Dynamics of aboveground phytomass of the circumpolar Arctic tundra during the past three decades

2012 Environ. Res. Lett. 7 015506

(http://iopscience.iop.org/1748-9326/7/1/015506)

IOP PUBLISHING ENVIRONMENTAL RESEARCH LETTERS

Environ. Res. Lett. **7** (2012) 015506 (12pp) doi:10.1088/1748-9326/7/1/015506

Dynamics of aboveground phytomass of the circumpolar Arctic tundra during the past three decades

Howard E Epstein[1], Martha K Raynolds[2], Donald A Walker[2], Uma S Bhatt[3], Compton J Tucker[4] and Jorge E Pinzon[4]

[1] Department of Environmental Science, University of Virginia, Charlottesville, VA 22904-4123, USA
[2] Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK 99775-7000, USA
[3] Department of Atmospheric Sciences, Geophysical Institute, University of Alaska, Fairbanks, AK 99775-7320, USA
[4] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Received 2 September 2011
Accepted for publication 22 December 2011
Published 18 January 2012
Online at stacks.iop.org/ERL/7/015506

Abstract

Numerous studies have evaluated the dynamics of Arctic tundra vegetation throughout the past few decades, using remotely sensed proxies of vegetation, such as the normalized difference vegetation index (NDVI). While extremely useful, these coarse-scale satellite-derived measurements give us minimal information with regard to how these changes are being expressed on the ground, in terms of tundra structure and function. In this analysis, we used a strong regression model between NDVI and aboveground tundra phytomass, developed from extensive field-harvested measurements of vegetation biomass, to estimate the biomass dynamics of the circumpolar Arctic tundra over the period of continuous satellite records (1982–2010). We found that the southernmost tundra subzones (C–E) dominate the increases in biomass, ranging from 20 to 26%, although there was a high degree of heterogeneity across regions, floristic provinces, and vegetation types. The estimated increase in carbon of the aboveground live vegetation of 0.40 Pg C over the past three decades is substantial, although quite small relative to anthropogenic C emissions. However, a 19.8% average increase in aboveground biomass has major implications for nearly all aspects of tundra ecosystems including hydrology, active layer depths, permafrost regimes, wildlife and human use of Arctic landscapes. While spatially extensive on-the-ground measurements of tundra biomass were conducted in the development of this analysis, validation is still impossible without more repeated, long-term monitoring of Arctic tundra biomass in the field.

Keywords: Arctic tundra, circumpolar, NDVI, remote sensing, spatial and temporal dynamics, vegetation biomass

1. Introduction

Numerous observations of the Arctic tundra over time, using both field and remotely sensed methodologies, have indicated that the aboveground component of tundra vegetation has been increasing since at least the middle of the 20th century. An extensive set of repeat photographs of areas throughout the North Slope of Alaska indicated an expansion of several types of shrubs, including alder, willow and birch, largely on hillslopes and in valley bottoms over the past 50 or so years (Tape *et al* 2006, Sturm *et al* 2001). Multi-spectral remote sensing from Earth-orbiting satellites corroborated and added to this finding for northern Alaska (Jia *et al* 2003), detecting a 16.9% increase in the peak normalized difference vegetation index (NDVI—an index of green vegetation) over the period from 1981 to 2001, from Advanced Very High

Resolution Radiometer (AVHRR) sensors with 8 km × 8 km pixel resolution (and from 1990 to 2000 with 1 km resolution). In a broader study of Alaska, Verbyla (2008) confirmed these findings of increased annual maximum NDVI for the Alaskan tundra from 1982 to 2003, with the greatest changes occurring within the Alaska Coastal Plain, also noting rapid increases in NDVI during the early part of the growing season (first half of June).

For the high latitudes of continental North America (Alaska and Canada), numerous studies have examined these greening trends, also using coarse-resolution, multispectral remote sensors. Goetz *et al* (2005) found increased photosynthetic activity (i.e. NDVI), using the 8 km AVHRR data for North American tundra over the period 1981–2003, including an earlier onset to the tundra growing season. Bunn *et al* (2005) analyzed the same dataset from 1981 to 2000, and found that tundra photosynthetic activity responded largely to maximum summer temperatures, which increased over this time period. For Canada specifically, Jia *et al* (2009) found that greening has occurred in all five Arctic tundra bioclimate subzones (Walker *et al* 2005 subzones A–E ranging from north to south), with increases in peak NDVI of 0.49–0.79% yr^{-1} for the High Arctic (subzones A–C) and increases of 0.46–0.67% yr^{-1} for the Low Arctic (subzones D–E) over the period 1982–2006. Arctic subzones A–C exhibited a trend of earlier peak NDVI over time, whereas subzones D–E had earlier onsets of vegetation growth. In a finer resolution study, Pouliot *et al* (2009) used both 1 km AVHRR data and 30 m Landsat data to identify significant positive trends in NDVI for 22% of the Canadian land surface from 1985 to 2006, with some of the greatest increases occurring in the tundra. Olthof *et al* (2008) also indicated that increasing vegetation trends in Canadian tundra were greater for areas dominated by vascular plants, as opposed to those that were lichen-dominated.

Finally, at the circumpolar scale, the greening of the northern high latitudes and the Arctic tundra specifically has been observed with remotely sensed data for some time (Myneni *et al* 1997, Tucker *et al* 2001, Zhou *et al* 2001, Slayback *et al* 2003), and more recent studies have noted the continuation of this trend (Bunn and Goetz 2006, Bunn *et al* 2007, Neigh *et al* 2008, Bhatt *et al* 2010). Neigh *et al* (2008) used several higher resolution datasets (e.g. Landsat, IKONOS) to elucidate the causal mechanisms for change and found that tundra vegetation was largely responding to climatic changes. Bhatt *et al* (2010) examined the link between sea-ice decline and tundra vegetation increases, dividing the circumpolar Arctic into oceanic sub-regions *sensu* Treshnikov (1985). They found a nearly ubiquitous greening of the near-coastal tundra, in both the maximum NDVI and the seasonally integrated NDVI, with some decline in the Bering and West Chukchi regions. Interestingly, the tundra vegetation of North America appears to be greening to a greater extent than that of Eurasia (Dye and Tucker 2003, Bunn *et al* 2007, Bhatt *et al* 2010, Goetz *et al* 2011). Bhatt *et al* (2010) found a 9% increase in the maximum NDVI for North American tundra from 1982 to 2008, but only a 2% increase for Eurasian tundra.

