SUPPLEMENTARY INFORMATION

Changes in Growing Season Duration and Productivity of Northern Vegetation Inferred from Long-term Remote Sensing Data

Taejin Park, Sangram Ganguly, Hans Tømmervik, Eugénie S. Euskirchen, Kjell-Arild Høgda, Stein Rune Karlsen, Victor Brovkin, Ramakrishna R. Nemani and Ranga B. Myneni

This document provides Supplementary information not provided in the main text of the article "Changes in Growing Season Duration and Productivity of Northern Vegetation Inferred from Long-term Remote Sensing Data". It contains (*i*) Supplementary Data and Methods, which provides an extended description of the data and methods used; (*ii*) Supplementary References; (*iii*) Supplementary Tables, and (*iv*) Supplementary Figures.

Supplementary Data and Methods

1. Study region and vegetation cover map

This study focuses on northern vegetated region (>45°N), which includes Boreal and Arctic ecosystems. To define both regions, we compiled the latest version of the MODIS International Geosphere-Biosphere Programme (IGBP) land cover map (Friedl *et al* 2010, WWW-MCD12Q1) and the Circumpolar Arctic Vegetation Map (CAVM) (Walker *et al* 2005, WWW-CAVM). MODIS IGBP identified 17 land cover classes including 11 natural vegetation classes, three developed and mosaicked land classes, and three non-vegetated land classes. The CAVM map was used to identify the tundra vegetation and associated characteristics of the circumpolar region as a supplement to the IGBP classes. Arctic (8.16 million km^2) is defined as the vegetated area north of 65°N, excluding crops and forests, but including the tundra south of 65°N. Boreal region (17.86 million km^2) is defined as the vegetated area between 45°N and 65°N, excluding crops, tundra, broadleaf forests, but including needleleaf forests north of 65°N. Grasslands south of the mixed forests are excluded as these are not conventionally considered as Boreal vegetation. Combined vegetation map of the Arctic and Boreal regions with 14 different vegetation classes (additionally aggregated into 4 vegetation groups) are described in Supplementary Figure S1.

2. Data

2.1. GIMMS NDVI3g (WWW-NDVI3g): In this study, we mainly used the Global Inventory Modeling and Mapping Studies (GIMMS) NDVI dataset obtained from the Advanced Very High Resolution Radiometer (AVHRR) sensors onboard the NOAA satellite series (7 to 19). The latest version of GIMMS NDVI data (a.k.a. NDVI3g) spans 1981–2014 with a native resolution of 1/12° at bimonthly temporal resolution (Pinzon and Tucker 2014). Recently resolved high latitude discontinuity issue and improved snowmelt and cloud detection have granted a better observation for northern high latitude vegetation dynamic research. Based on given growing season and productivity definition, obtained metrics were used to investigate long-term northern vegetation phenology and productivity changes.

2.2. MODIS Phenology (MCD12Q2) (WWW-MCD12Q2): The MODIS Land Cover Dynamics (MCD12Q2) product (a.k.a., MODIS Global Vegetation Phenology product) provides estimates of the timing of vegetation phenology based on Nadir-BRDF Adjusted Reflectance (NBAR) enhanced vegetation index (EVI). Four different phenological phases provided are the onset of greenness increase (same as SOS in this study), onset of greenness maximum, onset of greenness decrease and onset of greenness minimum (same as EOS in this study). Cumulative EVI area provided in MCD12Q2 is conceptually overlapped with GSSNDVI of NDVI3g. Native resolution is 500m and temporal coverage spans from 2001 to 2012 (12 years). For comparison purpose, annual growing season and productivity metrics are spatially harmonized with GIMMS NDVI3g data (1/12°). We have to note that MODIS phenology uses different quality control, seasonal trajectory fitting (logistic model) and phenology detection (curvature based approach). Details can be found in Zhang *et al* (2003) and Ganguly *et al* (2010).

2.3. MODIS NDVI (MOD13C1) (WWW-MOD13C1): MODIS Collection 5 standard NDVI product which spans from 2000 to 2014 with 16-day temporal composite at 0.05 degree is used in this study. For comparison purpose, it is harmonized with GIMMS NDVI3g spatial resolution

(1/12°) via bicubic method. Growing season (i.e., SOS, EOS, and LOS) and productivity (i.e., GSSNDVI) are obtained by exactly same definition and method used in NDVI3g.

