same authors created a
5 protocol for (a) identification of an operational suite of controls on shrub growth and
6 expansion, and (b) characterization of an evidence base for controls on Arctic shrub
7 growth and expansion. Evidence for a suite of 23 proximal controls that operate
8 directly on shrub growth and expansion was found, while the evidence base was only
9 focused on just four controls like air temperature, snow dynamics, soil moisture and
10 herbivory. In particular, 65% of the evidence was generated within the warmest tundra
11 climates (i.e. Low Arctic), while 24% of the evidence was from only one of 28 floristic
12 sectors, indicating huge gaps (Martin et al. 2016) in the available evidence (Fig. 1
13 in), so not comprehensive enough to answer key questions concerning Pan-Arctic
14 shrub change.
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25 Significant expansion of shrubs has been observed within Arctic and Boreal regions
26 during recent decades and in eastern sub-arctic Canada, where dendrochronological
27 studies have demonstrated that the majority of shrub stands sampled were young, since
28 the dominant stems were developed after 1990 (Paradis et al. 2016) which seem to be in
29 accordance with Park et al. (2016). Stratified sampling of shrubs revealed that woody
30 biomass was maximal within the lower canopy stratum, whereas foliar biomass tracked
31 the development of the respective stands' vertical structure. Shrub height as a
32 parameter explained snow depth, winter ground level temperature and summed
33 freezing-degree days, while woody biomass best explained summer ground level
34 temperature. Hence, shrub canopy structure will exert significant control on the abiotic
35 environment in subarctic ecosystems (Paradis et al. 2016).
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45 Shrub expansion is more likely to occur in areas with high soil moisture and nutrient
46 availability, conditions typically found in sub-surface water channels called water
47 tracks. Curasi et al. (2016) quantified the distribution of water tracks and their
48 contribution CO₂ dynamics during the growing season for a Siberian tundra landscape
49 using field measurements, satellite observations and meteorological data. They found
50 that water tracks occupied 7.4% of the study area, and account for a slightly larger
51 proportion of growing season carbon uptake relative to surrounding tundra and also
52 larger relative to graminoids within the same water tracks. Water tracks are an
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4 important component of this landscape and they will influence ecosystem structural
5 and functional responses to climate, and is therefore of importance for modeling.
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9 Increased wetness confounded Landsat-derived NDVI trends central Alaska North
10 Slope region (Raynolds and Walker 2016) during 1985 to 2011. Regional trends
11 showed decreases in NDVI for most vegetation types, but increases in tasseled-cap
12 greenness, greatest for shrub dominated vegetation, and tasseled-cap wetness. This was
13 consistent with thawing of polygon ice wedges. Increasing cover of water may be
14 masking increases in vegetation when summarized using the more water-sensitive
15 NDVI. This is also consistent with reduced NDVI due to melting of tundra as well as
16 mire and pond formation from increasing precipitation in some regions of Northwest
17 Siberia (Miles & Esau 2016), which show that care should be taken when relying
18 solely on NDVI data (Raynolds and Walker 2016) .
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28 Disturbances can have particularly large effects on Arctic ecosystems when ecosystem
29 structure and function are controlled by strong feedbacks between soil conditions,
30 vegetation moisture, and sub-surface thermal regime (Cameron et al 2016). An
31 example of such disturbance includes e.g. road construction and maintenance on
32 vegetation structure and biomass along the Dempster Highway. Using field data and
33 very high-resolution remotely sensed data, Cameron et al. (2016) found that increased
34 shrub proliferation adjacent to the road was caused by greater soil moisture (see also
35 Myers-Smith et al. 2015).
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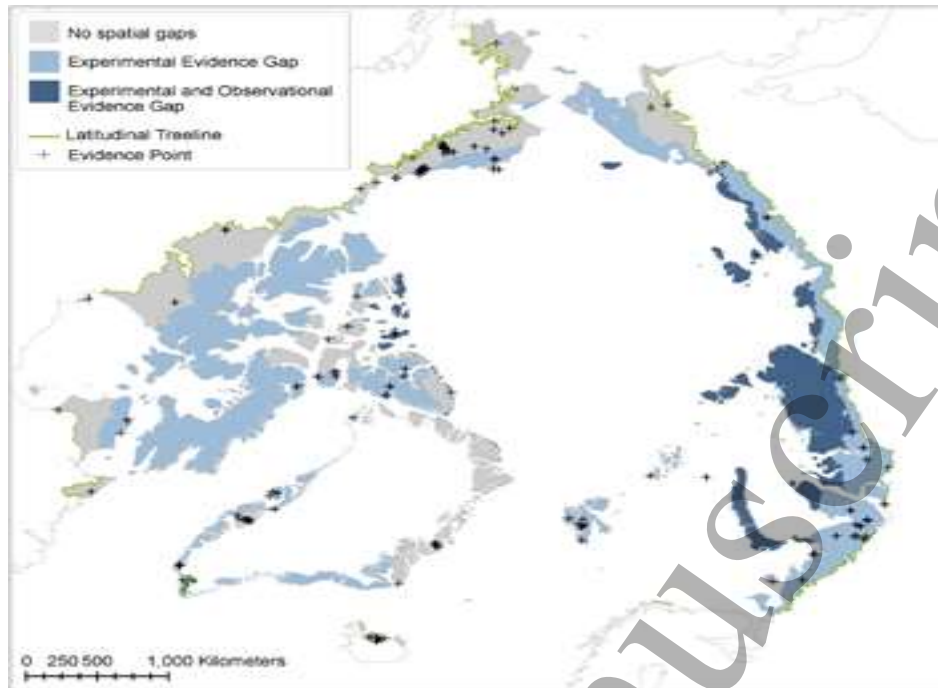


Figure 1. Map demonstrating regions of the Arctic for which there were evidence gaps during the period January 2012–January 2017 (Martin et al. 2017).

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 (2016) 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.

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4 Juutinen et al. (2017) assessed the spatial variation and seasonal dynamics of leaf-area
5 index (LAI) linking ground observations and very-high-spatial resolution multispectral
6 satellite images (e.g. Worldview-2). They illustrated how the short growing season,
7 rapid development of the LAI, yearly climatic variation, and timing of satellite data
8 should be accounted for in matching imagery and field verification data in the Arctic.
9 Among the main plant functional types, graminoid LAI displayed the largest seasonal
10 amplitudes and was the main cause of varying NDVI spatial patterning.
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18 The utilization of earth observation data in vegetation monitoring is highly dependent
19 on a long heritage of ground-based observations in the Arctic (Walker et al. 2016).
20 Several products of the Conservation of Arctic Flora and Fauna are key to our current
21 understanding (Shuchman et al. 2015, Christen T et al. 2013)) They have concluded
22 that there is an urgent need for more consistent standards of plot-based observations
23 and recommend improvements regarding the linkage between plot-based observations
24 biodiversity studies and satellite-based observations of Arctic vegetation.
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32 33 **3.5 New tools**

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35 Bratsch et al (2017) assessed the ability of hyperspectral remote sensing data to
36 estimate low arctic tundra biomass in Alaska. The main result was that the ability to
37 identify unique biomass-spectra relationships within respective vegetation types using
38 hyperspectral sensors was decreased during the peak of the growing season, since
39 shrubs obscure lower-statured, bryophyte-dominated vegetation types. Hence, this
40 study supports previous studies that shrubs control the spectral reflectance in Low
41 Arctic communities (see also Forbes et al. 2010).
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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 (cf. 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 (Fig. 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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14 095007
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