While there are extensive studies of Arctic vegetation change over the past several decades, there are still many aspects of these dynamics that are not well understood. For one, we do not really have a good sense for what changes of NDVI actually mean on the ground. Several studies have developed and used relationships between NDVI and aboveground vegetation biomass (phytomass) for Arctic tundra (Shippert *et al* 1995, Boelman *et al* 2003, 2005, Walker *et al* 2003, Raynolds *et al* 2006, Reidel *et al* 2005, Jia *et al* 2006). Some of these studies constructed relationships between NDVI from hand-held spectrometry and aboveground phytomass for specific tundra sites (Boelman *et al* 2003, 2005, Reidel *et al* 2005), while others used a more regional scale approach with field biomass data and satellite-derived NDVI across some different locations (Shippert *et al* 1995, Walker *et al* 2003, Jia *et al* 2006). Raynolds *et al* (2006) used the NDVI–biomass relationships developed for the Alaska North Slope from Walker *et al* (2003), combined with published biomass data for the low and high ends of the NDVI gradient to estimate circumpolar aboveground biomass. This NDVI–biomass relationship has recently been modified with improved remote sensing information and biomass data from two extensive Arctic transects (Walker *et al* 2011, Raynolds *et al* 2012).

A second gap in our understanding of tundra phytomass dynamics is that a comprehensive spatial analysis of vegetation change within the Arctic tundra biome has not been conducted. Both Bhatt *et al* (2010) and Jia *et al* (2006) have made advances in this regard, with Bhatt *et al* (2010) analyzing heterogeneity across Arctic oceanic sub-regions, and Jia *et al* (2006) analyzing NDVI changes across Arctic tundra subzones, but only for Canada. In the present study, we attempt to fill these two gaps. First, we use a newly developed and highly robust relationship between satellite NDVI and field-sampled aboveground tundra biomass, constructed from points along North American and Eurasian Arctic transects, encompassing the full latitudinal extent of Arctic tundra (Raynolds *et al* 2012). Second, we examine the biomass dynamics throughout the circumpolar Arctic tundra with respect to geographic regions, tundra bioclimatic subzones, floristic provinces, and vegetation types.

2. Methods

Aboveground biomass data were collected along two transects that spanned the full climate range of the Arctic (figure 1). The North America Arctic Transect was sampled from 2002 to 2006 and included eight field locations (Walker *et al* 2012). The Eurasian Arctic Transect was sampled from 2007 to 2010 and included five field locations (Walker *et al* 2011). The field locations were chosen to represent the zonal vegetation of each of the five Arctic bioclimate subzones as displayed on the Circumpolar Arctic Vegetation Map (CAVM) (Walker *et al* 2005)—from subzone A in the north where shrubs are absent, mosses and lichens are dominant, and bare ground is common, to subzone E in the south, which is characterized by complete ground cover and abundant erect dwarf shrubs.

At each of the 13 field locations (eight in North America and five in Eurasia), several 20 cm × 50 cm quadrats were

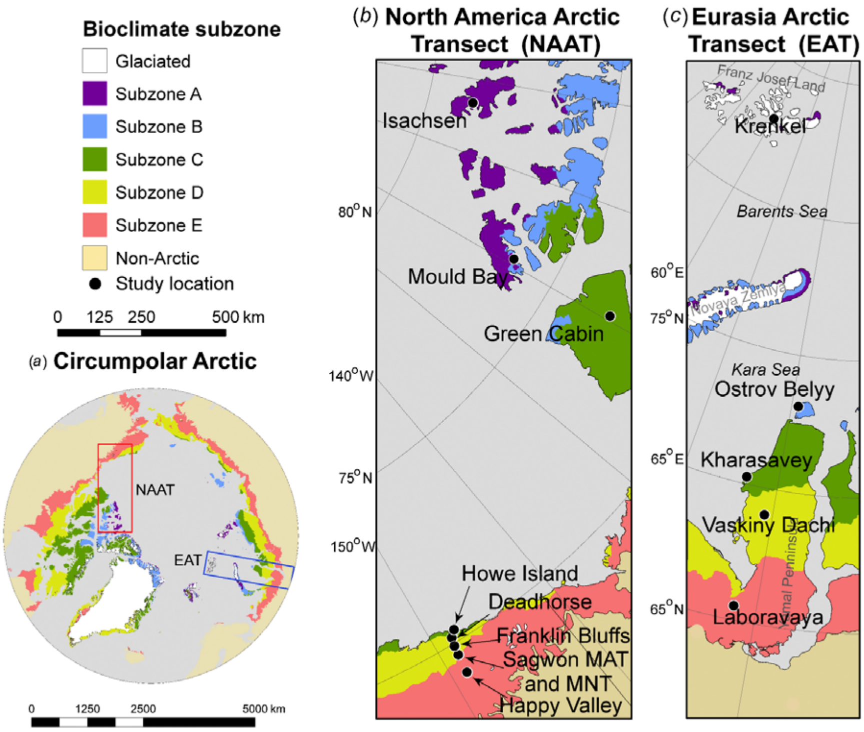

Figure 1. Locations of the North American and Eurasian Arctic Transects, 13 field sampling sites, and the five Arctic subzones (A–E).

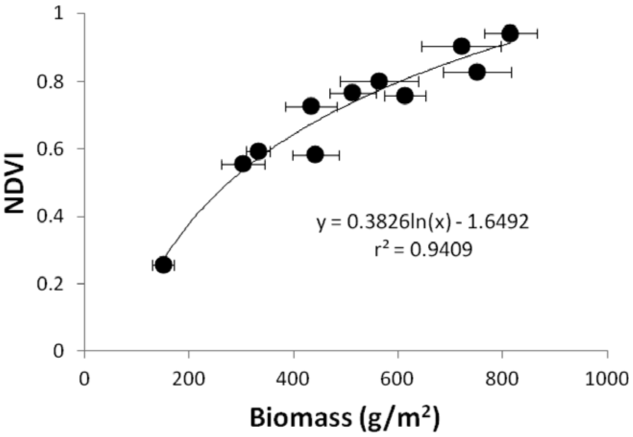

Figure 2. The relationship between aboveground tundra biomass (g m^{-2}) and NDVI for 13 field sites across North America and Eurasia. Data are from Raynolds *et al* (2012). Bars are ± one standard error for the biomass samples within each site.

harvested for aboveground biomass estimates. For the North American Arctic Transect field sites, where vegetation cover was more heterogeneous, five samples were taken from each of several microhabitats identified within a 10 m × 10 m landscape. Landscape level phytomass was then calculated as the area-weighted average of the component vegetation types, based on the 10 m × 10 m map. For the Eurasian Arctic Transect, five samples were harvested for each field site, distributed uniformly within a 50 m × 50 m grid. These five values were averaged for a landscape level estimate. When sampling, the 20 cm × 50 cm sections of tundra were removed from the field intact. Vegetation above the dead moss layer (or above the mineral soil layer, when there was no dead moss present) was removed, dried, and weighed for estimates of aboveground biomass. Raynolds *et al* (2012) describe the biomass sampling procedures in greater detail.