2.4. MODIS NBAR NDVI (MCD43C4) (WWW-MCD43C4): Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (NBAR), which spans same temporal coverage (2000-2014) with MOD13C1 is used in this study. Spatial resolution (0.05°) is adjusted into NDVI3g (1/12°) and then growing season (i.e., SOS, EOS, and LOS) and productivity (i.e., GSSNDVI) metrics are obtained via identical definition and method used in GIMMS NDVI3g.

2.5. FLUXNET GPP (WWW-FLUXNET): We used gap-filled daily tower GPP data at 39 flux tower sites (140 site-years observation) distributed across northern hemisphere to validate remotely sensed growing season and a proxy of GPP based on GIMMS NDVI3g. Selection of valid site and data is performed by following two criteria: (i) more than 95 % of the days had daily GPP data, and (ii) the mean daily quality flag was more than 0.75 (Richardson *et al* 2010). The daily data was then aggregated to monthly and later to yearly time step. Details of the individual towers are provided in Table S2. The data used in this study is obtained from FLUXNET "Fair-Use" data archive and the spatial distribution of the flux towers is shown in Figure S1.

2.6. MODIS GPP (MOD17A3) (WWW-MOD17A3): Terra MODIS Net Primary Production (MOD17A3) provides 15 years (2000-2014) long annual 1km GPP estimate based on light-use efficiency model. Theoretical and practical details underpinning this product can be found in Running *et al* (1999). For evaluation purpose, we coarsely aggregated 1km GPP product into NDVI3g grid format (1/12°).

2.7. Model Tree Ensemble GPP (MTE-GPP) (WWW-MTE): Statistical model based MTE-GPP is used for evaluating GSSNDVI of GIMMS NDVI3g. This model incorporates flux tower local observations, satellite retrievals of fraction of absorbed photosynthetically active radiation (fAPAR), and climate fields to upscale ground level GPP. A machine learning system where the target variable (i.e., GPP) is predicted by a set of multiple linear regressions from explanatory variable is implemented in this model. Detail information on MTE-GPP can be found in Jung *et* *al* (2011). This product provides global annual GPP from 1982 to 2011 at 0.5 degree with monthly time step. Annually aggregated and specially resampled MTE-GPP is compared with NDVI3g GSSNDVI for evaluation purpose.

2.8. MODIS Snow Cover (MOD10C2) (WWW-MOD10C2)**:** MODIS Snow Cover 8-Day product (MOD10C2) is used to obtain snow cover information to additionally minimize snow-contamination during processing of GIMMS NDVI3g, MOD13C1, and MCD43C4 growing season and productivity determination. We first combined two consecutive 8-day composite to 16-day composite with conservative way (Minimum value composite: take lower snow cover percentage as representative). This approach can be justified, as all vegetation indices are composited by maximum value compositing approach. Then we defined a pixel as snow-contaminant pixel when snow occupies more than 20%. Identified 15-years (from 2000 to 2014) snow cover information is incorporated to determine background NDVI.

2.9. MEaSUREs Freeze-Thaw (FT) (WWW-FT)**:** The FT-ESDR is a NASA MEaSUREs (Making Earth System Data Records for Use in Research Environments) funded effort to provide a consistent long-term global data record of land surface freeze/thaw (FT) state dynamics for all vegetated regions where low temperatures are a major constraint to ecosystem processes (Kim *et al* 2012). The FT-ESDR data set provides four FT status (frozen, thawed, transitional and inverse transitional) and five filled values for the whole global with daily temporal frequency. In our analysis, we defined those days classified as frozen, transitional and inverse transitional as non-photosynthetic days. To the contrary, the other days are defined as photosynthetic days. The NDVI based growing season was adjusted by the photosynthetic/non-photosynthetic information derived from FT data set. The rule is that a day must be in the NDVI based growing season and identified as photosynthetically active days by FT data set.

2.10. MERRA Temperature (WWW-MERRA): Daily MERRA Temperature products are used in this study. To obtain temperature based potential growing season and growing season summed warmth index, we firstly aggregated daily temperature to 15-day time step to smooth and enhance efficiency, then used following role to define thermal growing season metrics: (a) the start of the temperature based growing season is the day when the temperature is crossing 0 °C with rising phase; (b) the end of the temperature based growing season is the day when the temperature is crossing 0 °C decreasing phase; (c) the length of thermal growing season is the duration between start day and end day of the thermal growing season; (d) the growing season summed warmth index is the summation of temperature during the growing season.

Supplementary References

Ganguly S *et al* 2010. Land surface phenology from MODIS: Characterization of the Collection 5 global land cover dynamics product. *Remote Sens. Environ.* **114** 1805–1816.

