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Spatiotemporal Dynamic of French Forest Phenology from *MODIS* and *GLOBCARBON* products

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ABSTRACT : Phenological trends studies based on remote sensing data appear to be a realistic and cost-effective way to monitor forest ecosystems over time. Although such vegetation trends have been widely investigated at the global scale, still little is known on pheno-phases anomalies at regional scales. Remote sensing time series at medium spatial resolution (≤ 1km) are now available to fill this gap but the derived phenological products still need to be validated. Our retrospective analysis is based on remotely sensed phenological metrics delivered over 10 years (1998-2007) through the GLOBCARBON project (VGCP product) and from MODIS sensors (MCD12Q2 product). For validation, we took advantage of tree canopy phenological observations of the French Permanent Plot Networks for Forest Monitoring (RENECOFOR) carried out at the ground on the same period. Focusing on two emblematic deciduous broadleaf tree species (beech and oaks) we also investigated phenological responses at the tree species level on a national extent. In-situ comparison of broadleaf forests leaf-on date shows a prediction uncertainty of 8 and 13.8 days and systematics errors of 2.2 and 9.8 days for MODIS and GLOBCARBON. Considering only pure beech forests reduce bias to 1.6 and 5.5 days respectively but no significant relationship could be retrieved for oaks forests. On the France extent, cross-product comparaison remain stable against tree species. Neither early leaf-on nor senescence stages could accurately be depicted by satellite based metrics. Inter-annual leaf-on trends are consistent with ground observations and spatial patterns of green-up dates are related to latitudinal gradients for oaks forests and altitudinal gradients for beech forests.

1 INTRODUCTION

Tree phenology reflects their adaptive responses to climate variability and therefore constitutes an efficient bio-indicator of forest condition and productivity. Because warming climate has led to phenological timing shifts over the past half century (Chmielewski & Rotzer, 2001; Menzel et al., 2006), tracking the rhythm of the seasons is still challenging (Morisette et al., 2009) and remote sensing is a key tool for measuring and monitoring forest phenology on a large extent. Vegetation indices derived from satellite data are commonly used for this purpose essentially at global or continental scale. Finer spatial scale studies of vegetation trends can now be retrospectively be performed as medium spatial resolution (≤ 1km) data time series become available over the last decade.

Those satellite data are regularly reprocessed to improve information quality (snow, clouds, aerosols correction) or combined via multiple sensors acquisition to get a higher temporal frequency. However, the remote sensing community regularly emphasizes the need for ground validation and multiple sensor comparisons to validate the accuracy of those products (Morisette et al., 2009).

Based on long-term in-situ forest phenological observations, the aim of this study was to evaluate the ability of high-level remote sensing products in monitoring forest foliar dynamics both in time and space. We report here the evaluation of the MODIS and GLOBCARBON "phenological" products (Cf. 2.1). For ground validation, we focus on two major deciduous broadleaf tree species: Beech (*Fagus sylvatica*) and Oaks (*Quercus sp.*) because there is significant seasonal trends differences between those two species (Davi et al., 2006; Vitasse et al., 2009a) but consistent within each one (Vitasse et al. 2009b).

2 MATERIALS & METHODS

To explore spatio-temporal trends at a national scale we look at long term remote sensing data time series, corrected for atmospheric and bidirectional effects, and for which phenological indicators were already computed.

2.1 Remote sensing data

First, we investigate the latest version of the MODIS "land Cover Dynamics" product available on the LPDAAC server, namely MCD12Q2 (V5), which combines the "Terra" and "Aqua" sensors reflectance measurements over the period 2001 to 2006 (see Ganguly et al., 2010 for complete description). The interest of this recent version lies in both a high spatial and temporal resolution (500m and 8 days respectively). Ensuing yearly products gather several land surface phenology indicators derived from Enhanced Vegetation Index (EVI) annuals curves extended to ± 6 months. Those metrics characterize vegetation growth cycle using transition dates namely, Onset Greenness Increase (OGI), Maximum (OGMax), decrease (OGD), minimum (OGMin) and the annual integral of the vegetation index curve (EVI area). We also computed (OGMax-OGI)/2 as an indicator of the date of the growing season inflexion point (hereafter referred as OG).