The NDVI for each sampling date and location were extracted from a maximum annual NDVI dataset based on AVHRR 12.5 km pixel data extending from 1982 to 2010. This Global Inventory Modeling and Mapping Studies 3rd generation (GIMMS3g) dataset was developed specifically for polar areas, with a polar projection and revised calibration optimized for the Arctic. The new dataset addresses several issues in the previous GIMMS dataset for polar areas, including a calibration discontinuity at 72°N, and areas of the Arctic that were missing in previous versions of the GIMMS NDVI data. This new GIMMS3g dataset was first used in Bhatt *et al* (2010), and the methodologies describing the dataset development have yet to be published, however the data compare well to those from the Moderate Resolution Imaging Spectroradiometer (MODIS) across their years of overlap (Pinzon *et al* 2011). We used the single AVHRR GIMMS3g pixel that encompassed each of our field locations for developing the relationship between NDVI and aboveground phytomass.

The relationship between aboveground biomass and NDVI was calculated using the logarithmic regression (NDVI $= 0.383\ln(\text{biomass}) - 1.649$, $r^2 = 0.94$, $p < 0.001$, where biomass is in g m^{-2}) (figure 2). This relationship was applied to the GIMMS3g maximum annual NDVI data (1982–2010) to calculate biomass. Trends in biomass were calculated by applying a linear regression to the time series for each pixel. The significance of the trends was calculated, and only pixels with significant trends ($p < 0.05$) are displayed on

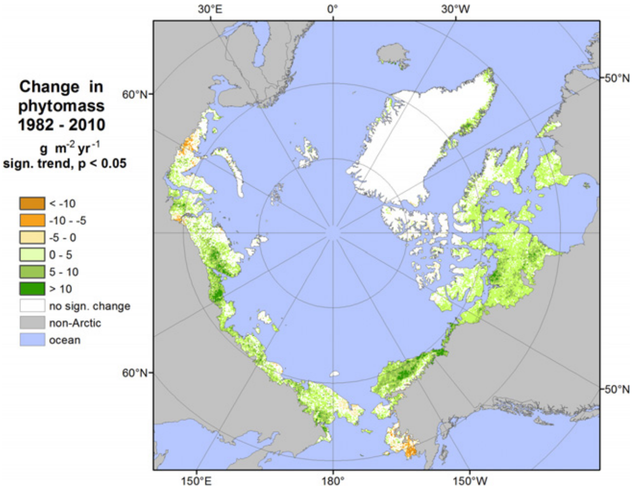

Figure 3. Significant changes ($p < 0.05$) in aboveground tundra phytomass from 1982 to 2010.

the trend map (figure 3). Summaries of aboveground biomass, changes in biomass, and trends in biomass were calculated for different portions of the Arctic, as defined by the CAVM.

3. Results

In all cases, the tundra phytomass (biomass) being considered here is only the aboveground fraction as calculated from the remotely sensed NDVI and the relationship between field-sampled aboveground phytomass and NDVI. The aboveground phytomass of circumpolar Arctic tundra increased from 2.02 Pg (10^{15} g) in 1982 to 2.41 Pg in 2010 for a total increase of 0.40 Pg, a change of ~19.8% over a 29 yr time period (0.7% y^{-1}) (table 1). A relatively ubiquitous increase in tundra phytomass over time is observed circumpolarly, with isolated areas of phytomass decline in Beringian Alaska and the Kanin–Pechora region of western Eurasia (figure 3). With respect to the different tundra bioclimatic subzones, the three southernmost subzones (C, D and E) exhibited extensive increases in aboveground phytomass (20.9%, 25.6% and 20.6% respectively), whereas the two northernmost subzones (A and B) showed substantially smaller increases (2.1% and 6.4% respectively) (table 1); the temporal differences in tundra biomass for subzones C, D and E are greater than the standard errors for site-level biomass samples. In addition, subzones C, D and E comprise 87.5% of the tundra landmass and 95.5% of the initial tundra biomass in 1982; therefore the dynamics of the three southern subzones dominate the circumpolar tundra phytomass change. Whereas subzone D showed the greatest relative phytomass increase of 25.6%, subzone E exhibited the greatest average absolute biomass increase of 96.1 g m^{-2} (3.4 g m^{-2} yr^{-1}).

North America (Alaska and Canada) represented approximately 43.2% of the tundra landmass and 45.4% of the tundra aboveground biomass in 1982 (table 2). Eurasian tundra was approximately 27.1% of the tundra landmass, and 44.0% of the tundra aboveground biomass. However, increases in tundra phytomass in North America over the past 29 yr were generally greater than those in Eurasia. Alaskan tundra phytomass increased 7.8%, and Canadian tundra phytomass increased 36.5%, whereas tundra biomass in Russia increased 15.7% (9.4% in western Siberia and 23.4% in eastern Siberia). The total aboveground tundra phytomass is therefore now slightly less equally distributed between North America and Eurasia (0.91 Pg in North America and 0.89 Pg in Eurasia in 1982 compared to 1.07 Pg and 1.02 Pg respectively in 2010). On average though, aboveground phytomass in 2010 for North America was only 353 g m^{-2}, whereas for Eurasia the average phytomass was 494 g m^{-2}.

Absolute phytomass increases were substantive for several of the larger Arctic regions. Alaskan tundra phytomass increased 40.3 g m^{-2} over the 29 yr period, Canadian tundra phytomass increased 83.6 g m^{-2}, and tundra phytomass in Russia increased 68.6 g m^{-2}. For floristic provinces, the greatest changes were seen in Central Canada and West Hudsonian provinces (45.3% and 41.1% increase, respectively) as well as Anabar–Olenyek and Kharaulakh provinces in eastern Siberia (44.6% and 41.7% increase respectively); the absolute phytomass increases for these provinces were extremely high at 188.3 g m^{-2} and 155.6 g m^{-2} respectively (table 3). Kanin–Pechora (western Siberia) and Beringian Alaska provinces showed small declines in tundra phytomass of 2.7% and 3.5% respectively. With regard to vegetation types, some of the greatest changes were seen in the moist non-acidic tundra (MNT) with a 33.4% increase and an absolute phytomass increase of 129.2 g m^{-2} (table 4). Wet mires of subzone E had the smallest increases of any vegetation-dominated type at 3.9%.

