Contribution of phenological and physiological variations on northern vegetation productivity changes

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2015.10.22

❖ Control of gross primary productivity

- ✓ Terrestrial gross primary productivity (GPP) varies time and space.
- ✓ Variability in GPP is driven by a broad range of biotic and abiotic factors.
- ✓ Mainly changes in vegetation phenology and physiological processes regulate spatiotemporal GPP variation.

PNAS

Joint control of terrestrial gross primary productivity by plant phenology and physiology

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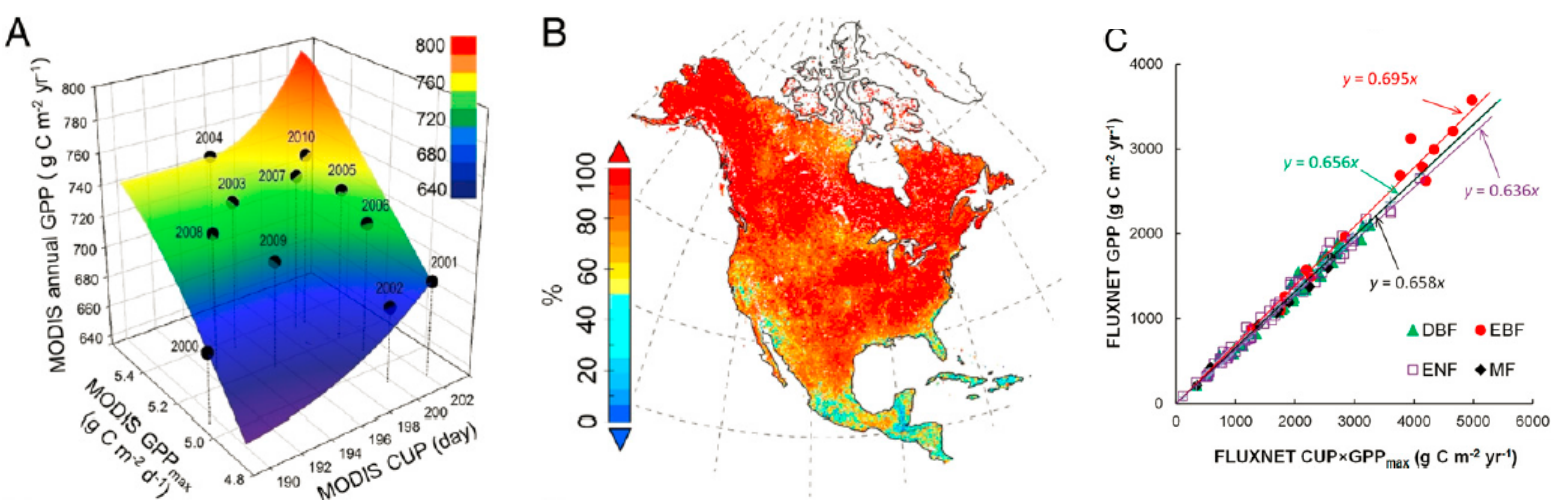

❖ Control of gross primary productivity

LETTERS
PUBLISHED ONLINE: 1 JUNE 2014 | DOI: 10.1038/NCLIMATE2253
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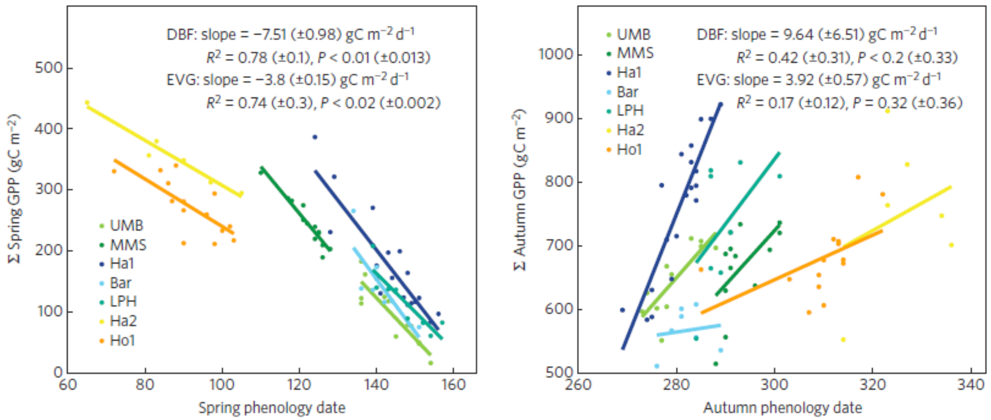
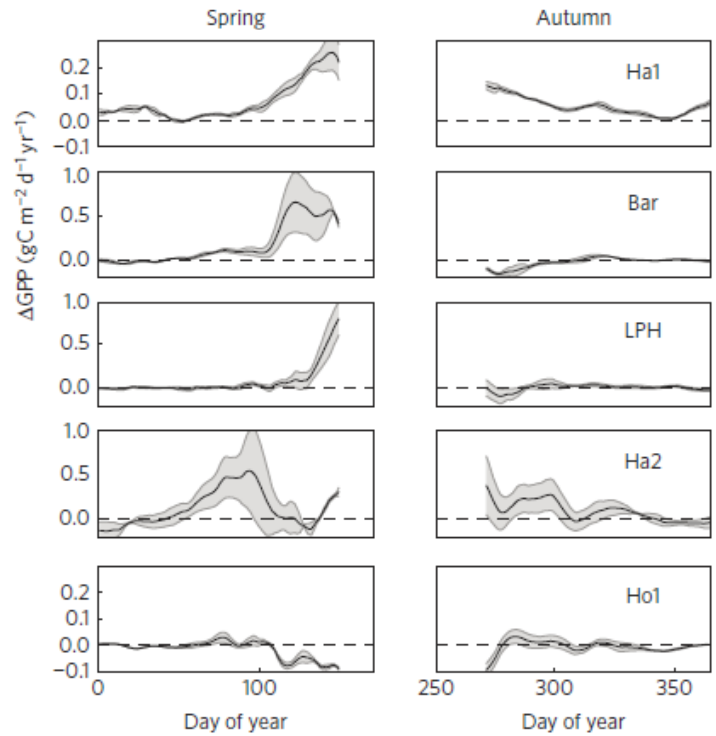
Net carbon uptake has increased through warming-induced changes in temperate forest phenology





- ✓ Phenology driven gross and net productivity increases were observed
- ✓ Autumnal phenology change causes larger productivity change than that of spring
- ✓ Increasing spring (or autumn) photosynthesis was larger in late spring (or early autumn) than early spring (or later autumn).
- ✓ More fully developed leaf area during late spring (or early autumn) contribute more increase of photosynthesis.

❖ Motivation and Overall research flow

- ✓ ***To quantify changes in growing season and productivity***
- ✓ ***To investigate how growing season components regulate annual productivity change***
- ✓ ***To identify climatic factors driving inter-annual productivity variation***

1. Define growing season and productivity using GIMMS NDVI3g data
2. Evaluate extracted metrics using independent datasets
3. Investigate spatiotemporal vegetation phenology and productivity changes
4. Quantify and characterize relative contribution of growing season and maximum photosynthetic capacity
5. Quantify climatic controls on vegetation productivity

❖ Mainly used datasets

✓ AVHRR GIMMS NDVI3g

- January 1982 to December 2014 (33 years)
- Bimonthly with 0.083 degree resolution (24 data / year)

✓ MODIS Snow Cover

- January 2001 to December 2014 (14 years)
- 8-day composite with 0.05 degree resolution (46 data /year)
- To define background NDVI in preprocessing step

✓ F/T ESDR (Global Freeze-thaw status)

- Special Sensor Microwave Imager (SSM/I)
- January 1982 to December 2012 (32 years)
- To refine growing season in after NDVI based growing season detection

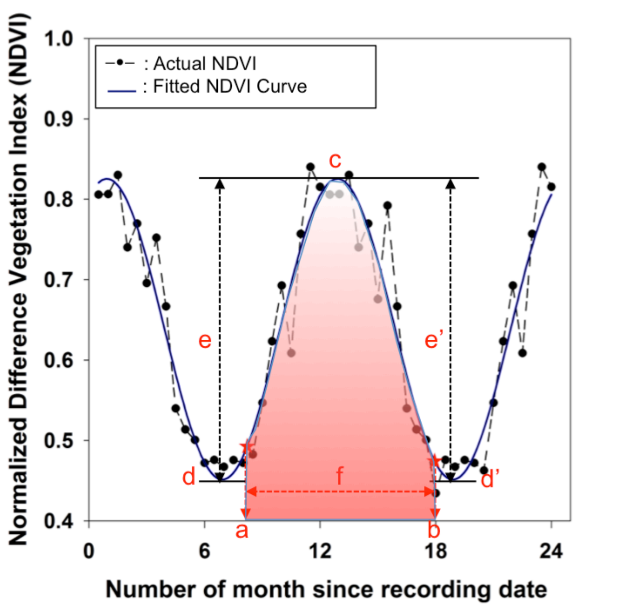
- *Preprocessing to maintain distinctive seasonal vegetation trajectory and minimize various spurious signals (e.g., cloud and snow)*
    - *implementing the Savitzky-Golay filter to smooth the NDVI3g time series*
    - *identifying background NDVI and replacing NDVI that varied irregularly during a winter period*