On another hand, GLOBCARBON v2 “Vegetation Growth Cycle Parameters” product at 1km was used for the years 1998 to 2007. The baseline input combine satellite data from the ESA Earth Observations (ATSR-2, AATSR, MERIS) and SPOT VEGETATION sensors. Complete description of the GLOBCARBON initiative can be found in Plummer et al. (2007).The generation of annual growth cycle parameters is based on derived LAI profiles smoothed over 54 decades. Authors argue that LAI should be less sensitive to extraneous effects which are often seen on vegetation index time series (e.g. NDVI, EVI). Similarly to the MODIS product, several phenological metrics are provided (n=8) such as the day before the highest first derivative of LAI curve reach 90% of its maximum (hereafter referred as Dbefore).

2.2 In-situ phenological observations

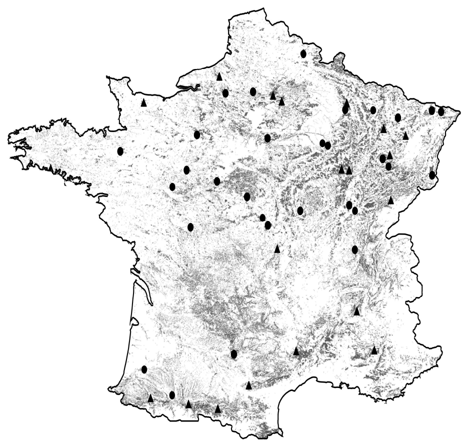

Figure 1: RENECOFOR forest network: location of the deciduous broadleaf forest stands (dots=oaks stands, triangles=beech stands. Grey area represents the Corine Land Cover 2006 broadleaf forest class.

Forest phenological observations are carried out annually since 1997 over the whole French Permanent Plot of the European Network for the Monitoring of Forest Ecosystems (RENECOFOR, see Figure 1).

Table 1: Detailed geographic characteristics of the 46 RENECOFOR deciduous broadleaf forest plots (O=oak, B=beech).

Plot	Tree Age (year)	Long. (°)	Lat. (°)	Elevation (m)	Slope (%)
O1	149	4°18'E	48°20'N	115	0
O2	61	0°50'W	43°44'N	20	5
O3	85	0°01'W	47°27'N	57	0
O4	115	5°46'E	49°01'N	220	0
O5	85	3°45'E	50°10'N	149	3
O6	69	0°02'W	43°12'N	370	12
O7	50	6°12'E	47°52'N	240	0
O8	82	5°14'E	46°58'N	190	0
O9	103	5°14'E	46°10'N	260	3
O10	130	2°43'E	46°40'N	260	0
O11	98	4°27'E	48°17'N	160	0
O12	93	2°07'E	47°15'N	176	1
O13	102	5°04'E	47°04'N	220	0
O14	70	1°30'E	49°21'N	175	0
O15	116	1°32'W	48°10'N	80	0
O16	107	1°15'E	47°34'N	127	0
O17	154	4°57'E	49°02'N	180	2
O18	100	6°29'E	48°52'N	315	4
O19	143	7°27'E	49°00'N	320	15
O20	76	3°39'E	46°58'N	270	7
O21	75	2°18'E	49°23'N	55	1
O22	103	0°40'E	48°31'N	220	5
O23	152	7°28'E	47°41'N	256	0
O24	79	0°22'E	47°47'N	170	0
O25	113	1°44'E	44°02'N	300	18
O26	97	0°29'E	46°37'N	116	4
O27	144	6°02'E	48°01'N	330	0
O28	91	7°43'E	48°59'N	350	10
O29	128	2°43'E	48°27'N	80	0
B1	68	3°07'E	49°12'N	145	0
B2	102	2°59'E	46°11'N	590	15
B3	103	5°48'E	44°07'N	1300	50
B4	167	1°16'E	42°55'N	1250	32
B5	98	0°51'W	49°10'N	90	4
B6	143	4°51'E	47°48'N	400	3
B7	56	6°16'E	47°11'N	570	2
B8	173	5°17'E	44°55'N	1320	12
B9	158	3°32'E	44°06'N	1400	25
B10	121	5°04'E	47°47'N	440	0
B11	104	5°00'E	49°10'N	250	0
B12	77	2°52'E	49°19'N	138	0
B13	82	0°39'W	43°09'N	400	44
B14	175	0°26'E	43°01'N	850	25
B15	102	1°19'E	49°42'N	210	0
B16	123	2°10'E	43°24'N	700	0
B17	83	6°14'E	48°06'N	400	3

This network encompasses a wide range of bioclimatic conditions of France, from oceanic to Mediterranean and from continental to high elevation mountain context. A subset of this network is composed by 49 stands of 0.5 ha of pure deciduous broadleaved forests. Stands are mostly managed has even-aged high forests (106 years on average, Table 1). *Quercus sp.* stands are mainly sampled in the northern part of France and homogeneously regarding to longitude. *Fagus sylvatica* stands are located in north-eastern plains and in southern French mountains. Average elevation is 200 m [20-370 m] for oak plots and 615 m [90-1400 m] for beech plots (Table 1).