4. Discussion

Based on remotely sensed vegetation indices and strong empirical relationships between tundra biomass and the NDVI, aboveground phytomass of Arctic tundra increased by 0.40 Pg or 19.8% over the past three decades. One key point of clarification for the numbers presented in this paper is that the Arctic tundra is statically defined by the CAVM (Walker *et al* 2005). Changes in tundra boundaries are not taken into consideration; therefore northward movement of the latitudinal treeline, which would change the designation from tundra to taiga (reducing tundra area and therefore its phytomass), is not figured into this analysis. However, northward movement of treeline is uncertain, and any potential reduction in tundra due to expansion of taiga is likely to be minimal over this time period relative to the extensive areas of tundra that are greening (Chapin *et al* 2010, Berner *et al* 2011, Lloyd *et al* 2011). Since Arctic tundra effectively extends to the northernmost landmasses on the planet, there are no similar issues with regard to northward expansion of tundra into areas previously defined as other vegetation types. Our analysis does however include pixels identified as either glacier or lake, which may or may not contain some areas of tundra vegetation; therefore reductions or expansions of glaciers and lakes and their effects on tundra biomass are represented in this analysis. We

Table 1. Arctic tundra biomass dynamics by subzone.

Bioclimate subzone	Area (km^2)	Mean biomass ($g\ m^{-2}$)				Change in mean biomass ($g\ m^{-2}$)	Rate of change ($g\ m^{-2}\ yr^{-1}$)	Total biomass ($Pg - 10^{15}$ g)				
		1982	SD	2010	SD			1982	2010	Change	% change	Rate of change (% yr^{-1})
Greenland ice cap	1795 920	83.8	14.0	84.4	18.0	0.6	0.02	0.15	0.15	0.0011	0.70	0.025
A	200 964	98.3	39.2	100.3	53.4	2.0	0.07	0.02	0.02	0.0004	2.05	0.073
B	530 780	142.7	100.9	151.8	118.4	9.1	0.33	0.08	0.08	0.0048	6.39	0.228
C	1380 760	199.6	116.6	241.2	148.7	41.6	1.49	0.28	0.33	0.0575	20.85	0.745
D	1708 430	319.8	145.6	401.5	195.2	81.7	2.92	0.55	0.69	0.1396	25.56	0.913
E	2027 020	467.5	142.5	563.6	153.1	96.1	3.43	0.95	1.14	0.1948	20.55	0.734
Total								2.02	2.41	0.3982	19.75	0.705

Table 2. Arctic tundra biomass dynamics by country and continent.

		Mean biomass ($g\ m^{-2}$)						Total biomass ($Pg - 10^{15}$ g)				
Country	Area (km^2)	1982	SD	2010	SD	Change in mean biomass ($g\ m^{-2}$)	Rate of change ($g\ m^{-2}\ yr^{-1}$)	1982	2010	Change	% change	Rate of change (% yr^{-1})
United States (Alaska)	538 929	517.1	153.4	557.3	149.3	40.3	1.44	0.28	0.30	0.0217	7.79	0.278
Canada	2768 760	229.3	116.4	312.9	199.5	83.6	2.99	0.63	0.87	0.2315	36.46	1.302
Denmark (Greenland[a])	2273 500	93.6	47.2	96.9	62.4	3.3	0.12	0.21	0.22	0.0074	3.50	0.125
Iceland	7 073	314.3	168.6	436.9	248.0	122.5	4.38	0.00	0.00	0.0009	38.98	1.392
Norway (mostly Svalbard)	65 809	107.2	60.5	127.3	130.2	20.1	0.72	0.01	0.01	0.0013	18.73	0.669
Russia	1999 650	438.0	155.1	506.6	188.6	68.6	2.45	0.88	1.01	0.1371	15.65	0.559
Percentages												
North America (%)	43.2							45.4	48.4	63.3		
Eurasia[b] (%)	27.1							44.0	42.5	34.8		

[a] Includes ice cap.

[b] Not including Greenland.

Table 3. Arctic tundra biomass dynamics by floristic province.

		Mean biomass (g m^{-2})						Total biomass (Pg $-$ 10^{15} g)				
Floristic province	Area (km^2)	1982	SD	2010	SD	Change in mean biomass (g m^{-2})	Rate of change (g m^{-2} yr^{-1})	1982	2010	Change	% change	Rate of change (% yr^{-1})
Glacier	1795 920	83.8	14.0	84.4	18.0	0.6	0.02	0.15	0.15	0.0011	0.70	0.025
North Beringian Islands	5 689	315.1	132.4	411.6	195.7	96.5	3.45	0.00	0.00	0.0005	30.63	1.094
Beringian Alaska	327 663	592.6	135.7	572.2	127.1	−20.4	−0.73	0.19	0.19	−0.0067	−3.45	−0.123
Northern Alaska	232 946	434.3	112.3	574.1	172.7	139.8	4.99	0.10	0.13	0.0326	32.19	1.150
Central Canada	1064 630	246.1	112.0	357.6	206.9	111.5	3.98	0.26	0.38	0.1187	45.30	1.618
West Hudsonian	799 706	248.0	121.0	350.0	204.8	102.0	3.64	0.20	0.28	0.0816	41.13	1.469
Baffin–Labrador	601 202	226.8	91.8	271.3	126.9	44.5	1.59	0.14	0.16	0.0268	19.63	0.701
Ellesmere–North Greenland	407 156	98.1	36.9	99.2	46.0	1.2	0.04	0.04	0.04	0.0005	1.20	0.043
N. Iceland–Jan Mayen	8 764	332.9	134.0	510.3	245.2	177.4	6.34	0.00	0.00	0.0016	53.29	1.903
N. Fennoscandia	3 075	337.7	74.5	478.4	166.1	140.7	5.02	0.00	0.00	0.0004	41.66	1.488
Svalbard–F.J. Land	78 879	97.0	30.4	110.0	92.4	13.0	0.46	0.01	0.01	0.0010	13.36	0.477
Kanin–Pechora	175 440	651.5	112.7	633.7	120.0	−17.7	−0.63	0.11	0.11	−0.0031	−2.72	−0.097
Polar Ural–Novaya Zemlya	134 079	304.0	216.8	309.6	224.2	5.6	0.20	0.04	0.04	0.0007	1.83	0.065
Yamal–Gydan	317 053	483.4	101.9	505.9	125.2	22.5	0.80	0.15	0.16	0.0071	4.66	0.166
Taimyr	497 260	385.9	125.3	470.8	196.3	84.8	3.03	0.19	0.23	0.0422	21.97	0.785
Anabar–Olenyek	146 533	421.8	77.3	610.1	156.6	188.3	6.72	0.06	0.09	0.0276	44.64	1.594
Kharaulakh	16 606	373.1	63.5	528.7	111.2	155.6	5.56	0.01	0.01	0.0026	41.70	1.489
Yana–Kolyma	260 162	449.9	106.0	531.5	153.5	81.6	2.92	0.12	0.14	0.0212	18.14	0.648
W. Chukotka	195 429	423.1	142.4	506.1	163.1	83.0	2.96	0.08	0.10	0.0162	19.61	0.700
E. Chukotka	126 698	375.2	111.0	432.2	134.3	57.0	2.04	0.05	0.05	0.0072	15.19	0.543
S. Chukotka	107 632	518.7	108.5	633.1	126.2	114.4	4.08	0.06	0.07	0.0123	22.05	0.787
Wrangel Island	8 457	83.0	0.0	83.0	0.0	0.0	0.00	0.00	0.00	0.0000	0.00	0.000
Northwest Greenland	39 209	135.9	67.4	160.1	125.7	24.1	0.86	0.01	0.01	0.0009	17.75	0.634
Southwest Greenland	39 978	244.5	89.8	276.3	137.8	31.8	1.14	0.01	0.01	0.0013	13.01	0.465
Centralwest Greenland	48 588	255.1	108.4	316.5	163.3	61.4	2.19	0.01	0.02	0.0030	24.07	0.860
South Greenland	24 448	230.8	122.6	241.7	127.3	10.8	0.39	0.01	0.01	0.0003	4.69	0.167
Southeast Greenland	52 432	84.7	10.9	84.9	11.3	0.2	0.01	0.00	0.00	0.0000	0.20	0.007
Centraleast Greenland	94 101	108.5	63.6	117.7	91.6	9.2	0.33	0.01	0.01	0.0009	8.44	0.301
Northeast Greenland	47 973	104.0	50.0	113.0	73.8	9.0	0.32	0.00	0.01	0.0004	8.63	0.308