❖ Definition of growing season and productivity

✓ Photosynthetically Active Growing season (hereafter, growing season)

- 25% of the amplitude of the growing season (NDVI > 0.1)
- Thawing ground condition
- Start (SOS), End (EOS), and Length (LOS) of growing season

✓ Growing Season Integrated NDVI (GSINDVI): Measure of vegetation productivity (i.e., Gross Primary Productivity: GPP) during growing season (Goward et al., 1985; Box et al., 1989; Wang et al., 2004)



a: starting of growing season
b: end of growing season
c: maximum NDVI
d: minimum NDVI (Left / d': right)
e: Amplitude of season (Left/ e': right)
f: Growing season duration

$$GSINDVI_{(p,y)} = \sum_{t=a}^{b} f_{NDVI}(t)_{(p,y)}, \ (b - a \leq 365, \ a \leq b)$$

$\cdot f_{NDVI}(t) = Fitted\,annual\,daily\,NDVI$

$\cdot t$: day of year

$\cdot p$: pixel

$\cdot y$: year

$\cdot a$: onset of growing season

when, $f_{NDVI}(t) = \alpha \cdot (c - d)$ and $f_{NDVI}(t) > 0.1$ and thawed,

$a = t(\alpha = 0.25)$

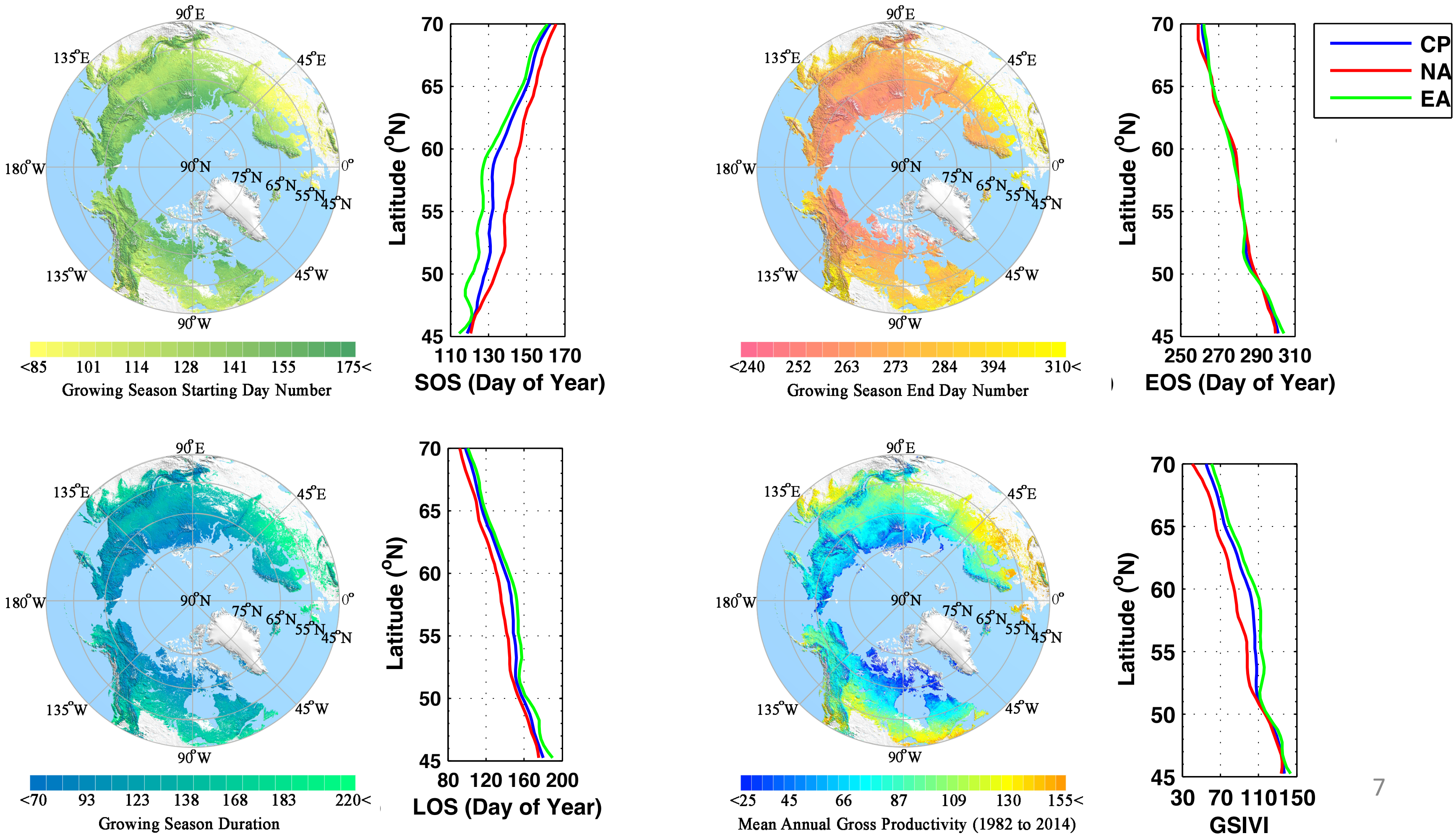
$\cdot b$: end of growing season

when, $f_{NDVI}(t) = \alpha \cdot (c - d')$ and $f_{NDVI}(t) > 0.1$ and thawed,

$b = t$

❖ NDVI3g based growing season and productivity

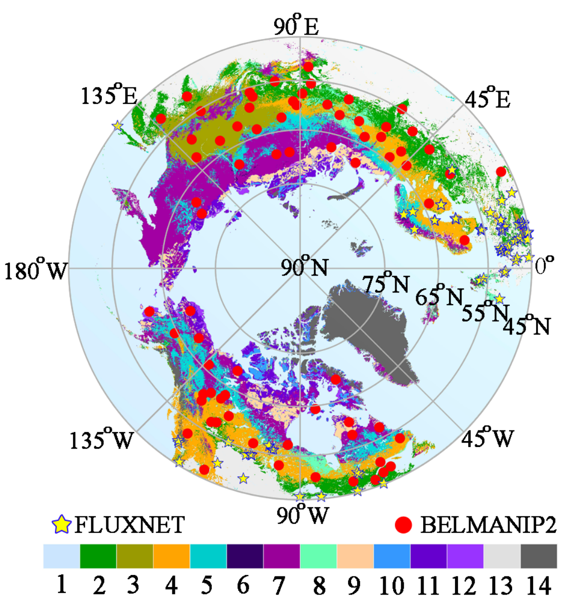
- ✓ SOS: DOY 85 (Mid of Mar.) – DOY 175 (End of Jun.)
- ✓ EOS: DOY 240 (Early Sep.) – DOY 310 (Early Nov.)
- ✓ LOS: 2.5 months (Arctic costal region) – 7 months (Europe)
- ✓ GSINDVI: 25 (Canadian Archipelago, Hudson bay) – 155 (Europe)



❖ Evaluation of retrieved NDVI3g metrics

✓ Seven different evaluation datasets

Data	*Data Independency*	*Method Independency*	*Overlap period*	*Spatial scale*	*SOS*	*EOS*	*LOS*	*GSINDVI*
FLUXNET GPP	O	O	1996-2006 (119 site-years)	Site only (36 sites)	O	O	O	O
MODIS MCD12Q2	O	O	2001-2012	Site & Continental scale	O	O	O	O
MODIS MCD43C4	O	X	2000-2014		O	O	O	O
MODIS MOD13C1	O	X	2000-2014		O	O	O	O
MODIS MOD17A3	O	O	2001-2014		X	X	X	O
MPI MTE GPP	X	O	1982-2011		X	X	X	O
MERRA TSURF	O	O	1982-2014		O	O	O	O