Each year, the same 36 trees/plot are monitored and phenological key stages are recorded weekly in Julian days by local foresters. In spring (March-June), the onset and the end of the green-up phase are defined when leaf-unfolding occurred on 10% and 90% of the trees (hereafter reported as LU10% and LU90%). The same approach is achieved during the autumn season (September-November) for the leaf colouring stages (LC10% and LC90%). For consistent analysis, we selected the 46 stands (17 beech stands and 29 oaks stands, see Table 1) where at least 7 years were effectively observed during the decade 1998-2007 (63% were observed every year of the whole period). Inter-annual average of ground observations dates were plotted against each phenological metrics given by both remote sensing products and simple linear regression was computed. Difference between ground and remotely sensed data was reported as bias and the RMSE was used to evaluate the average satellite records uncertainty relative to in-situ observations.

2.3 Forest Cover

Cross-sensor validation was investigated at the national scale for all broadleaf forests and for each studied tree species. To this end, comparative analysis was conducted on image subsets to avoid mixture of landcover classes in a same pixel. As no accurate tree species map was available on this spatial extend, we first used the latest version of Corine Land Cover 2006 to identify pixels covered by a majority of broadleaved forests. Then, we took advantage of the National Forest Inventory database over the period 2005-2008 (9080 NFI plots network based on a systematic sampling design) to locate pure beech or oaks forests. Finally, we combined those data for each tree species to select pixels covered by at least 95% of broadleaved forest (Broadleaf) and for which the NFI observations where pure tree species (Oaks and Beech). Because of different spatial resolution pixels selection was repeated for each remote sensing product.

3 RESULTS AND DISCUSSION

3.1 In-situ comparison

All phenological indicators of both products were compared with ground measurements. For the leaf unfolding phase, significant relationships could only be retrieved using OGa and Dbefore indicators for MODIS and GLOBCARBON respectively (Table 2). The earlier stage of leaf unfolding (LU10%) is overestimated by both indicators with a systematic error greater than 10 days. At the end of this phenological stage (LU90%) bias is reduced by 10 days, ranging from 1.6 to 12.6 days. Bias and RMSE are always lower for OGa as compared to Dbefore. Soudani et al. (2008) also found that OGa is a good marker of leaf unfolding stage with the earlier version of the product (MOD12Q2, bias = 7.5 days as compared to LU90%). Improved result reported here on the same plots (bias= 2.2 days for LU90%) can be due to the longer time series but also the higher spatial and temporal resolution of the MCD12Q2 product.

Better predictions of the LU90% stage are reached if beech stands are considered separately. Bias is then better for beech (1.6 and 5.4 days) than for

Table 2: Regression analysis in mean Julian days between in-situ observations of leaf unfolding dates (LU10% and LU90%) and satellite-based phenological dates (OGa for Modis and Dbefore for GLOBCARBON). Values shown in bold are Pearson's coefficients of correlation statistically significant at 5% probability level.

		Oaks (n=29)		Beech (n=17)		Broadleaf (n=46)	
		Modis*	GlobCarbon**	Modis*	GlobCarbon**	Modis*	GlobCarbon**
In-situ LU10%	r^2	0.08	0.01	**0.58**	**0.21**	**0.41**	0.03
	Bias	13.8	23.8	10.05	13.8	12.4	20.0
	RMSE	15.2	26.3	12.75	15.0	14.6	22.3
In-situ LU90%	r^2	0.01	0.05	**0.47**	**0.27**	**0.23**	**0.10**
	Bias	2.6	12.6	1.6	5.4	2.2	9.8
	RMSE	8.0	17.0	6.9	8.0	8.0	13.8

* *OGa : Average date of Modis Onset Greenness Increase and Onset Greenness Maximum*

** *Dbefore: Day before the highest first derivative of LAI curve reach 90% of its maximum.*

oaks (2.6 and 12.6 days) for OGa and Dbefore respectively. Those tree species discrepancies can be related to the potential mixture of different oaks species (and/or understory species) which may affect the spatial phenological variability within a pixel considered her as “monospecific”.

Neither MODIS nor GLOBCARBON products can reflect dates of foliar discoloration of tree senescence phase (no correlations with ground data). However, we find that MODIS EVI area can be used as a proxy of the annual length of the growing season (computed as LC90%-LU10%, n=46, R^2=0.35, p=1.6 e10^{-5}).