Table 4. Arctic tundra biomass dynamics by vegetation type. (Note: B1: polar desert—cryptogam, cushion-forb barren; G1: herb AB—rush/grass, cryptogam tundra; B2: shield—cryptogam barren (bedrock); P1: dry shrub BC—prostrate dwarf-shrub, herb tundra; G2: gram BC—graminoid, prostrate dwarf-shrub, forb tundra; P2: Cassiope—prostrate/hemiprostrate dwarf-shrub tundra; G3: MNT—non-tussock sedge, dwarf-shrub, moss tundra; G4: TT—tussock sedge, dwarf-shrub, moss tundra; S1: dwarf shrub—erect dwarf-shrub tundra; S2: low shrub—low-shrub tundra; W1: mire BC—sedge/grass, moss wetland; W2: mire D—sedge, moss dwarf-shrub wetland; W3: mire E—sedge, moss, low-shrub wetland; B3: acid mtns.—non-carbonate mountain complex; B4: carb. mtns.—carbonate mountain complex.)

		Mean biomass (g m^{-2})						Total biomass (Pg – 10^{15} g)				
Vegetation type	Area (km^2)	1982	SD	2010	SD	Change in mean biomass (g m^{-2})	Rate of change (g m^{-2} yr^{-1})	1982	2010	Change	% change	Rate of change (% yr^{-1})
B1	239 251	111.6	48.3	123.2	76.4	11.6	0.41	0.03	0.03	0.0028	10.39	0.371
G1	144 381	171.0	106.1	187.1	134.7	16.0	0.57	0.02	0.03	0.0023	9.38	0.335
B2	406 234	200.2	68.6	267.0	129.0	66.9	2.39	0.08	0.11	0.0272	33.40	1.193
P1	418 688	205.4	103.6	252.3	148.8	47.0	1.68	0.09	0.11	0.0197	22.88	0.817
G2	455 898	281.7	127.6	347.6	158.4	65.9	2.35	0.13	0.16	0.0300	23.40	0.836
P2	150 070	185.5	83.8	237.8	134.6	52.2	1.87	0.03	0.04	0.0078	28.15	1.005
G3	612 119	377.2	121.5	506.4	176.4	129.2	4.61	0.23	0.31	0.0791	34.25	1.223
G4	364 411	500.6	105.7	580.9	126.1	80.3	2.87	0.18	0.21	0.0293	16.04	0.573
S1	769 723	399.1	125.7	500.7	157.1	101.6	3.63	0.31	0.39	0.0782	25.45	0.909
S2	673 161	521.2	136.4	610.3	141.6	89.1	3.18	0.35	0.41	0.0600	17.09	0.610
W1	108 247	280.4	146.7	337.9	173.7	57.5	2.05	0.03	0.04	0.0062	20.51	0.733
W2	144 688	402.9	121.7	465.5	136.2	62.6	2.23	0.06	0.07	0.0091	15.53	0.555
W3	176 824	536.3	148.0	557.1	157.9	20.8	0.74	0.09	0.10	0.0037	3.88	0.138
B3	578 906	241.6	157.7	287.4	204.3	45.8	1.64	0.14	0.17	0.0265	18.95	0.677
B4	135 463	247.9	184.2	288.4	231.0	40.5	1.45	0.03	0.04	0.0055	16.34	0.584
Nunatak	95 331	87.9	19.0	90.0	42.5	2.1	0.08	0.01	0.01	0.0002	2.43	0.087
Glacier	2086 060	84.8	16.8	86.2	28.2	1.4	0.05	0.18	0.18	0.0029	1.66	0.059
Lake	71 498	310.1	129.7	418.1	199.9	108.0	3.86	0.02	0.03	0.0077	34.81	1.243
Lagoon	11 378	349.0	159.7	350.5	172.7	1.5	0.05	0.00	0.00	0.0000	0.43	0.015

feel confident in our estimates of circumpolar aboveground tundra biomass; other recent estimates, generally using less comprehensive datasets of remotely sensed NDVI, maps of tundra vegetation types, and field-sampled aboveground biomass, have all yielded values in the range of 2.4–2.5 Pg (Walker *et al* 2003, Raynolds *et al* 2006, Walker *et al* 2008), and our estimate is 2.41 Pg. An additional clarification to make, though, is that while the information used to develop the extrapolations in this study comes from the full range of bioclimate subzones in the Arctic, the vegetation sampled was on mesic zonal landscapes. The relationship may not apply equally well for wet tundra, dry tundra or mountainous tundra landscapes, which are extensive. There also may be some uncertainties given that only the leaf fraction of increasing aboveground biomass contributes to the NDVI signal, whereas the NDVI–biomass relationship includes both foliar and woody phytomass components.

The 0.40 Pg of aboveground biomass change could represent a substantive sink of carbon by the Arctic tundra over the past three decades. If we make some basic assumptions that there is an equivalent amount of below-ground biomass increase over this time period and that 50% of vegetation biomass is carbon, the total difference in carbon in live vegetation is 0.40 Pg C. Note that this carbon difference is not equivalent to the carbon sequestered over the 29 yr time period; the amount sequestered would also be a function of the plant tissue turnover rates and the ultimate fate of this dead tissue. If we assume a linear increase in vegetation C over the 29 yr time period, then a very high-end estimate of sequestered carbon would be 5.8 Pg C or 0.20 Pg C yr^{-1}; in this estimate, all of this additional plant C (on average 0.20 Pg) turns over every year and enters a long-term storage pool.