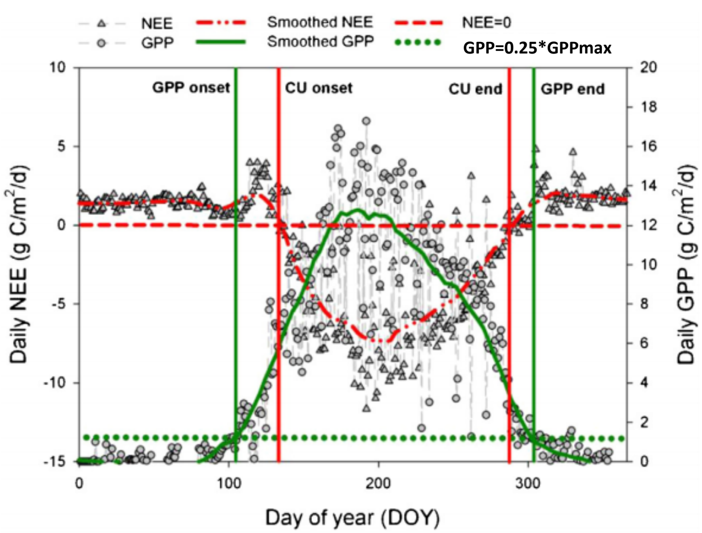
Northern Vegetation Map

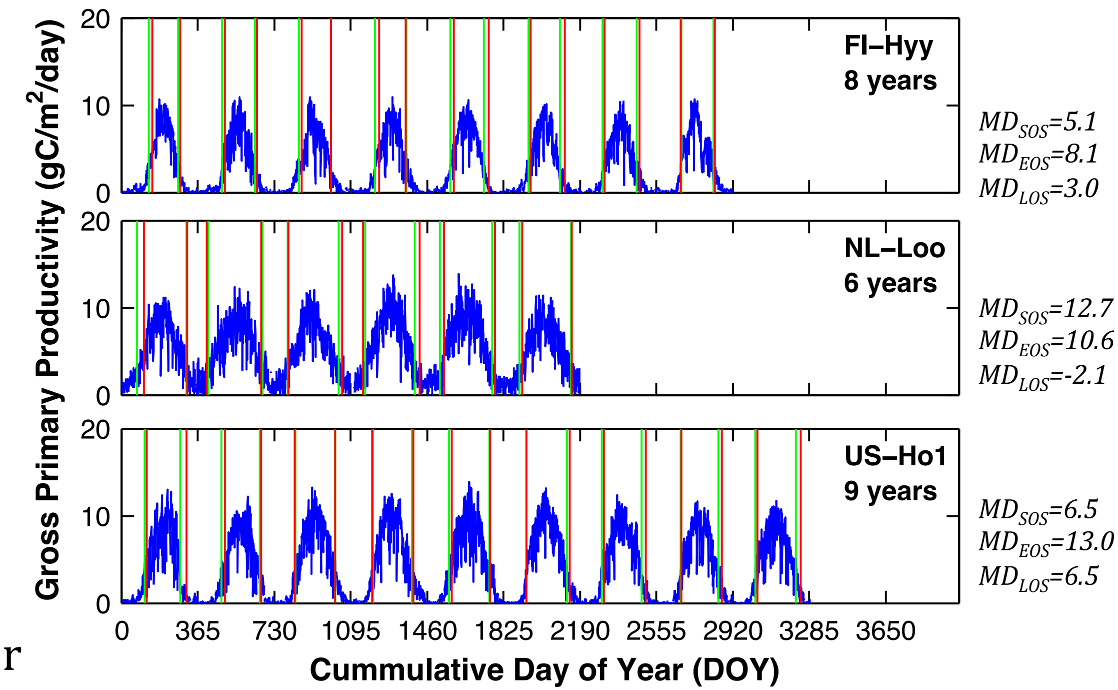
- ✓ Evaluation for retrieved NDVI3g growing season and productivity is crucial for this study
- ✓ Seven different evaluation datasets were prepared
- ✓ Site and continental scale evaluations were performed
- ✓ BELMANIP2 sites were used for site-scale evaluation
- ✓ Vegetation map is incorporated with MODIS IGBP and CAVM map (Xu et al., 2013)

Note that site-scale evaluation over BELMANIP2 sites was performed, but shown in supplementary section only

❖ Evaluation of retrieved NDVI3g metrics – Flux GPP

- ✓ 25% of GPP amplitude was used to define Flux-GPP growing season
- ✓ 119 site-years (36 sites) were used for evaluation purpose
- ✓ Examples (3 sites which have more than 6-year observations)



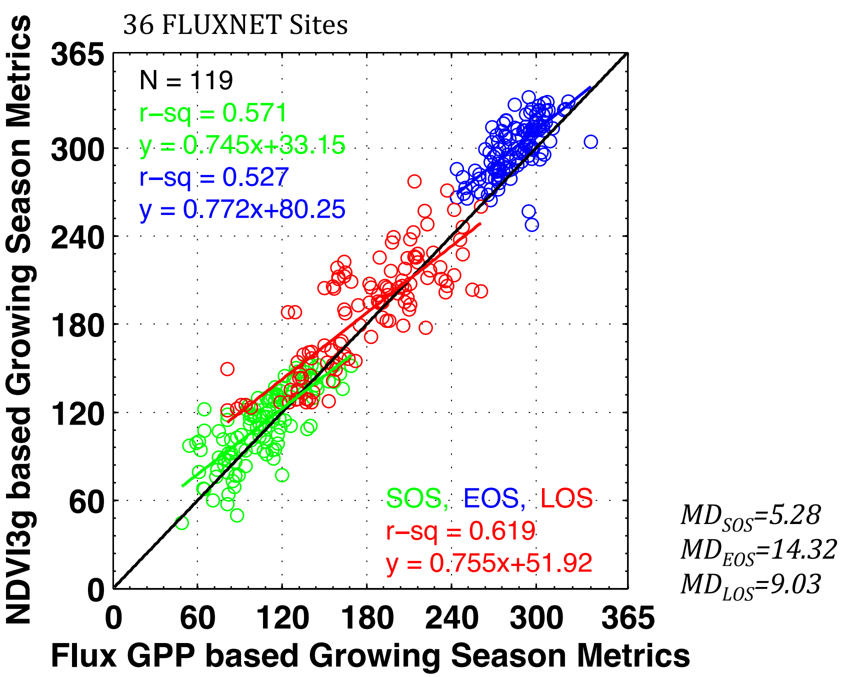


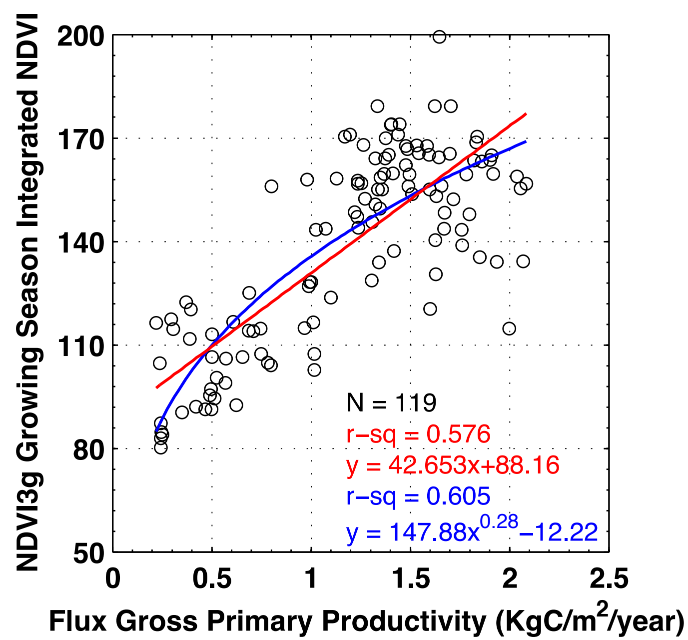
- ✓ Well captured GPP-SOS, not for GPP-EOS (reason?: might be larger variation in senescence due to multi-limiting factors & scaling)

Site	SOS		EOS		LOS	
	M.D	R (p-val)	M.D	R (p-val)	M.D	R (p-val)
Fl-Hyy	5.1	0.67 (0.07)	8.1	0.17 (0.67)	3.0	0.57 (0.78)
NL-Loo	12.7	0.76 (0.07)	10.6	0.02 (0.96)	-2.1	0.29 (0.57)
US-Ko1	6.5	0.77 (0.02)	13.0	0.29 (0.46)	6.5	0.30 (0.43)