Jung M *et al* 2011. Global patterns of land‐atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *J. Geophys. Res–Biogeo.* **116** G00J07.

Kim Y *et al* 2012. Satellite detection of increasing Northern Hemisphere non-frozen seasons from 1979 to 2008: Implications for regional vegetation growth. *Remote Sens. Environ.* **121** 472–487.

Pinzon J E and Tucker C J 2014. A non-stationary 1981–2012 AVHRR NDVI3g time series. *Remote Sens.* **6** 6929–6960.

Richardson A D *et al* 2010. Influence of spring and autumn phenological transitions on forest ecosystem productivity. *Philos. T. Roy. Soc. B.* **365** 3227–3246.

Running S W *et al* 1999. MODIS daily photosynthesis (PSN) and annual net primary production (NPP) product (MOD17) Algorithm Theoretical Basis Document. University of Montana, SCF At-Launch Algorithm ATBD Documents (Available at http://ntsg. umt. edu/modis/ATBD/ATBD_MOD17_v21. pdf).

Walker D A *et al* 2005. The circumpolar Arctic vegetation map. *J. Veg. Sci.* **16** 267–282.

WWW-CAVM. Circumpolar Arctic Vegetation Map (CAVM). Alaska Geobotany Center. Available at http://www.geobotany.uaf.edu/cavm/.

WWW-FT. Land Surface Freeze/Thaw State ESDR. National Snow and Ice Data Center. Available at http://nsidc.org/data/docs/measures/nsidc-0477/.

WWW-MCD12Q1. Land Cover Type Yearly L3 Global 500 m SIN Grid (MCD12Q1). Land Process Distributed Active Archive Center. Available at https://lpdaac.usgs.gov/ products/modis_products_table/mcd12q1.

WWW-MCD12Q2. Land Cover Dynamics Yearly L3 Global 500 m SIN Grid (MCD12Q2). Land Process Distributed Active Archive Center. Available at https://lpdaac.usgs.gov/ products/modis_products_table/mcd12q2.

WWW-MCD43C4. Nadir BRDF- Adjusted Reflectance 16-Day L3 0.05Deg CMG (MCD43C4). Land Process Distributed Active Archive Center. Available at https://lpdaac.usgs.gov/ products/modis_products_table/mcd43c4.

WWW-MOD10C2. MODIS/Terra Snow Cover 8-Day L3 Global 0.05Deg CMG (MOD10C2). National Snow and Ice Data Center. Available at http://nsidc.org/data/docs/daac/modis_v5/mod10c2_modis_terra_snow_8-day_global_0.05deg_cmg.gd.html.

WWW-MOD13C1. Vegetation Indices 16-Day L3 Global 0.05Deg CMG (MOD13C1). Land Process Distributed Active Archive Center. Available at https://lpdaac.usgs.gov/ products/modis_products_table/mod13c1.

WWW-MOD17A3. Terra/MODIS Net Primary Production Yearly L4 Global 1km (MOD17A3). Numerical Terradynamic Simulation Group (NTSG). Available at http://www.ntsg.umt.edu/project/mod17#data-product.

WWW-MERRA. MERRA-land 2d land surface diagnostics (time averaged, single level, at native resolution). Modeling and Assimilation Data and Information Services Center. Available at http://disc.sci.gsfc.nasa.gov/daac-bin/DataHoldings.pl.

Zhang X *et al* 2003. Monitoring vegetation phenology using MODIS. *Remote Sens. Environ.* **84** 471–475.

Supplementary Tables

Table S1. Information of selected global FLUXNET Sites (N=39, Number of observed site-years =140). Selection of valid site and data is performed by following two criteria: (i) more than 95 % of the days have daily GPP data, and (ii) the mean daily quality flag is more than 0.75 (Richardson *et al* 2010).