This likely overestimated annual value represents $<$10% of the annual terrestrial carbon sink; the land sink for carbon is rather variable interannually, but has been estimated at 2.3 ± 0.4 Pg C yr^{-1} for 2008 (Le Quéré *et al* 2009) and 2.3 ± 0.4 Pg C yr^{-1} for 2000 (Pan *et al* 2011). The northern hemisphere terrestrial carbon sink was estimated to be ∼1.7 Pg C yr^{-1} from 2000 to 2004 (Ciais *et al* 2010). Our estimated tundra carbon sink is however a substantive part of the Arctic land sink, which includes boreal forest and other vegetation types in permafrost regions, and was estimated to be 0.3–0.6 Pg C yr^{-1} during the late decades of the 20th century (McGuire *et al* 2009). From a broader perspective however, based on these remotely sensed observations over the past three decades, the Arctic tundra greening will likely not lead to any important reduction of atmospheric carbon dioxide, although it may offset some of the losses of soil carbon to the atmosphere that are occurring in the Arctic and expected with continued warming (McGuire *et al* 2010, Euskirchen *et al* 2009).

There was a high degree of spatial variability of change, particularly across subzones. Most of the biomass changes were seen in the three southernmost subzones (C—20.9%, D—25.6% and E—20.6%), with very little change in subzones A (2.1%) and B (6.4%) (figure 4). The greatest relative changes occurred in subzone D, which is consistent with a remote sensing analysis of Alaska from 1981–2001 (Jia *et al* 2003), whereas a remote sensing analysis of Canadian tundra showed subzone C peak NDVI increasing by 0.79% $\text{yr}^{-1}$and subzone D peak NDVI increasing by 0.67% yr^{-1} from 1982 to 2003 (Jia *et al* 2009). Phytomass increases in North America were greater than in Eurasia. Alaska and Canada aboveground biomass increased by 7.8% and 36.5% respectively, compared to 15.7% for Russia (9.4% and 23.4% for western and eastern Siberia respectively). These results are consistent with substantially greater summer warming for the North American Arctic tundra compared to the Eurasian Arctic tundra, and also for eastern Siberia compared to western Siberia (Bhatt *et al* 2010). Potential aboveground phytomass increases in response to warming could also be constrained by grazing of managed reindeer herds in regions throughout western Siberia (Forbes *et al* 2009, Yu *et al* 2009, 2011). The large difference in percentage increase between Alaska and Canada is also due to spatial heterogeneity of change; whereas Canada exhibited relatively consistent greening, strong increases in aboveground vegetation on the North Slope of Alaska are countered by declines in green vegetation in the Bering Region of Alaska. The vegetation type with the greatest increase in aboveground biomass (34.3%) was the moist non-acidic tundra (MNT—non-tussock sedge, dwarf-shrub, moss tundra), which is widespread in subzones C and D of northern Alaska and Canada.

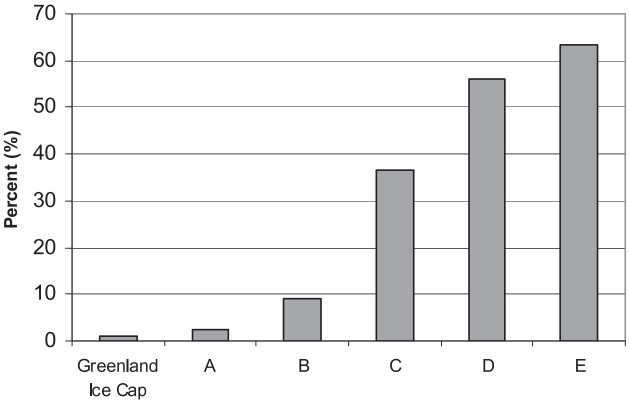

Figure 4. Per cent of subzone pixels with significant ($p < 0.05$) positive trend.

While this NDVI-based analysis suggests some increases in aboveground tundra biomass of $>$100 g m^{-2} and $>$40% over the past three decades, it is still extremely difficult to compare these results to changes that have been observed in the field, largely due to the paucity of studies that have repeated field biomass measurements over time (Fung 1997). Experimental studies conducted between 1981 and 2000 at the Toolik Lake Long Term Ecological Research site in subzone E of northern Alaska included biomass monitoring through field-harvests over time; while plant community composition in un-manipulated control plots changed throughout this time period, there was no indication of any directional change in total aboveground phytomass (Chapin *et al* 1995, Shaver *et al* 2001). Study sites at

Alexandra Fiord, Ellesmere Island, Nunavut, Canada have provided the only plot-based observational data demonstrating a recent increase in aboveground tundra biomass over time. Hudson and Henry (2009) found an increase of 53.4 g m^{-2} (160%) over the 27 yr period from 1981 to 2008 in a coastal lowland heath community, and Hill and Henry (2011) found a 158% increase in aboveground tundra biomass for wet sedge communities from 1981 to 2005.

Greenhouse warming studies conducted in Arctic tundra over periods of up to 13 yr essentially have not shown changes in aboveground biomass (van Wijk *et al* 2004), however warming studies using open-top chambers (OTCs) as part of the International Tundra Experiment (ITEX) have indicated common increases in vegetation height (Walker *et al* 2006), which could correspond to biomass increases. The widespread expansion of tall shrubs throughout the circumpolar Low Arctic into areas previously occupied by much shorter-stature vegetation (Tape *et al* 2006, Lantz *et al* 2009, 2010, Blok *et al* 2010, 2011, Naito and Cairns 2011) most likely leads to large increases in aboveground biomass (Bret-Harte *et al* 2001), although there have not yet been any comprehensive assessments of the potential biomass implications of this phenomenon.

Recent simulation modeling of Arctic tundra response to climate warming has projected relatively comparable biomass changes to what we are estimating here. Using a production efficiency model (PEM), based on satellite remote sensing data similar to those used in this study, Zhang *et al* (2008) estimated increases in tundra net primary productivity (NPP) of 0.5% yr^{-1} compared to our 0.7% yr^{-1} change in biomass. Using the same production efficiency model as Zhang *et al* (2008), Kimball *et al* (2007) estimated tundra NPP for Alaska and western Canada to have increased 0.8% yr^{-1} from 1982 to 2000. Kimball *et al* (2007) also found for the same region and time period that the Terrestrial Ecosystem Model (TEM) and BIOME-BGC model both estimated NPP increases of 0.5% yr^{-1}. Also using the TEM model, Euskirchen *et al* (2009) projected NPP increases in sedge tundra ranging from 0.3 to 0.8 g C m^{-2} yr^{-1}, and NPP increases in shrub tundra ranging from 0.9 to 2.7 g C m^{-2} yr^{-1}, values that are comparable to our estimates of biomass increases (assuming biomass is typically 45–50% C). The ArcVeg model (Epstein *et al* 2000, Yu *et al* 2009) projects tundra biomass increases on the order of 1–10 g m^{-2} yr^{-1}, projections that overlap with, yet extend to greater than, the range of estimates from this study.

