Article

Monitoring Spatial and Temporal Variabilities of Gross Primary Production using MAIAC MODIS Data

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Abstract: Remotely sensed vegetation indices (RSVIs) can be used to efficiently estimate terrestrial primary productivity across space and time. Terrestrial productivity, however, has many facets (e.g., spatial and temporal variability, including seasonality, interannual variability, and trends), and different vegetation indices may not be equally good at predicting them. Their accuracy in monitoring productivity has been mostly tested in single-ecosystem studies, but their performance in different ecosystems distributed over large areas still needs to be fully explored. To fill this gap, we identified the facets of terrestrial gross primary production (GPP) that could be monitored using RSVIs. We compared the temporal and spatial patterns of four vegetation indices (NDVI, EVI, NIR_V, and CCI), derived from the MODIS MAIAC data set and of GPP derived from data from 58 eddy-flux towers in eight ecosystems with different plant functional types (evergreen needle-leaved forest, evergreen broad-leaved forest, deciduous broad-leaved forest, mixed forest, open shrubland, grassland, cropland, and wetland) distributed throughout Europe, covering Mediterranean, temperate, and boreal regions. The RSVIs monitored temporal variability well in most of the ecosystem types, with grasslands and evergreen broad-leaved forests most strongly and weakly correlated with weekly and monthly RSVI data, respectively. The performance of the RSVIs monitoring temporal variability decreased sharply, however, when the seasonal component of the time series was removed, suggesting that the seasonal cycles of both the GPP and RSVI time series were the dominant drivers of their relationships. Removing winter values from the analyses did not affect the results. NDVI and CCI identified the spatial variability of average annual GPP, and all RSVIs identified GPP seasonality well. The RSVI estimates, however, could not estimate the interannual variability of GPP across sites or monitor the trends of GPP. Overall, our results indicate that RSVIs are suitable to track different facets of GPP variability at the local scale, therefore they are reliable sources of GPP monitoring at larger geographical scales.

Table S1. List of the sites with starting and ending dates (FLUXNET Tier 1). Vegetation types (IGBP); ENF, evergreen needleleaved forest; EBF, evergreen broadleaved forest; DBF, deciduous broadleaved forest; MF, mixed forest; OSH, open shrubland; GRA, grassland; CRO, cropland; WET, permanent wetland.