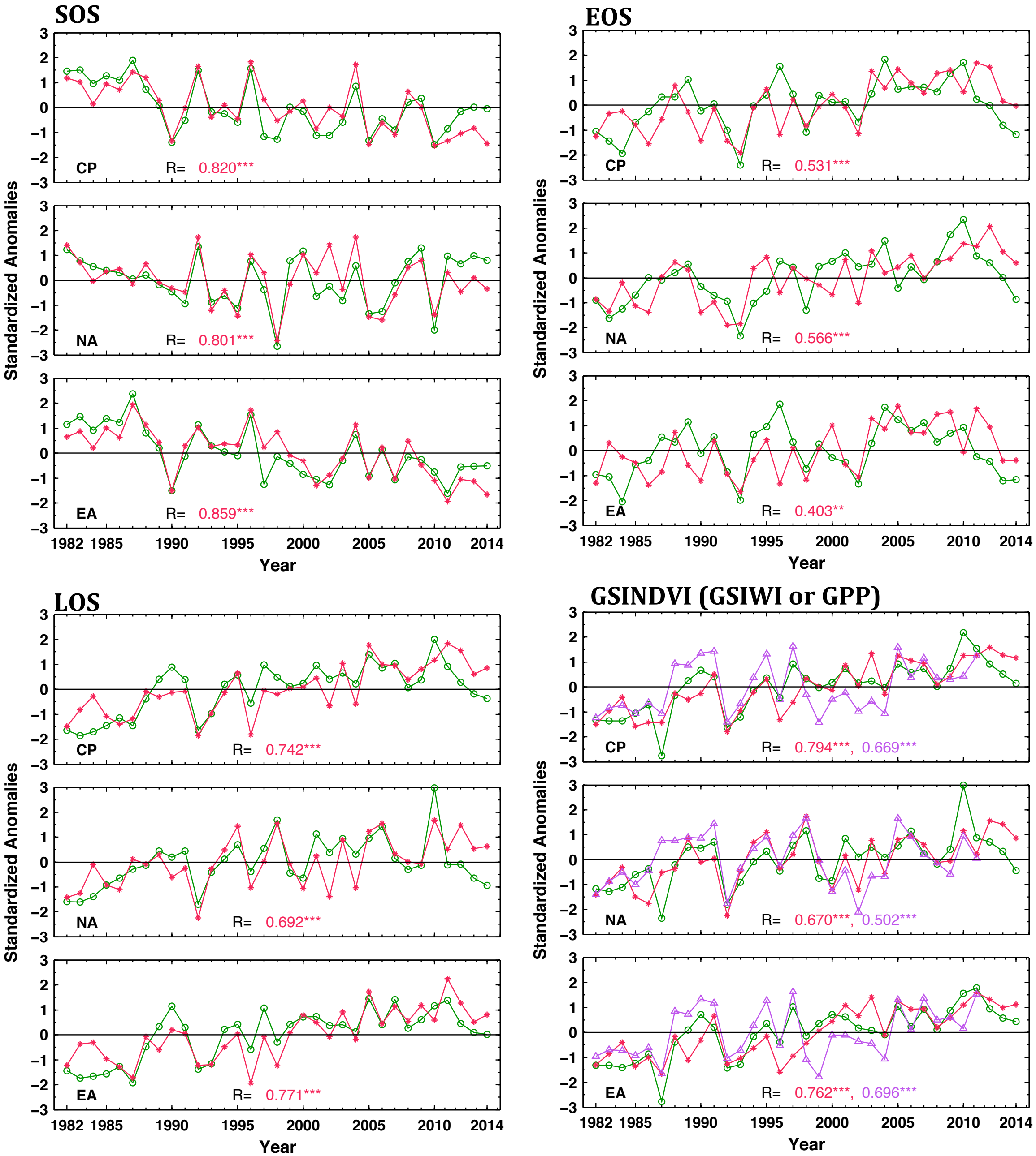
❖ Evaluation of retrieved NDVI3g metrics – Flux GPP

- ✓ 57%, 53%, and 62% of variations in Flux-GPP based SOS, EOS, and LOS can be explained by those of NDVI3g, respectively
- ✓ NDVI3g SOS and EOS show 5.3 and 14.3 days latter than Flux-GPP's
- ✓ NDVI3g LOS shows 9.3 days longer than LOS of Flux-GPP
- ✓ NDVI3g GSINDVI explains 61% of Flux-GPP variation



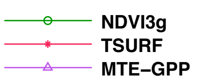


❖ Evaluation of retrieved NDVI3g metrics – TSURF & MTE GPP



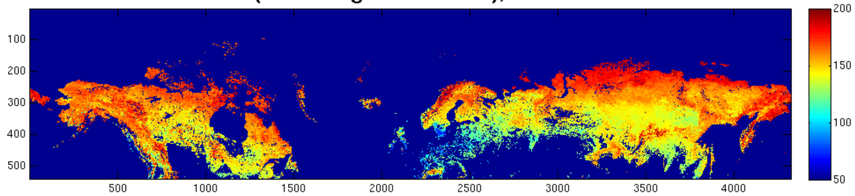
- ✓ The photosynthetic growing season has closely tracked the pace of warming and extension of the potential growing season in spring (R=0.82, p<0.01).
- ✓ Relatively weaker relation in autumn (R=0.53, p<0.01) (light and moisture limitation may constrain photosynthesis)
- ✓ GSINDVI co-varies well with MTE-GPP (R=0.67, p<0.01) and GSIWI (R=0.79, p<0.01) for three decades.

Note that site-scale evaluation over BELMANIP2 sites was performed, but shown in supplementary section only