Regardless of the carbon implications, an average 19.8% Arctic-wide increase in biomass throughout the past 29 yr has major implications for nearly all aspects of tundra ecosystems including hydrology, active layer depths, permafrost regimes, wildlife and human use of Arctic landscapes, especially if the trend continues as projected by most models. We still however do not know where all of this increase in biomass is occurring, both within landscapes and within the different layers of the plant canopy. Clearly, more extensive studies of NDVI–biomass relationships are needed across a greater range of tundra habitats and across additional Arctic climate gradients, with varying substrates and precipitation regimes. Long-term studies of tundra biomass across the full range of Arctic climates are absolutely needed. In the meantime, studies with time series of high spatial resolution remote sensors, such as Landsat, and very high resolution sensors, such as Quickbird and GeoEye, will help us answer the question of where the changes are occurring, and detailed studies of how vegetation canopies are changing over time will provide much-needed information.

In summary, we used a strong regression model between NDVI and aboveground tundra phytomass, developed from extensive field-harvested measurements of vegetation biomass, to estimate the biomass dynamics of the circumpolar Arctic tundra over the period of the satellite AVHRR record (1982–2010). We found that tundra subzones C–E dominate the increases in biomass, ranging from 20 to 26%, although there was a high degree of heterogeneity across regions, floristic provinces, and vegetation types. The estimated change in carbon in live vegetation of 0.40 Pg C over the past three decades is substantive, albeit quite small relative to anthropogenic C emissions. However, a 19.8% average increase in aboveground biomass has major implications for the structure and functioning of Arctic tundra ecosystems. While spatially extensive on-the-ground measurements of tundra biomass were conducted in the development of this analysis, validation is still impossible without more repeated, long-term monitoring of Arctic tundra biomass in the field.

Acknowledgments

Funding for this work was provided by the US NSF grants ARC-0531166, ARC-0902152 and NASA grants NNG6GE00A, NNX09AK56G. Jerrica Frazier contributed to the literature review, production of tables and manuscript formatting.

References

Berner L T, Beck P S A, Bunn A G, Lloyd A H and Goetz S J 2011 High latitude tree growth and satellite vegetation indices: correlations and trends in Russia and Canada (1982–2008) *J. Geophys. Res.* **116** G01015

Bhatt U S *et al* 2010 Circumpolar Arctic tundra vegetation change is linked to sea ice decline *Earth Interact.* **14** 8

Blok D, Heijmans M M P D, Schaepman-Strub G, Kononov A V, Maximov T C and Berendse F 2010 Shrub expansion may reduce summer permafrost thaw in Siberian tundra *Glob. Change Biol.* **16** 1296–305

Blok D, Sass-Klaassen U, Schaepman-Strub G, Heijmans M M P D, Sauren P and Berendse F 2011 What are the main climate drivers for shrub growth in Northeastern Siberian tundra? *Biogeosciences* **8** 1169–79

Boelman N T, Steiglitz M, Griffin K L and Shaver G R 2005 Inter-annual variability of NDVI in response to long-term warming and fertilization in wet sedge and tussock tundra *Oecologia* **143** 588–97

Boelman N T, Stieglitz M, Rueth H M, Sommerkorn M, Griffin K L, Shaver G R and Gamon J A 2003 Response of NDVI, biomass, and ecosystem gas exchange to long-term warming and fertilization in wet sedge tundra *Oecologia* **135** 414–21

Bret-Harte M S, Shaver G R, Zoerner J P, Johnstone J F, Wagner J L, Chavez A S, Gunkelman R F, Lippert S C and

Laundre J A 2001 Developmental plasticity allows *Betula nana* to dominate tundra subjected to an altered environment *Ecology* **82** 18–32

Bunn A G and Goetz S J 2006 Trends in satellite-observed circumpolar photosynthetic activity from 1982 to 2003: the influence of seasonality, cover type, and vegetation density *Earth Interact.* **10** 12

Bunn A G, Goetz S J and Fiske G J 2005 Observed and predicted responses of plant growth to climate across Canada *Geophys. Res. Lett.* **32** L16710

Bunn A G, Goetz S J, Kimball J S and Zhang K 2007 Northern high-latitude ecosystems respond to climate change *EOS* **88** 333–40

Chapin F S, Shaver G R, Giblin A E, Nadelhoffer K J and Laundre J A 1995 Responses of Arctic tundra to experimental and observed changes in climate *Ecology* **76** 694–711

Chapin F S *et al* 2010 Resilience of Alaska's boreal forest to climate change *Can. J. For. Res.* **40** 1360–70

Ciais P *et al* 2010 Can we reconcile atmospheric estimates of the Northern terrestrial carbon sink with land-based accounting? *Curr. Opin. Environ. Sustain.* **2** 225–30

Dye D G and Tucker C J 2003 Seasonality and trends of snow-cover, vegetation index, and temperature in northern Eurasia *Geophys. Res. Lett.* **30** 1405

Epstein H E, Walker M D, Chapin F S and Starfield A M 2000 A transient nutrient-based model of Arctic plant community response to climatic warming *Ecol. Appl.* **10** 824–41

Euskirchen E S, McGuire A D, Chapin F S, Yi S and Thompson C C 2009 Changes in vegetation in northern Alaska under scenarios of climate change, 2003–2010: implications for climate feedbacks *Ecol. Appl.* **19** 1022–43

Forbes B C, Fauria M M and Zetterberg P 2009 Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows *Glob. Change Biol.* **16** 1542–54

Forbes B C, Stammler F, Kumpula T, Meschtyb N, Pajunen A and Kaarlejarvi E 2009 High resilience in the Yamal-Nenets social-ecological system, West Siberian Arctic, Russia *Proc. Natl Acad. Sci. USA* **106** 22041–8

Fung I 1997 Climate change—a greener north *Nature* **386** 659–60

Goetz S J, Bunn A G, Fiske G J and Houghton R A 2005 Satellite-observed photosynthetic trends across boreal North America associated with climate and fire disturbance *Proc. Natl Acad. Sci. USA* **102** 13521–5

Goetz S J *et al* 2011 Vegetation productivity and disturbance changes across Arctic northern Eurasia: satellite observations and simulation modeling *Eurasian Arctic Land Cover and Land Use in a Changing Climate* ed G Gutman and A Reissell (New York: Springer)

Hill G B and Henry G H R 2011 Responses of High Arctic wet sedge tundra to climate warming since 1980 *Glob. Change Biol.* **17** 276–87

Hudson J M G and Henry G H R 2009 Increases plant biomass in a High Arctic heath community from 1981 to 2008 *Ecology* **90** 2657–63

Jia G S, Epstein H E and Walker D A 2003 Greening of Arctic Alaska, 1981–2001 *Geophys. Res. Lett.* **30** 2067