Site	Latitude	Longitude	IGBP	N. Obs.	Site	Latitude	Longitude	IGBP	N. Obs.
AT-Neu	47.117	11.318	GRA	1	IT-Lav	45.955	11.281	ENF	2
BE-Bra	51.309	4.521	MF	3	IT-MBo	46.016	11.047	GRA	4
BE-Vie	50.306	5.997	MF	7	IT-Mal	46.117	11.703	GRA	1
CA-Man	55.880	-98.481	ENF	2	IT-Ren	46.588	11.435	ENF	5
CA-NS1	55.879	-98.484	ENF	2	NL-Loo	52.168	5.744	ENF	7
CA-NS2	55.906	-98.525	ENF	2	PL-wet	52.762	16.309	WET	2
CA-NS3	55.912	-98.382	ENF	3	RU-Fyo	56.462	32.924	ENF	7
CA-NS5	55.863	-98.485	ENF	1	SE-Deg	64.183	19.550	WET	1
CA-NS7	56.636	-99.948	OSH	2	SE-Fla	64.113	19.457	ENF	3
CA-Qcu	49.267	-74.037	ENF	4	SE-Nor	60.087	17.480	ENF	4
CA-Qfo	49.693	-74.342	ENF	3	SE-Sk2	60.130	17.840	ENF	1
CZ-BK1	49.503	18.538	ENF	1	UK-EBu	55.866	-3.206	GRA	1
DE-Bay	50.142	11.867	ENF	2	UK-Gri	56.607	-3.798	ENF	5
DE-Gri	50.950	13.513	GRA	1	US-Ho1	45.204	-68.740	ENF	9
DE-Tha	50.964	13.567	ENF	10	US-Ho2	45.209	-68.747	ENF	6
DE-Wet	50.454	11.458	ENF	5	US-ICh	68.607	-149.296	OSH	7
FI-Hyy	61.847	24.295	ENF	8	US-ICs	68.606	-149.311	OSH	7
FI-Kaa	69.141	27.295	WET	5	US-ICt	68.606	-149.304	OSH	7
FI-Sod	67.362	26.638	ENF	5	US-WCr	45.806	-90.080	DBF	2
IT-LMa	45.581	7.155	GRA	1					

GRA: Grass, MF: Mixed Forest, ENF: Evergreen Needleleaf Forest, DBF: Deciduous Broadleaf Forest, OSH: Open Shrubland, WET: Wetland

Table S2. Continental scale trend estimation for NDVI3g and MODIS based growing season and productivity metrics over common temporal periods. We used the two different common periods (one for 2001-2012 and the other for 2000-2014) due to relatively short timespan of MCD12Q2. Estimates in parentheses represent trends during 2000-2014. The trends were evaluated by Vogelsang's *t-PS_T* test. CP, NA and EA are for circumpolar, North America and Eurasia regions, respectively.

	NDVI3g			**MODIS**			
	CP	**NA**	**EA**		**CP**	**NA**	**EA**
SOS (days·dec^{-1})	0.06 (0.85)	2.25 (2.33)	-0.98 (0.00)	MOD13C1	-2.24 (-1.98)	0.01 (-1.05)	-3.33 (-2.51)
				MCD43C4	-3.29 (-4.71)	-1.73 (-4.13)	-4.04 (-5.03*)
				MCD12Q2	-3.46 (N.A.)	-1.88 (N.A.)	-4.23 (N.A.)
EOS (days·dec^{-1})	0.95 (-0.69)	1.88 (-0.56)	0.43 (-0.76)	MOD13C1	2.45 (1.34)	2.90 (1.41)	2.19 (1.30)
				MCD43C4	2.89 (1.58)	2.71 (1.49)	2.94 (1.63)
				MCD12Q2	1.38 (N.A.)	0.72 (N.A.)	1.71 (N.A.)
LOS (days·dec^{-1})	1.41 (-1.08)	0.18 (-2.30)	1.98 (-0.38)	MOD13C1	4.96 (3.45*)	3.43 (2.73*)	5.72 (3.85*)
				MCD43C4	6.52 (6.48)	5.22* (6.09)	7.19 (6.70*)
				MCD12Q2	4.65 (N.A.)	2.42* (N.A.)	5.80 (N.A.)
GSSNDVI (dec^{-1})	4.81 (1.87)	4.36 (1.65)	5.01 (2.00)	MOD13C1	3.10 (2.21*)	2.28 (1.92*)	3.50 (2.37*)
				MCD43C4	4.03 (4.42)	3.16 (4.19)	4.46 (4.55)
				MCD12Q2	1.29 (N.A.)	0.41* (N.A.)	1.74 (N.A.)

***: $p<0.01$, **: $p<0.05$, *: $p<0.1$

N.A.: Not available

Table S3. Area of long-term (1982-2014) SOS, EOS, LOS, MAX and GSSNDVI trends by continents and biomes. Significant trends are calculated by Vogelsang's *t-PS_T* test at 10% significance level. Total area focused from this study is 26.02 million km^2. CP, NA, EA, AR and BO are for circumpolar, North America, Eurasia, arctic and boreal regions, respectively. All areal quantities in percent (%) are calculated with respect to total vegetated area in CP.