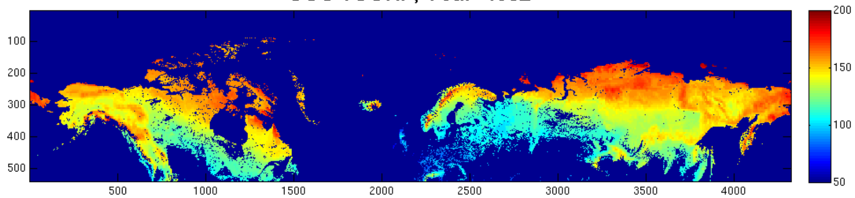


❖ Evaluation of retrieved NDVI3g metrics – TSURF & MTE GPP

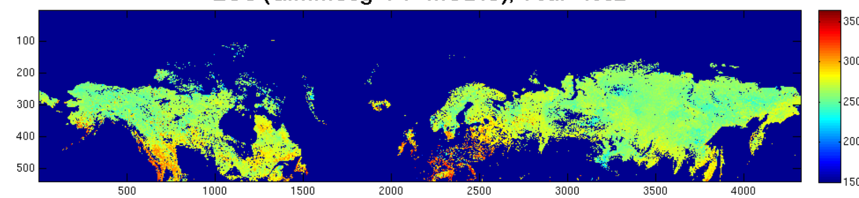
SOS (GIMMS3g+FT+MODIS), Year=1982



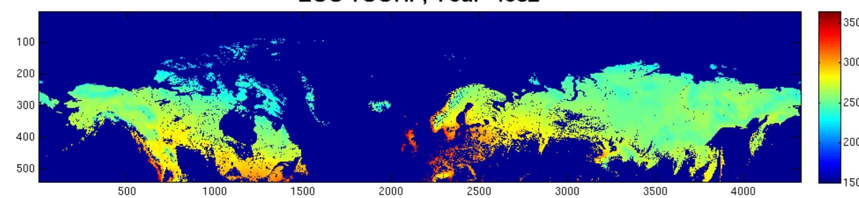
SOS TSURF, Year=1982



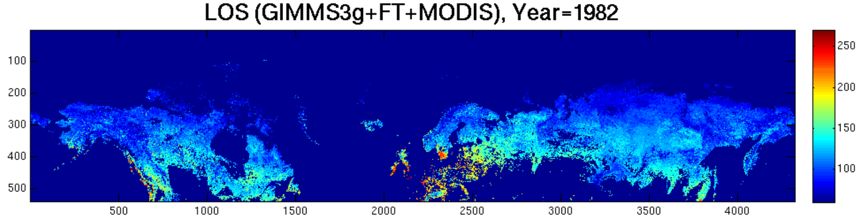
EOS (GIMMS3g+FT+MODIS), Year=1982



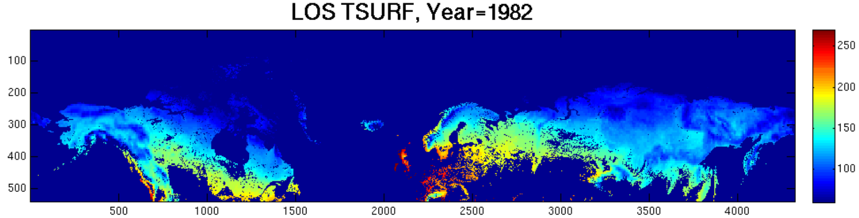
EOS TSURF, Year=1982



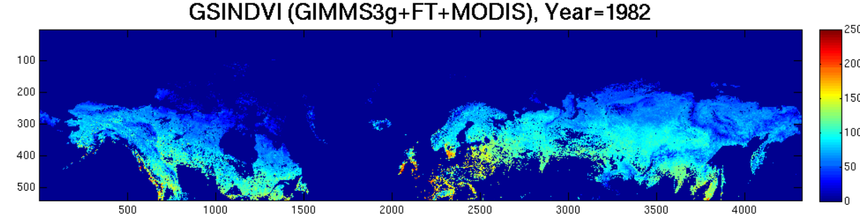
LOS (GIMMS3g+FT+MODIS), Year=1982



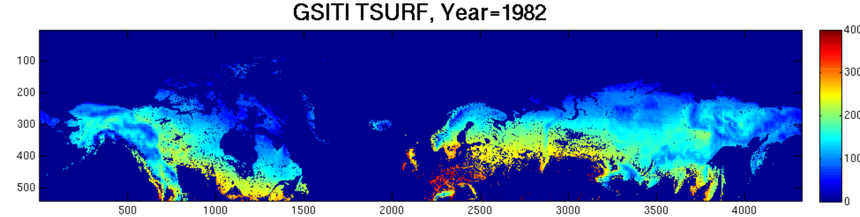
LOS TSURF, Year=1982



GSINDVI (GIMMS3g+FT+MODIS), Year=1982



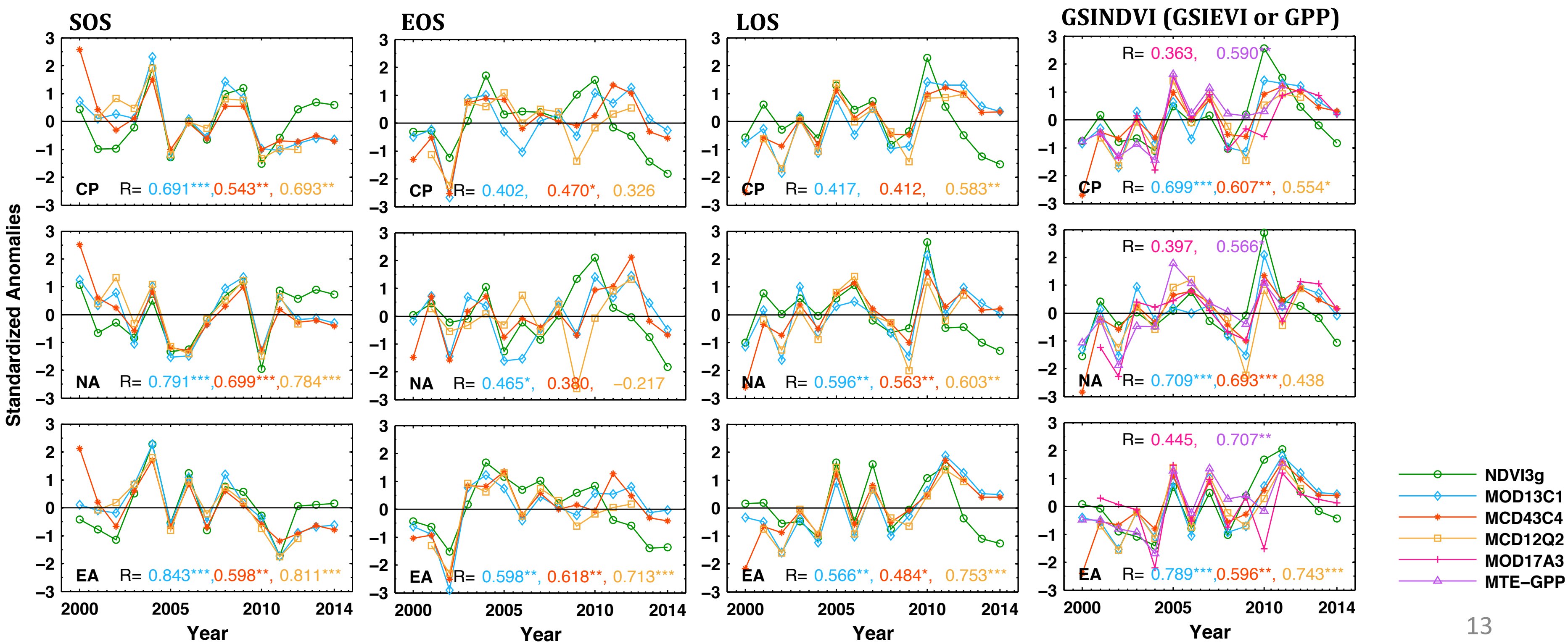
GSITI TSURF, Year=1982



❖ Evaluation of retrieved NDVI3g metrics – All RS data

- ✓ Overall, NDVI3g based SOS, EOS, LOS, and GSINDVI has similar inter-annual variations with five different source of growing season and productivity metrics at continental scale.
- ✓ However, after around 2012, NDVI3g shows relatively later SOS, earlier EOS, shorter LOS, and less productivity compared to others.

Note that site-scale evaluation over BELMANIP2 sites was performed for all cases, but shown in supplementary section only



❖ Trend analysis: Productivity changes over 33 years

- ✓ Photosynthetic and thermal potential growing season has lengthened by about 8.6 and 10.9 days ($P < 0.01$, 1982–2014), respectively

- ✓ Lengthening has been stronger and more significant in EA than NA in both cases.

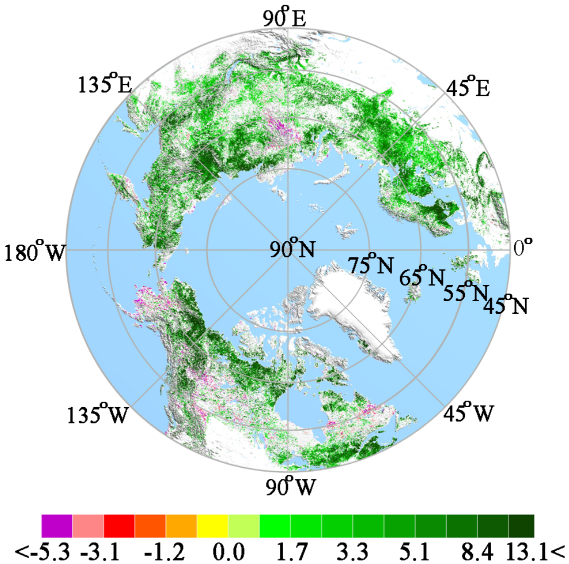
- ✓ Less autumnal extension of the photosynthetic growing season than that of the thermal potential growing season

- ✓ Significant GSINDVI and GSIWI increase in all continental cases, especially for EA.

	NDVI3g (1982-2014)			Temperature (1982-2014)		
	CP	NA	EA	CP	NA	EA
SOS (days·yr^{-1})	-0.161**	-0.013	-0.245**	-0.154***	-0.068	-0.203**
EOS (days·yr^{-1})	0.067*	0.120*	0.036	0.172**	0.203**	0.154**
LOS (days·yr^{-1})	0.260**	0.183**	0.304**	0.329***	0.273***	0.360**
GSINDVI (NDVI·yr^{-1})	0.297***	0.232***	0.334***	7.300***	5.333***	8.421**

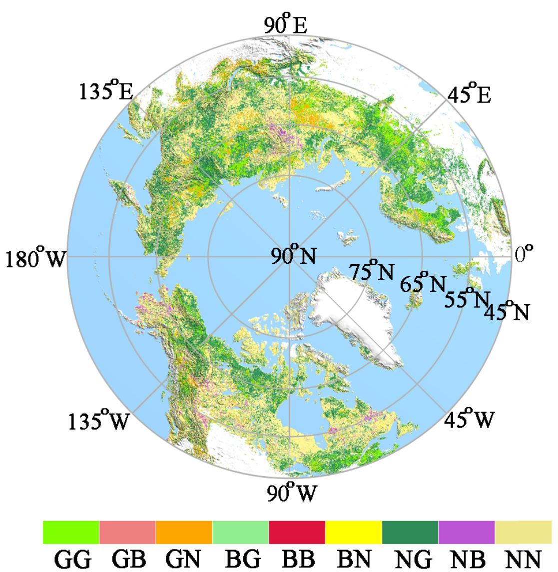
***: $p<0.01$, **: $p<0.05$, *: $p<0.1$

❖ Trend analysis: Productivity changes over 33 years



Trend in Annual Gross Productivity (% per decade)