Jia G S, Epstein H E and Walker D A 2006 Spatial heterogeneity of tundra vegetation response to recent temperature changes *Glob. Change Biol.* **12** 42–55

Jia G S, Epstein H E and Walker D A 2009 Vegetation greening in the Canadian Arctic related to decadal warming *J. Environ. Monit.* **11** 2231–8

Kimball J S *et al* 2007 Recent climate-driven increases in vegetation productivity for the western Arctic: evidence of an acceleration of the northern terrestrial carbon cycle *Earth Interact.* **11** 4

Lantz T C, Gergel S E and Kokelj S V 2010 Spatial heterogeneity in the shrub tundra ecotone in the Mackenzie Delta region, Northwest Territories: implications for Arctic environmental change *Ecosystems* **13** 194–204

Lantz T C, Kokelj S V, Gergel S E and Henry G H R 2009 Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps *Glob. Change Biol.* **15** 1664–75

Le Quéré C *et al* 2009 Trends in the sources and sinks of carbon dioxide *Nature Geosci.* **2** 831–6

Lloyd A H, Bunn A G and Berner L 2011 A latitudinal gradient in tree growth response to climate warming in the Siberian taiga *Glob. Change Biol.* **17** 1935–45

McGuire A D, Anderson L G, Christensen T R, Dallimore S, Guo L D, Hayes D J, Heimann M, Lorenson T D, Macdonald R W and Roulet N 2009 Sensitivity of the carbon cycle in the Arctic to climate change *Ecol. Monogr.* **79** 523–55

McGuire A D *et al* 2010 An analysis of the carbon balance of the Arctic Basin from 1997 to 2006 *Tellus* B **62** 455–74

Myneni R B, Keeling C D, Tucker C J, Asrar G and Nemani R R 1997 Increased plant growth in the northern high latitudes from 1981 to 1991 *Nature* **386** 698–702

Naito A T and Cairns D M 2011 Patterns and processes of global shrub expansion *Prog. Phys. Geogr.* **35** 423–42

Neigh C S R, Tucker C J and Townshend J R G 2008 North American vegetation dynamics observed with multi-resolution satellite data *Remote Sens. Environ.* **112** 1749–72

Olthof I, Pouliot D, Latifovic R and Chen W J 2008 Recent (1986–2006) vegetation-specific NDVI trends in northern Canada from satellite data *Arctic* **61** 381–94

Pan Y *et al* 2011 A large and persistent carbon sink in the world's forests *Science* **333** 988–93

Pinzon J E *et al* 2011 unpublished data

Pouliot D, Latifovic R and Olthof I 2009 Trends in vegetation NDVI from 1 km AVHRR data over Canada for the period 1985–2006 *Int. J. Remote Sens.* **30** 149–68

Raynolds M K, Walker D A, Epstein H E, Pinzon J E and Tucker C J 2012 A new estimate of tundra-biome phytomass from trans-Arctic field data and AVHRR NDVI *Remote Sens. Lett.* **3** 403–11

Raynolds M K, Walker D A and Maier H A 2006 NDVI patterns and phytomass distribution in the circumpolar Arctic *Remote Sens. Environ.* **102** 271–81

Reidel S M, Epstein H E and Walker D A 2005 Biotic controls over spectral reflectance of Arctic tundra vegetation *Int. J. Remote Sens.* **26** 2391–405

Shaver G R, Bret-Harte S M, Jones M H, Johnstone J, Gough L, Laundre J and Chapin F S 2001 Species composition interacts with fertilizer to control long-term change in tundra productivity *Ecology* **82** 3163–81

Shippert M M, Walker D A, Auerbach N A and Lewis B E 1995 Biomass and leaf-area index maps derived from SPOT images for Toolik Lake and Imnavait Creek areas, Alaska *Polar Rec.* **31** 147–54

Slayback D A, Pinzon J E, Los S O and Tucker C J 2003 Northern hemisphere photosynthetic trends 1982–99 *Glob. Change Biol.* **9** 1–15

Sturm M, Racine C and Tape K 2001 Climate change—increasing shrub abundance in the Arctic *Nature* **411** 546–7

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

Treshnikov A F 1985 *Atlas of the Arctic* (Moscow: Main Administration of Geodesy and Cartography) p 204 (in Russian)

Tucker W B, Weatherly J W, Eppler D T, Farmer L D and Bently D L 2001 Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s *Geophys. Res. Lett.* **28** 2851–4

van Wijk M T *et al* 2004 Long-term ecosystem level experiments at Toolik Lake, Alaska, and at Abisko, Northern Sweden: generalizations and differences in ecosystem and plant type responses to global change *Glob. Change Biol.* **10** 105–23

Verbyla D 2008 The greening and browning of Alaska based on 1982–2003 satellite data *Glob. Ecol. Biogeogr.* **17** 547–55

Walker D A, Kuss P, Epstein H E, Kade A, Vonlanthen C M, Raynolds M K and Daniels F J A 2011 Vegetation of zonal patterned-ground ecosystems along the North American Arctic Transect *Appl. Veg. Sci.* **14** 440–63

Walker D A *et al* 2003 Phytomass, LAI, and NDVI in northern Alaska: relationships to summer warmth, soil pH, plant functional types, and extrapolation to the circumpolar Arctic *J. Geophys. Res.—Atmos.* **108** 8169

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

Walker D A *et al* 2008 Arctic patterned-ground ecosystems: a synthesis of field studies and models along a North American Arctic transect *J. Geophys. Res.—Biogeogr.* **113** G03S01

Walker D A *et al* 2012 Environment, vegetation and greenness (NDVI) along the North America and Eurasia Arctic transects *Environ. Res. Lett.* **7** 015504

Walker M D *et al* 2006 Plant community responses to experimental warming across the tundra biome *Proc. Natl Acad. Sci. USA* **103** 1342–6

Yu Q, Epstein H and Walker D 2009 Simulating the effects of soil organic nitrogen and grazing on Arctic tundra vegetation dynamics on the Yamal Peninsula, Russia *Environ. Res. Lett.* **4** 045027

Yu Q, Epstein H E, Walker D A, Frost G V and Forbes B C 2011 Modeling dynamics of tundra plant communities on the Yamal Peninsula, Russia, in response to climate change and grazing pressure *Environ. Res. Lett.* **6** 045505

Zhang K, Kimball J S, Hogg E H, Zhao M S, Oechel W C, Cassano J J and Running S W 2008 Satellite-based model detection of recent climate-driven changes in northern high-latitude vegetation productivity *J. Geophys. Res.—Biogeogr.* **113** G03033

Zhou L M, Tucker C J, Kaufmann R K, Slayback D, Shabanov N V and Myneni R B 2001 Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981–1999 *J. Geophys. Res.—Atmos.* **106** 20069–83