Site	Longitude (°)	Latitude (°)	Start	End	IGBP	Reference
BE-Bra	4.52	51.31	1996	2014	MF	[45]
BE-Lon	4.75	50.55	2004	2014	CRO	[46]
BE-Vie	6	50.31	1996	2014	MF	[47]
CH-Cha	8.41	47.21	2005	2014	GRA	[48]
CH-Dav	9.86	46.82	1997	2014	ENF	NA
CH-Fru	8.54	47.12	2005	2014	GRA	[48]
CH-Lae	8.37	47.48	2004	2014	MF	[49]
CH-Oe1	7.73	47.29	2002	2008	GRA	[50]
CZ-BK1	18.54	49.5	2004	2008	ENF	[51]
CZ-BK2	18.54	49.49	2004	2006	GRA	[51]
CZ-wet	14.77	49.02	2006	2014	WET	NA
DE-Akm	13.68	53.87	2009	2014	WET	NA
DE-Geb	10.91	51.1	2001	2014	CRO	[52]
DE-Gri	13.51	50.95	2004	2014	GRA	[53]
DE-Hai	10.45	51.08	2000	2012	DBF	[54]
DE-Kli	13.52	50.89	2004	2014	CRO	[55]
DE-Lkb	13.3	49.1	2009	2013	ENF	[56]
DE-Obe	13.72	50.78	2008	2014	ENF	[57]
DE-RuR	6.3	50.62	2011	2014	GRA	[58]
DE-RuS	6.45	50.87	2011	2014	CRO	NA
DE-Seh	6.45	50.87	2007	2010	CRO	NA
DE-SfN	11.33	47.81	2012	2014	WET	NA
DE-Spw	14.03	51.89	2010	2014	WET	NA
DE-Tha	13.57	50.96	1996	2014	ENF	[59]
DK-Fou	9.59	56.48	2005	2005	CRO	NA
DK-Sor	11.64	55.49	1996	2014	DBF	[60]
ES-LgS	-2.97	37.1	2007	2009	OSH	[38]
ES-Ln2	-3.48	36.97	2009	2009	OSH	NA
FI-Hyy	24.3	61.85	1996	2014	ENF	[61]
FI-Jok	23.51	60.9	2000	2003	CRO	[53]
FI-Lom	24.21	68	2007	2009	WET	NA
FI-Sod	26.64	67.36	2001	2014	ENF	[62]
FR-Fon	2.78	48.48	2005	2014	DBF	[63]
FR-Gri	1.95	48.84	2004	2013	CRO	[64]
FR-LBr	-0.77	44.72	1996	2008	ENF	[65]
FR-Pue	3.6	43.74	2000	2014	EBF	[66]
IT-BCi	14.96	40.52	2004	2014	CRO	[67]
IT-CA1	12.03	42.38	2011	2014	DBF	[67]
IT-CA2	12.03	42.38	2011	2014	CRO	[67]
IT-CA3	12.02	42.38	2011	2014	DBF	[67]
IT-Col	13.59	41.85	1996	2014	DBF	[68]
IT-Cp2	12.36	41.7	2012	2014	EBF	[69]
IT-Cpz	12.38	41.71	1997	2009	EBF	[41]
IT-Isp	8.63	45.81	2013	2014	DBF	[70]
IT-La2	11.29	45.95	2000	2002	ENF	[71]
IT-Lav	11.28	45.96	2003	2014	ENF	[71]
IT-MBo	11.05	46.01	2003	2013	GRA	[72]
IT-Noe	8.15	40.61	2004	2014	CSH	[73]
IT-PT1	9.06	45.2	2002	2004	DBF	[72]
IT-Ren	11.43	46.59	1998	2013	ENF	[74]
IT-Ro1	11.93	42.41	2000	2008	DBF	[75]
IT-Ro2	11.92	42.39	2002	2012	DBF	[76]
IT-SR2	10.29	43.73	2013	2014	ENF	[76]
IT-SRo	10.28	43.73	1999	2012	ENF	[77]
IT-Tor	7.58	45.84	2008	2014	GRA	[78]
NL-Hor	5.07	52.24	2004	2011	GRA	[79]
NL-Loo	5.74	52.17	1996	2013	ENF	[80]
RU-Fyo	32.92	56.46	1998	2014	ENF	[81]

Table S2. Amounts of variance explained (R^2, mean ± standard error of the mean) for the raw and deseasonalised weekly and monthly time series of GPP by NDVI, EVI, NIR_v, and CCI after removing winter weeks (1–12 and 46–52) and months (December, January, February, and March). Significant coefficients are highlighted in bold. ENF, evergreen needleleaved forest; EBF, evergreen broadleaved forest; DBF, deciduous broadleaved forest; MF, mixed forest; OSH, open shrubland; GRA, grassland; CRO, cropland; WET, permanent wetland. "NA" stands for not available.