Vegetation Class	Area			Productivity	
	G (%)	B (%)	N (%)	I (%)	D (%)
Mixed Forests	10.43	0.10	7.03	6.12	-0.06
Deciduous Needleleaf Forests	3.67	0.07	5.36	1.40	-0.02
Evergreen Needleleaf Forests	8.10	0.71	12.01	4.93	-0.47
Forest-Shrubs Ecotone	4.01	0.51	7.91	1.81	-0.22
Closed Shrublands	0.16	0.01	0.21	0.08	-0.01
Open Shrublands	9.72	0.71	14.41	4.11	-0.28
Grasslands/ Wetlands (North of Forests)	0.35	0.02	0.88	0.25	-0.02
Erect Shrub Tundra	2.41	0.11	2.48	1.01	-0.06
Prostrate Shrub Tundra	0.57	0.04	1.30	0.18	-0.01
Graminoid Tundra	2.13	0.12	3.11	0.87	-0.05
Wetlands	0.41	0.08	0.88	0.17	-0.04
Total	41.96	2.48	55.56	20.92	-1.23

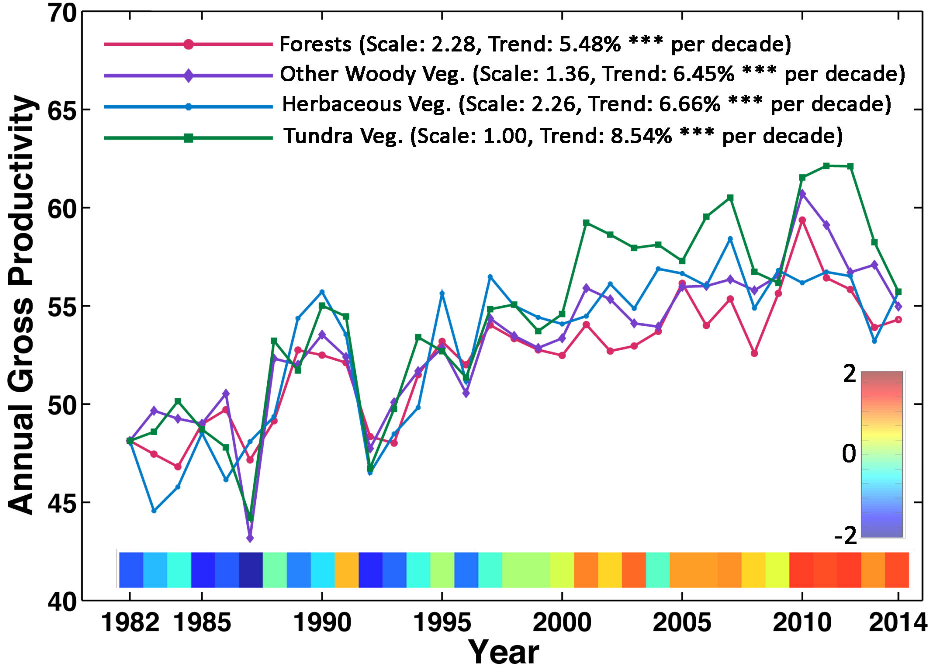


Trend Change between 1982-1999 and 1982-2014

1982-1999 (Base Year)	Greening 16.02% (4.01×10^6 km^2)			Browning 0.48% (1.21×10^5 km^2)			No Change 83.49% (2.09×10^7 km^2)		
	GG (%)	GB (%)	GN (%)	BG (%)	BB (%)	BN (%)	NG (%)	NB (%)	NN (%)
1982-2000	14.59	0.00	1.43	0.00	0.40	0.08	4.98	0.16	78.35
1982-2001	13.84	0.00	2.19	0.00	0.32	0.16	8.78	0.22	74.49
1982-2002	13.03	0.00	2.99	0.00	0.29	0.19	12.48	0.35	70.66
1982-2003	12.31	0.00	3.72	0.00	0.29	0.19	16.64	0.53	66.33
1982-2004	11.58	0.00	4.44	0.00	0.27	0.21	18.15	0.67	64.68
1982-2005	11.26	0.00	4.76	0.00	0.25	0.24	20.58	0.83	62.09
1982-2006	10.92	0.00	5.10	0.00	0.22	0.26	22.85	0.92	59.73
1982-2007	10.83	0.00	5.19	0.00	0.21	0.28	25.33	1.06	57.10
1982-2008	10.28	0.00	5.74	0.00	0.19	0.29	25.87	1.29	56.34
1982-2009	9.92	0.00	6.10	0.00	0.15	0.33	26.27	1.43	55.79
1982-2010	9.75	0.00	6.27	0.00	0.12	0.36	26.95	1.35	55.19
1982-2011	10.11	0.00	5.91	0.00	0.10	0.38	29.58	1.62	52.30
1982-2012	10.02	0.00	6.00	0.00	0.08	0.40	30.67	1.81	51.01
1982-2013	9.90	0.00	6.12	0.00	0.08	0.40	31.68	2.11	49.70
1982-2014	9.80	0.00	6.22	0.00	0.08	0.40	32.16	2.40	48.94

❖ Trend analysis: Productivity changes over 33 years

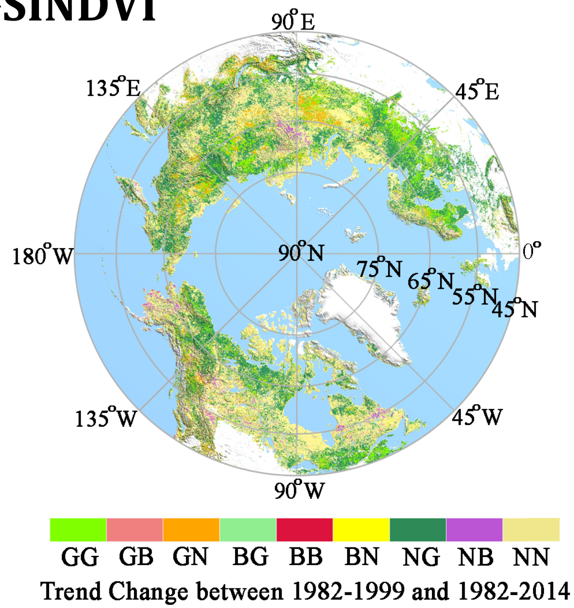
- ✓ Productivity Trend by four vegetation type
- ✓ Increasing productivity trend over last 33 years
  - All four different vegetation classes show increasing productivity trend
  - Relatively higher increasing rate (8.54%) can be found in Tundra vegetation
  - Relatively lower increasing rate (5.48%) can be found in Forests



- **Forests:** Evergreen needleleaf, Deciduous needleleaf, and Mixed forest
- **Other woody vegetation:** Forest-Shrubs Ecotone, Closed shrublands, and Open shrublands
- **Herbaceous vegetation:** Grasslands/Wetlands
- **Tundra vegetation:** Erect Shrub, Prostrate Shrub, Graminoid Tundra

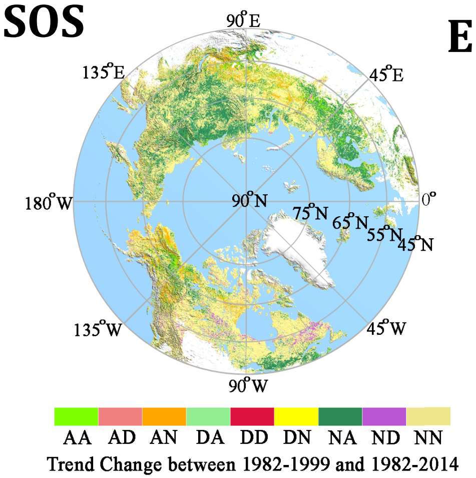
❖ How productivity is changing?