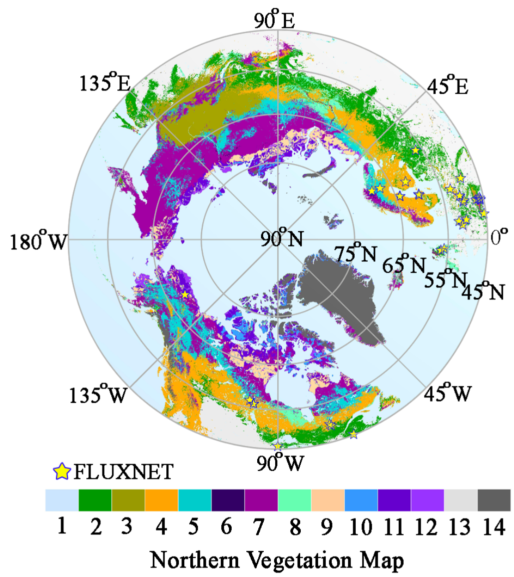
Metric Type	**Trend Type**	**CP**			**NA**			**EA**		
		All	AR	BO	All	AR	BO	All	AR	BO
SOS	Sig. Positive	2.7	0.5	2.2	2.3	0.4	1.8	0.5	0.1	0.4
	Sig. Negative	27.9	8.7	19.3	5.7	1.8	3.9	22.2	6.8	15.4
	InSig. or No Change	69.4	21.3	48.1	30.3	10.1	20.3	39.0	11.2	27.8
EOS	Sig. Positive	21.9	3.1	18.8	9.9	1.9	7.9	12.1	1.2	10.9
	Sig. Negative	7.7	4.3	3.5	1.9	0.8	1.1	5.8	3.5	2.3
	InSig. or No Change	70.3	23.0	47.3	26.5	9.5	16.9	43.9	13.5	30.4
LOS	Sig. Positive	33.2	7.7	25.4	10.1	2.8	7.3	23.1	4.9	18.2
	Sig. Negative	2.7	1.2	1.6	1.7	0.5	1.2	1.1	0.6	0.4
	InSig. or No Change	64.1	21.6	42.5	26.5	8.9	17.6	37.6	12.6	25.0
MAX	Sig. Positive	28.7	11.3	17.4	8.3	4.5	3.7	20.5	6.8	13.7
	Sig. Negative	5.2	1.1	4.0	3.1	0.4	2.7	2.1	0.7	1.4
	InSig. or No Change	66.1	18.0	48.1	26.9	7.3	19.6	39.1	10.7	28.5
GSSNDVI	Sig. Positive	42.0	12.8	29.1	12.8	5.2	7.6	29.1	7.6	21.5
	Sig. Negative	2.5	0.8	1.7	1.7	0.3	1.4	0.8	0.5	0.3
	InSig. or No Change	55.6	16.8	38.8	23.7	6.7	17.0	31.9	10.1	21.7

Table S4. Productivity (GSSNDVI) in 1982 and productivity change between 1982 and 2014 of vegetation classes. The Greening (abbreviated as G, shown in green color), Browning (abbreviated as B, shown in red color) and No change (abbreviated as N, shown in black color) was defined by calculating productivity trend between 1982 and 2014 pixel by pixel using the Vogelsang model at 10% significance level. Increased productivity (abbreviated as I, shown in green color) and decreased productivity (abbreviated as D, shown in red color) are calculated by $\sum_{p=1}^{NVC_i} 33yr \cdot T_p \cdot A_p$, where NVC_i is the total pixel number of the ith vegetation classes showing significant positive or negative changes, T_p is the yearly common productivity trend (yr^{-1}) of pixel p, A_p is the area weight (unitless) of pixel p. Area weighted total GSSNDVI over the greening ($G_{1982} = 9.04\times10^8$) and browning ($B_{1982} = 5.89\times10^7$) regions in 1982 was used as denominator to calculate Table 3 quantities. All quantities listed in below are unitless.