Overall, in-situ comparison shows higher estimations accuracy for MODIS product than GLOBCARBON and for beech forests as compared to oaks ones. Difference in spatial and temporal resolution can be invoked to explain lower accuracy level of the GLOBCARBON estimates as compared to MODIS. Another uncertainty source affecting the GLOBCARBON product might concern the LAI estimation which is based on the GLC2000 land cover map. Nethertheless, both of the satellite-based LU90% estimation accuracy are of the same order of magnitude than in-situ observations which are carried out on a weekly basis.

3.2 Spatiotemporal trends

On a wider dataset (NFI plots, Table 3), the correlation between the two satellite-based average leaf unfolding dates (OGa vs Dbefore) are low even if they are highly significative. As previously observed (Cf. Table 2), OGa indicates leaf unfolding dates of about 5 days earlier than Dbefore. Nevertheless, cross-product comparison shows a similar bias and accuracy level irrespective to tree species.

Table 3: Cross-comparison on specific NFI plots of the average leaf-unfolding date from MODIS OGa and GLOBCARBON Dbefore (see Table 2). Correlations are statistically significant (p<0.0001).

	Oaks	Beech	Broadleaf
n	816	349	17684
r^2	0.01	0.20	0.12
bias	5.4	5.8	5.4
RMSE	8.3	8.9	8.9

In spite of those differences, similar spatial trends can be retrieved. Leaf-unfolding maps reveal spatially consistent results, even for high elevation forests such as beech ones (Figure 2A). This altitudinal trend is quantitatively in accordance with ground observations of Vitasse et al. (2009) and further with satellite-based study of Guyon et al. (2010) on the French Pyrénées Mountains. They report a similar trend of 1 day / 100m, just as the slope of Dbefore against elevation (Figure 2A right). This also confirms analysis of Lebourgeois et al. (2010) who found on the RENECOFOR network that elevation is the first spatial component driving unfolding trait. Because of a wider distribution range, a latitudinal variation of spring phenology (1.2 day/°) can also be retrieved within oaks forests (n=621, r^2=0.03, p<0.0001), also reported by Ducousso et al. (1996). Figure 2B shows that both satellite products correctly depict interannual phenology variability except for the year 2006 for which Dbefore reach peculiarly high values. As compared to in-situ annual observations, the best prediction is achieved for beech forests using the MODIS OGa indicator.

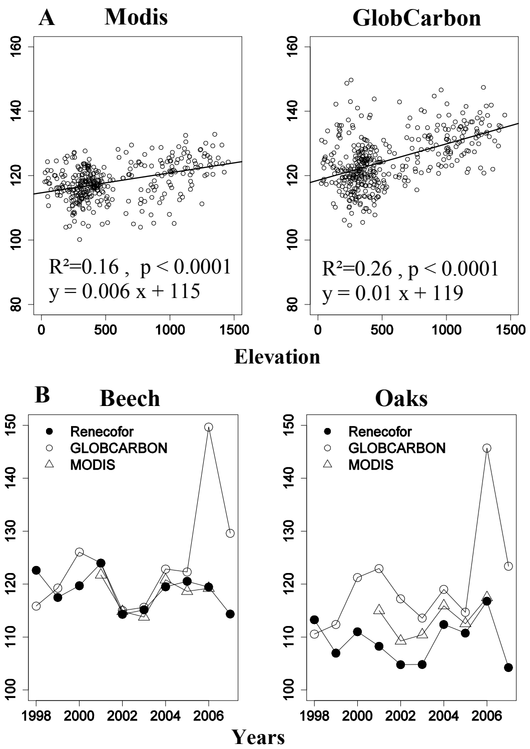

Figure 2: Satellite-based average leaf-unfolding dates (OGa, Dbefore) over specific NFI plots. A: regression analysis for beech forests against elevation (m). B: specific interranual variations. RENECOFOR LU90% records by species are also plotted.

4 CONCLUSION

Because of high variability of landscape feature but also because of the heterogeneity of climate change throughout France (Planton 2008), there is a clear expectation for different regional phenological responses. Those first results are promising and show the relevance and the spatial consistency of the medium spatial resolution for tracking regional trends in forest phenology. MODIS tends to provide more accurate estimates of leaf unfoldfing dates than GLOBCARBON but these conclusions are closely dependant of ground data observations at the plot level. Discrepancies between phenological responses of tree species emphasize the need for accurate forest type mapping. Further sub-pixels analyses have to be performed to better take into account for tree species composition in forest landscapes.

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