GSINDVI

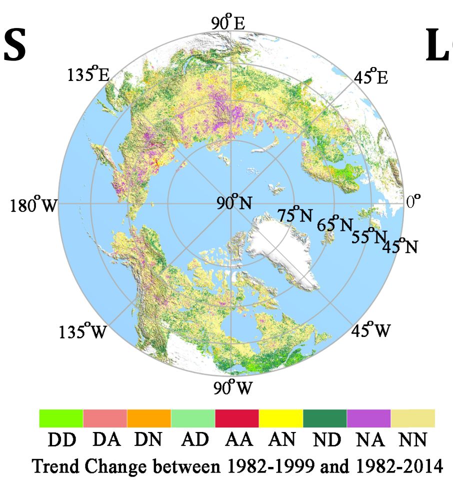


- ✓ GSINDVI change pattern can not be solely explained by maximum photosynthetic capacity or growing season length
- ✓ Productivity change is combination of changes in growing season length and photosynthetic capacity (Xia et al., 2015)

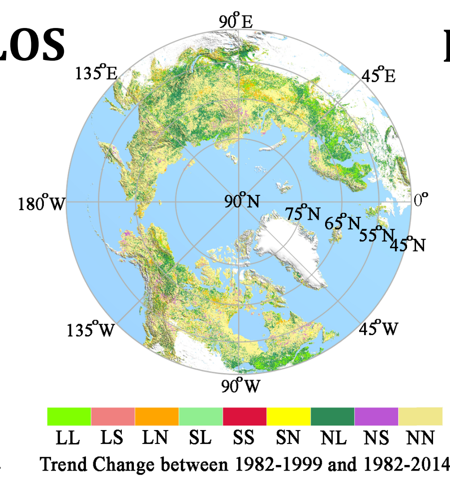
SOS



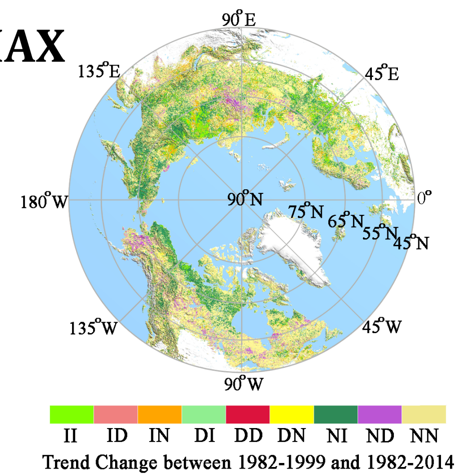
EOS



LOS

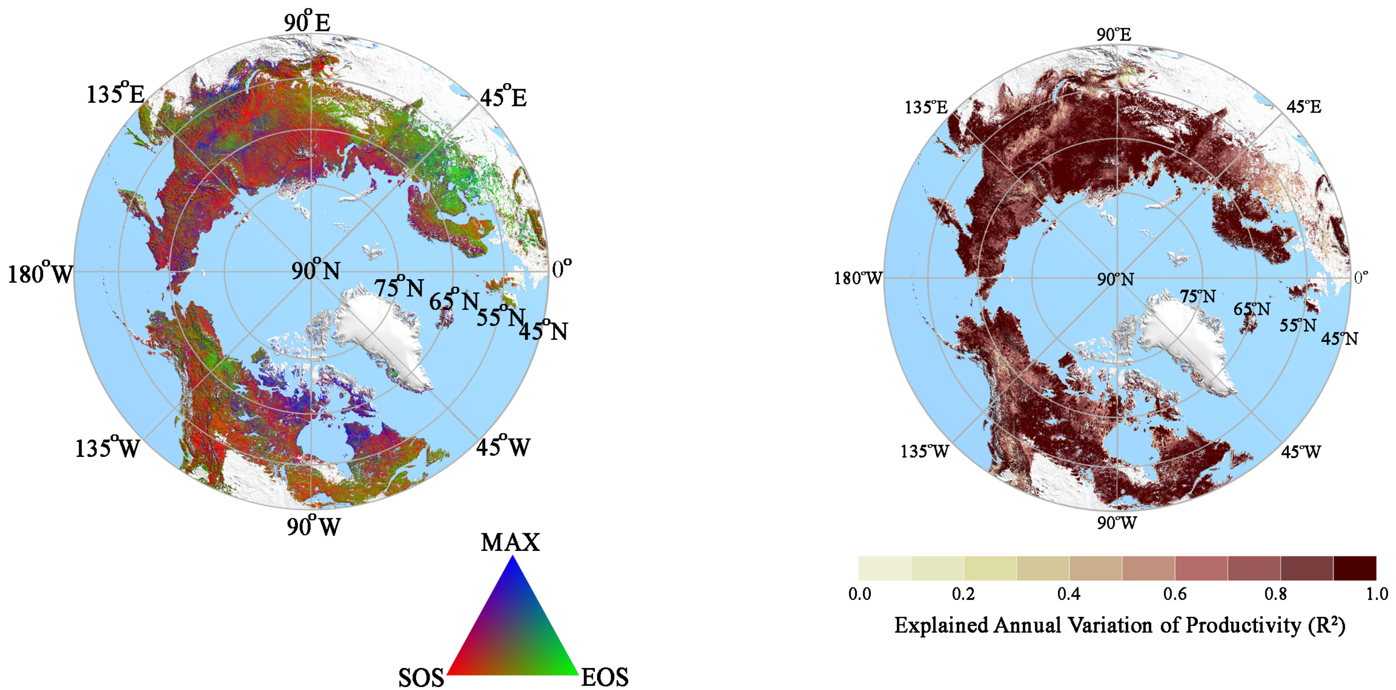


MAX

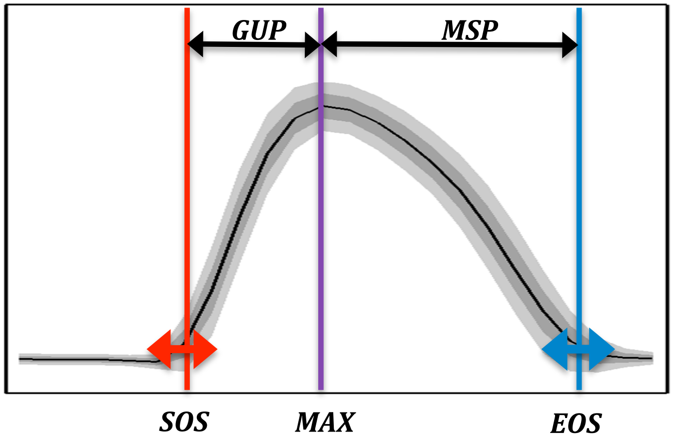


❖ Contribution of SOS, EOS and MAX on productivity

- ✓ To quantify relative contribution of SOS, EOS, and MAX, semi-partial correlation analysis is conducted
- ✓ Most of EA and NA shows SOS & MAX dual drivers (SOS contribute more-lagged effect is reported in FLUXNET community)
- ✓ High Arctic and high altitude region shows MAX driven productivity change
- ✓ European regions shows more contribution of EOS (MAX) in inter-annual productivity changes (note that lower explanatory power for this region)



❖ Characterization of productivity changes

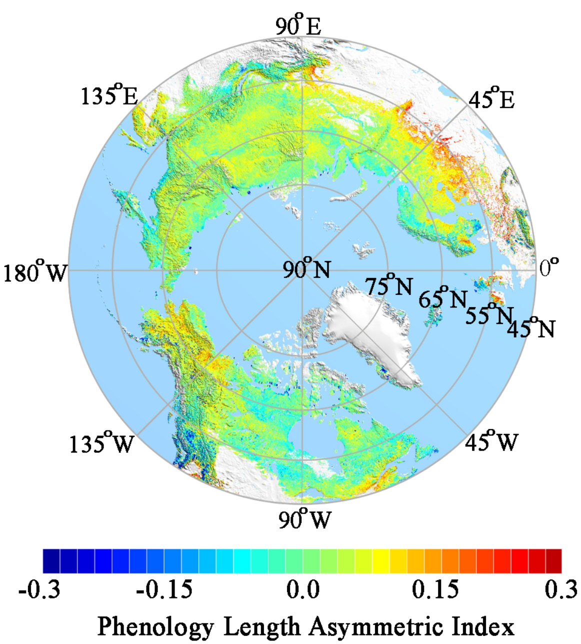


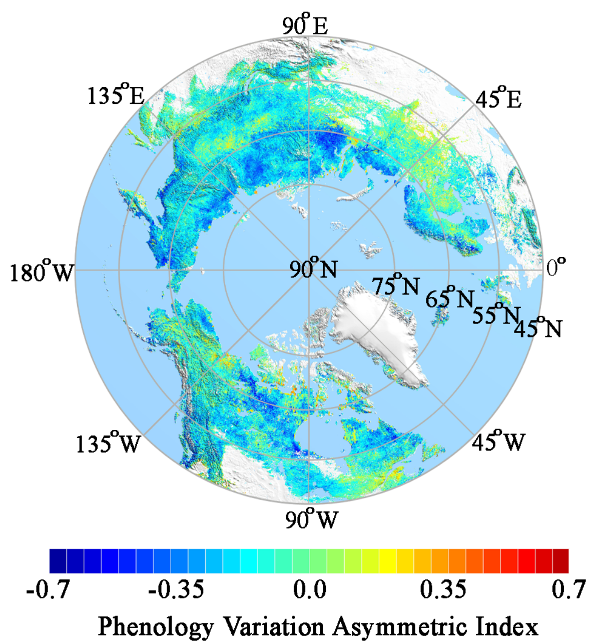
$$PLAI = 1 - \frac{2 \times GUP}{GUP + MSP}$$

GUP: Green-Up period (SOS to MAX)
MSP: Mature-Senescence period (MAX to EOS)
PLAI: Phenology Length Asymmetric Index
(+: MSP longer)

$$PVAI = 1 - \frac{2 \times SOS_{STD}}{SOS_{STD} + EOS_{STD}}$$

SOS_{std}: Std of SOS
EOS_{std}: Std of EOS
PVAI: Phenology Variation Asymmetric Index
(+: EOS varies more)