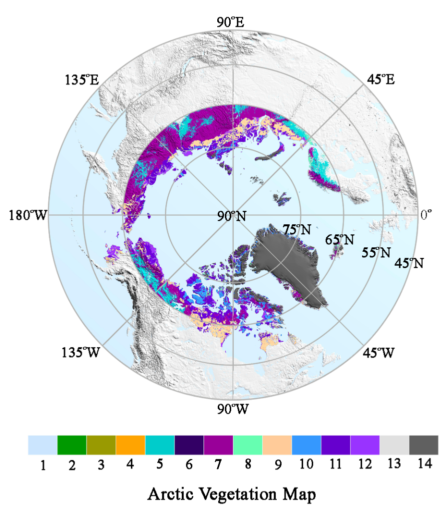
Vegetation Class	GSSNDVI in 1982			GSSNDVI Change (1982-2014)	
	G	B	N	I	D
Mixed Forests	3.18×10^8	3.66×10^6	2.19×10^8	5.89×10^7	-5.40×10^5
Deciduous Needleleaf Forests	8.76×10^7	1.87×10^6	1.32×10^8	1.35×10^7	-2.16×10^5
Evergreen Needleleaf Forests	2.01×10^8	2.13×10^7	3.08×10^8	4.75×10^7	-4.55×10^6
Forest-Shrubs Ecotone	7.58×10^7	1.16×10^7	1.63×10^8	1.74×10^7	-2.13×10^6
Closed Shrublands	2.91×10^6	2.87×10^5	4.29×10^6	7.63×10^5	-6.27×10^4
Open Shrublands	1.44×10^8	1.38×10^7	2.17×10^8	3.95×10^7	-2.67×10^6
Grasslands/ Wetlands (North of Forests)	9.72×10^6	5.60×10^5	1.82×10^7	2.41×10^6	-1.47×10^5
Erect Shrub Tundra	3.17×10^7	2.17×10^6	3.58×10^7	9.77×10^6	-5.44×10^5
Prostrate Shrub Tundra	4.73×10^6	3.98×10^5	7.91×10^6	1.70×10^6	-1.13×10^5
Graminoid Tundra	2.36×10^7	1.75×10^6	2.95×10^7	8.33×10^7	-5.03×10^5
Wetlands	4.80×10^6	1.47×10^6	1.13×10^7	1.62×10^6	-3.53×10^5
Total	9.04×10^8	5.89×10^7	1.15×10^9	2.01×10^8	-1.18×10^7

Supplementary Figures

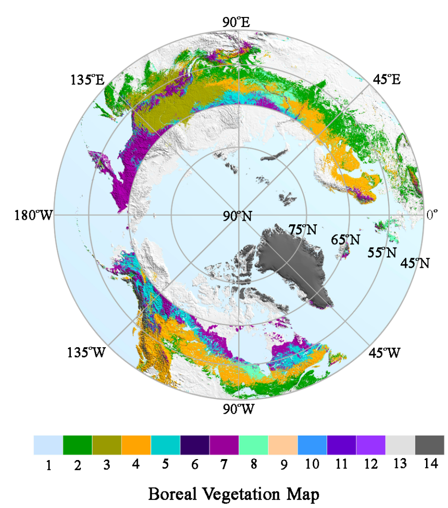
Figure S1. Northern Boreal and Arctic vegetation map (A). Vegetation classes 9 to 12 are as per the Circumpolar Arctic Vegetation Map (Walker *et al* 2005). The rest of the vegetation classes are based on the MODIS International Geosphere-Biosphere Programme (IGBP) land covers (definitions in Friedl *et al* 2010). Yellow star marker shows spatial distribution of used FLUXNET (N=39) sites for evaluation purposes. (B) Arctic vegetation only, (C) Boreal vegetation only. Class1: Oceans and inland lakes, Class2: Mixed Forests, Class3: Deciduous Needleleaf Forests, Class4: Evergreen Needleleaf Forests, Class5: Forest-Shrubs Ecotone, Class6: Closed Shrublands, Class7: Open Shrublands, Class8: Grasslands/ Wetlands (North of Forests), Class9: Erect Shrub Tundra, Class10: Prostrate Shrub Tundra, Class11: Graminoid Tundra, Class12: Wetlands, Class13: Other Vegetation (e.g., crops): Not considered in this study, Class14: Barren. Group1 (Forest): Class2-4, Group2 (Other woody vegetation): Class5-7, Group3 (Herbaceous vegetation): Class8, Group4 (Tundra): Class9-12.



(A)

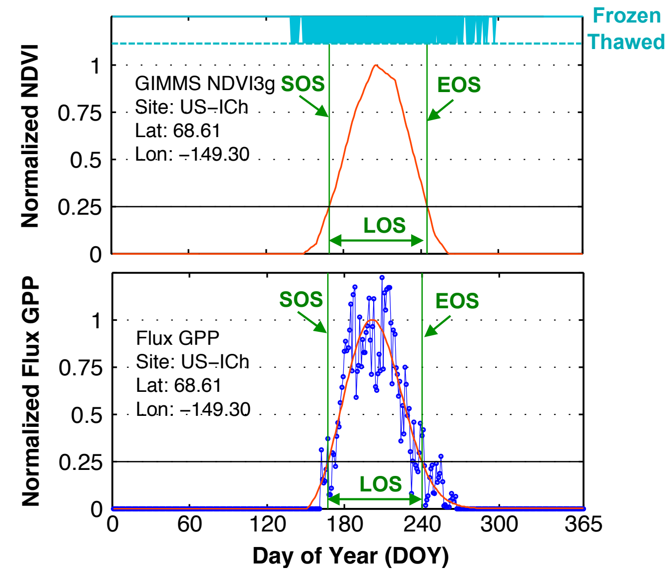


(B)