Ecosystem	NDVI	EVI	NIR_v	CCI	N
Weekly					
ENF	**0.22 ± 0.06**	**0.33 ± 0.05**	0.31 ± 0.06	0.22 ± 0.04	16
EBF	0.02 ± 0.01	0.08 ± 0.07	0.08 ± 0.06	0.07 ± 0.01	3
DBF	**0.35 ± 0.09**	**0.44 ± 0.09**	0.43 ± 0.09	0.31 ± 0.09	10
MF	**0.29 ± 0.07**	**0.48 ± 0.03**	0.46 ± 0.03	0.35 ± 0.05	3
OSH	0.28 ± NA	0.40 ± NA	0.38 ± NA	0.03 ± NA	1
GRA	**0.36 ± 0.08**	**0.37 ± 0.07**	0.37 ± 0.07	0.30 ± 0.08	9
CRO	**0.32 ± 0.04**	**0.39 ± 0.05**	0.38 ± 0.05	0.29 ± 0.05	9
WET	**0.40 ± 0.11**	**0.46 ± 0.09**	0.46 ± 0.10	0.36 ± 0.08	5
Mean	**0.29 ± 0.03**	**0.37 ± 0.03**	0.36 ± 0.03	0.27 ± 0.03	56
Weekly anomalies					
ENF	0.02 ± 0.00	0.03 ± 0.01	0.03 ± 0.01	0.01 ± 0.00	16
EBF	0.05 ± 0.02	0.04 ± 0.03	0.04 ± 0.03	0.09 ± 0.04	3
DBF	**0.12 ± 0.02**	**0.13 ± 0.02**	**0.12 ± 0.02**	**0.13 ± 0.02**	10
MF	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.02	0.01 ± 0.01	3
OSH	0.05 ± NA	0.04 ± NA	0.02 ± NA	0.00 ± NA	1
GRA	**0.08 ± 0.03**	**0.09 ± 0.02**	**0.08 ± 0.02**	0.05 ± 0.01	9
CRO	**0.08 ± 0.03**	**0.10 ± 0.03**	**0.10 ± 0.03**	0.08 ± 0.03	9
WET	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.01	5
Mean	**0.06 ± 0.01**	**0.07 ± 0.01**	**0.06 ± 0.01**	**0.06 ± 0.01**	56
Monthly					
ENF	**0.19 ± 0.07**	**0.43 ± 0.07**	**0.38 ± 0.07**	**0.28 ± 0.06**	11
EBF	0.01 ± NA	0.25 ± NA	0.25 ± NA	0.09 ± NA	2
DBF	**0.35 ± 0.11**	**0.53 ± 0.11**	**0.55 ± 0.10**	**0.33 ± 0.13**	6
MF	**0.43 ± 0.12**	**0.68 ± 0.03**	**0.66 ± 0.03**	**0.51 ± 0.06**	3
OSH	NA ± NA	NA ± NA	NA ± NA	NA ± NA	0
GRA	**0.49 ± 0.10**	**0.58 ± 0.07**	**0.53 ± 0.07**	**0.37 ± 0.10**	5
CRO	**0.29 ± 0.08**	**0.35 ± 0.10**	**0.37 ± 0.11**	**0.25 ± 0.09**	5
WET	0.67 ± NA	0.71 ± NA	0.67 ± NA	0.63 ± NA	1
Mean	**0.30 ± 0.03**	**0.48 ± 0.03**	**0.46 ± 0.03**	**0.32 ± 0.03**	33
Monthly anomalies					
ENF	**0.04 ± 0.01**	**0.05 ± 0.01**	**0.05 ± 0.01**	0.03 ± 0.01	11
EBF	0.07 ± NA	0.10 ± NA	0.10 ± NA	0.10 ± NA	2
DBF	**0.14 ± 0.02**	**0.14 ± 0.03**	**0.15 ± 0.02**	**0.09 ± 0.01**	6
MF	0.04 ± 0.03	0.04 ± 0.03	0.07 ± 0.04	0.01 ± 0.00	3
OSH	NA ± NA	NA ± NA	NA ± NA	NA ± NA	0
GRA	**0.11 ± 0.05**	**0.14 ± 0.06**	**0.09 ± 0.02**	0.04 ± 0.01	5
CRO	0.14 ± 0.07	0.15 ± 0.07	0.16 ± 0.08	**0.11 ± 0.07**	5
WET	0.00 ± NA	0.01 ± NA	0.00 ± NA	0.00 ± NA	1
Mean	**0.08 ± 0.01**	**0.10 ± 0.01**	**0.09 ± 0.01**	**0.05 ± 0.01**	33

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