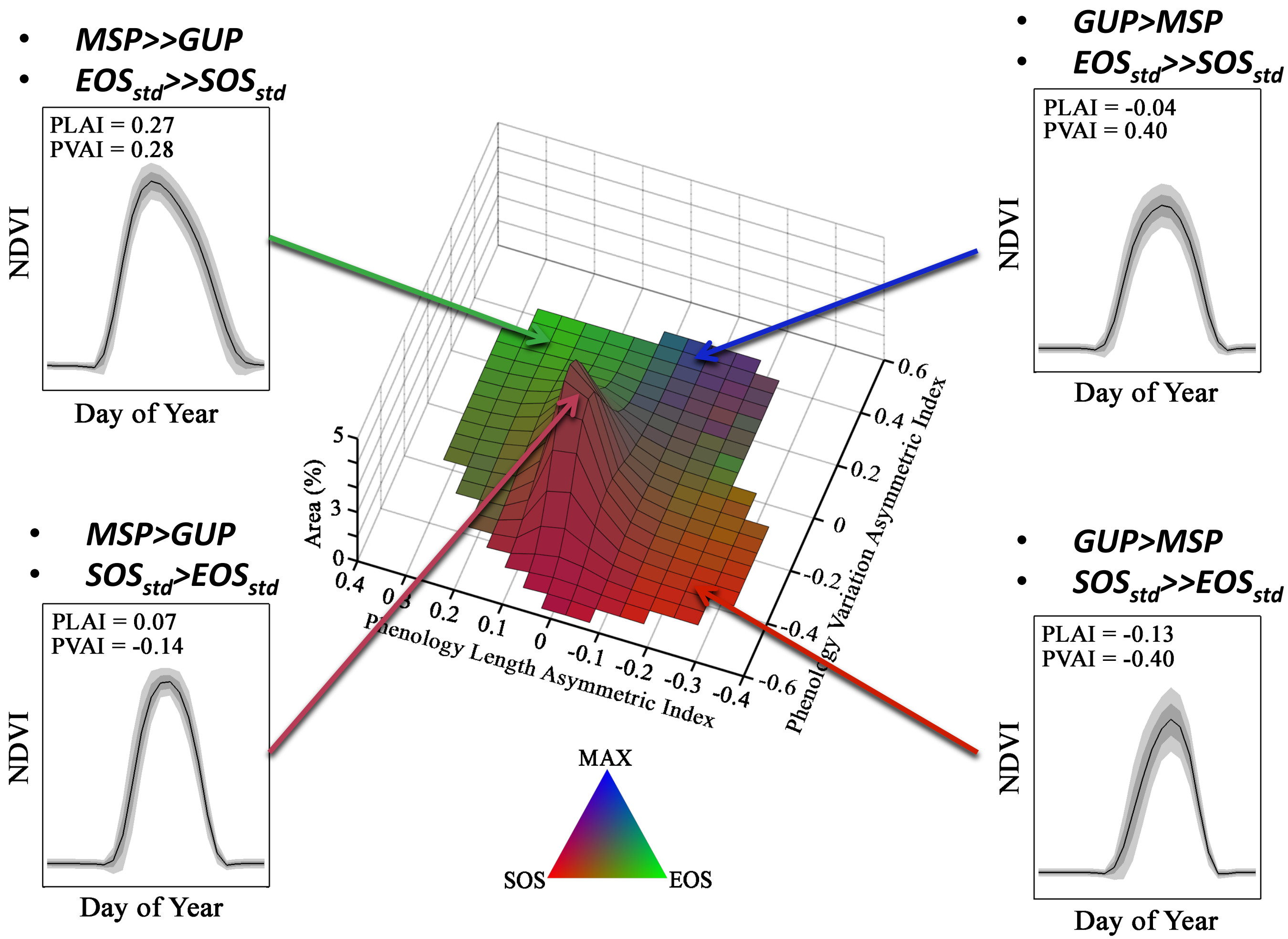




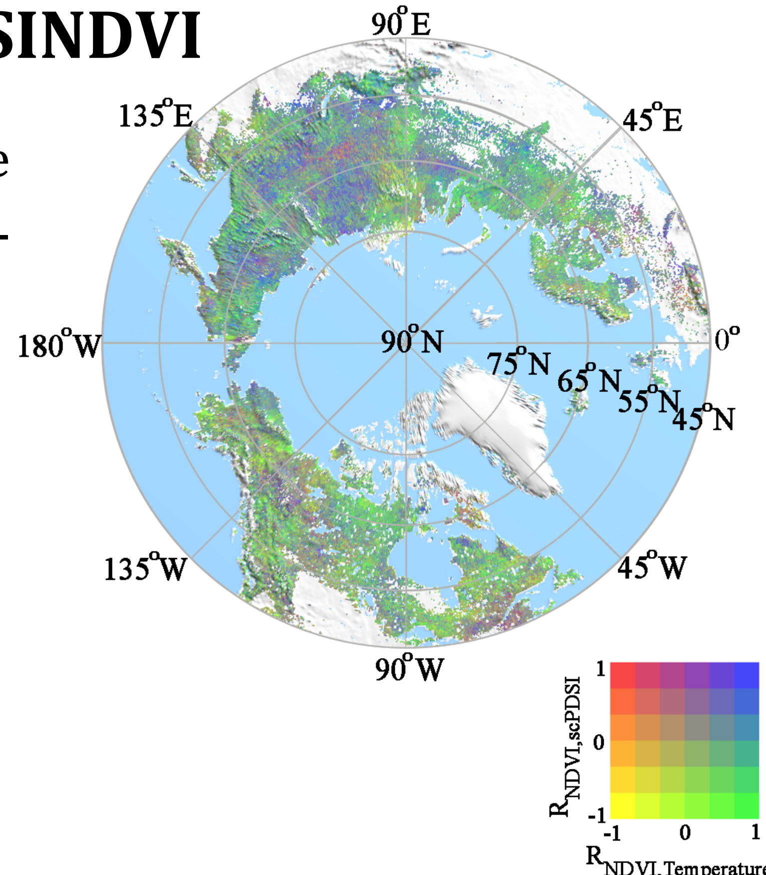
- ✓ Relatively longer MSP: Boreal, especially for European region (longer mature canopy with)
- ✓ Relatively larger variation in SOS: Along Arctic coastal region

❖ Characterization of productivity changes

✓ Shape and variation of phenological trajectory are capable of demonstrating contribution of phenological components on productivity change



❖ Climate control on NDVI3g GSINDVI



- ✓ CRU temperature and CRU scPDSI were used to represent temperature and water-stress on vegetation, respectively
- ✓ Most of regions in CP (60.1%) shows positive relation with temperature not for scPDSI => less water stress might mean… more snow induces shorter growing season or cold-weather damage
- ✓ Approximately half of EA shows both positive relations => lengthened growing season cause increasing evaporative demand
- ✓ Some boreal forest in EA and NA shows neutral or negative relation with temperature but positive relation with scPDSI => warming induced drought stress in boreal forest.

Area table

$R_{NDVI,scPDSI}$ \ $R_{NDVI,Temperature}$	-1.0 to -0.33	-0.33 to 0.0	0.0 to 0.33	0.33 to 1.0
0.33 to 1.0	0.02	0.39	2.31	4.06
0.0 to 0.33	0.05	1.87	14.33	24.99
-0.33 to 0.0	0.07	1.89	14.86	26.06
-1.0 to -0.33	0.02	0.49	2.83	5.77

❖ Summary

- ✓ NDVI3g based growing season and productivity can explain 57%, 53%, 62%, and 61% of variations in Flux-GPP based SOS, EOS, LOS and GPP, respectively
- ✓ Independent MODIS LSP and GPP also co-vary well with NDVI3g metrics (ex. after 2012)
- ✓ Photosynthetic and thermal potential growing season has lengthened by about 8.6 and 10.9 days ($P < 0.01$, 1982–2014), respectively
- ✓ About 42% and 2.5% of study regions show greening (interpreted as 20.1% of productivity gain) and browning (1.2% productivity loss) trends
- ✓ Relatively higher increasing rate (8.54%) in Tundra vegetation / lower increasing rate (5.48%) can be found in Forests
- ✓ SOS & MAX dual regulating system can be found in most of EA and NA
- ✓ Relative phenophase length (PLAI) and variation (PVAI) can characterize productivity changes and contribution of phenological components
- ✓ Temperature and moisture-stress characterize larger scale productivity changes

Thank you for your attention