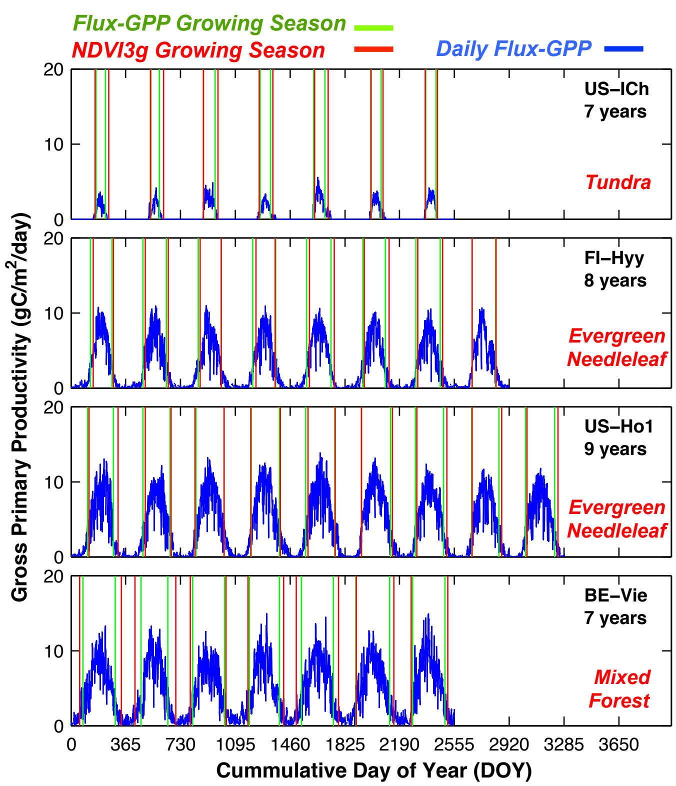


(C)

Figure S2. Definition of growing season and productivity from remotely sensed NDVI and FLUXNET GPP data (A). One year NDVI3g and tower measured GPP from US-ICh FLUXNET site were used for this example case. (B) Examples of retrieved NDVI3g and GPP based growing season metrics over four FLUXNET sites where have more than 6 years valid GPP observations.



(A)



(B)

Figure S3. Continental scale comparison between NDVI3g and MODIS (MOD13C1 and MCD43C4) spring (March to May) NDVIs. Correlation coefficients between NDVIs from NDVI3g and MODIS datasets are calculated (***: $p<0.01$, **: $p<0.05$, *: $p<0.1$) and given with corresponding color scheme. CP, NA and EA are for Circumpolar, North America and Eurasia regions, respectively. Increase in March-May NDVIs corresponds to an advance in the green-up date while a decrease corresponds to delay. As shown in below figure, the spring AVHRR NDVI showed strong negative anomalies and the other two vegetation indices from MODIS showed slight positive anomalies during 2012–2014. Therefore, the different response to vegetation growth of the AVHRR NDVI when compared with the MODIS vegetation indices appears to be responsible for the differences in the SOS and LOS variation. This comparison clearly indicates that divergence between NDVI3g and MODIS we observed (Figure 1A and 1C) should have been caused by the differences in response of vegetation indices to vegetation growth between sensors, rather than by the processing methods.

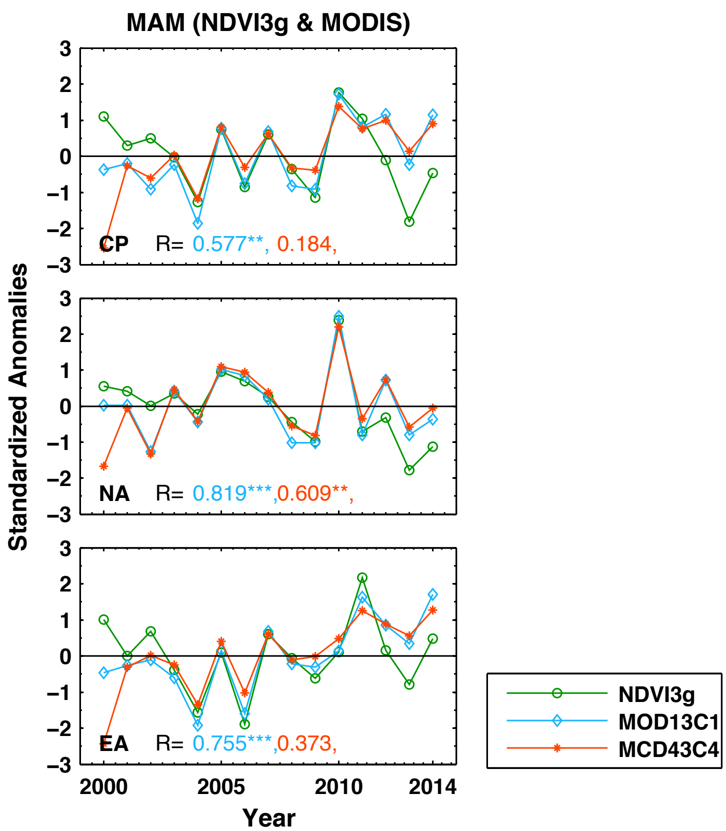
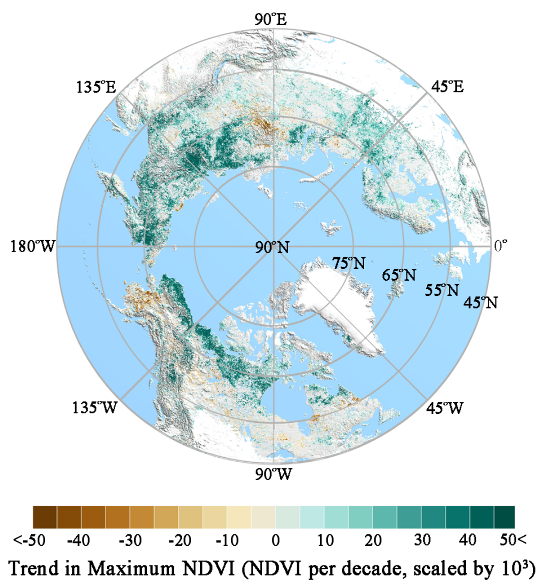
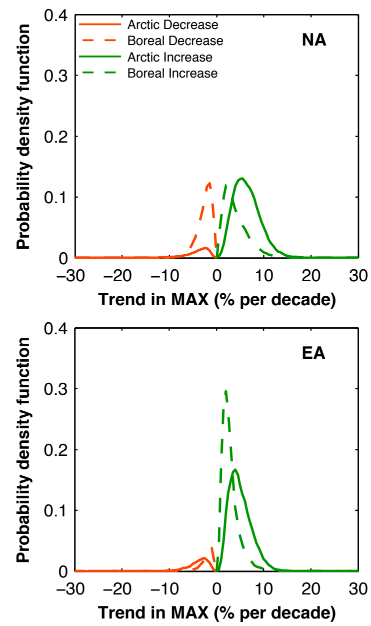


Figure S4. Long-term (1982-2014) trend in maximum NDVI (MAX) over Northern vegetated area (A). The trend was calculated using Vogelsang's *t-PS_T* test at 10% significance level. Non-vegetated pixels and pixels have no significant trend were shown in white and gray, respectively. Probability density function (PDF) of change rate per decade for only showing significant positive and negative changes is provided (B). All cases including insignificant or no changes can be found in Figure S4. PDFs are normalized to total area of significant changes in each continent and biome. NA and EA are for North America and Eurasia. In PDFs, green and red lines represent significant positive and negative PDFs. Solid and dash lines stand for arctic and boreal regions, respectively.



(A)



(B)

Figure S5. Probability density function (PDF) of change rate per decade for showing both significant and insignificant changes in onset (SOS), end (EOS) and length (LOS) of growing season, maximum (MAX) and growing season summed NDVI (GSSNDVI). Significant trends are calculated by Vogelsang's *t-PS_T* test at 10% significance level. PDFs are normalized to total vegetated area of each continent and biome. NA, EA, AR and BO are for North America, Eurasia, arctic and boreal regions, respectively (Table S3). In PDFs, green and red lines represent only significant positive and negative PDFs, while gray lines show all cases including significant and insignificant cases. Solid and dash lines stand for arctic and boreal regions, respectively. (A) SOS, (B) EOS, (C) LOS, (D) MAX and (E) GSSNDVI.