LONG-TERM MEASUREMENTS OF PLANT PHENOLOGY OVER EUROPE DERIVED FROM SEAWIFS AND MERIS

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ABSTRACT

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and the Medium Resolution Imaging Spectrometer Instrument (MERIS) provided accurate spectral measurements which have been used for deriving terrestrial geophysical parameters such as the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR). This paper examines plant phenology over the European domain over the last 14 years using FAPAR derived from SeaWiFS data (1998-2002) and MERIS (2003-2011). The analysis first focuses on the definition of a method to extract key phenological variables from space-derived FAPAR. Various vegetation phenological metrics, including the start, the length and the end of growing season have been then computed over Europe. The performance of FAPAR-derived phenology metrics have been checked by comparing them against ground-based observation over ecological sites (i.e. Fluxnet and PEP725). Results suggest that plant phenology derived from earth observation agrees well with that of in-situ measurements, although quantifying the end of the growing season presented some uncertainties.

1. INTRODUCTION

Vegetation responses to climate change relies on records of plant phenology that are often limited to particular species and locations [1]. Given the restrictions on the limited geographical scope and on the costs for recurring surveys, many researchers have used available satellite remote sensing instead. Earth Observation from space offers the unique opportunity to assess the state and changes of vegetation dynamics [2] providing data of large areas and long periods, at spatial and temporal sampling frequencies that are suitable to detect key phenological events [3]. Assessing the timing of and possible trends in these phenological events is critical to understand and predict how the biosphere interacts with the atmosphere through the carbon, water and energy cycles [4]. Knowledge of phenology is still limited: recent advances in phenology have been made in the detection of the start of growing season, but determining the end of growing seasons (and consequently the growing season lengths) remains complex and challenging. The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), a recognized Essential Climate Variable from satellite remote sensing, is used here as the empirical basis to estimate phenology. This dimensionless variable - varying between 0 and 1- is directly linked to the photosynthetic activity of vegetation, and therefore, can monitor changes in phenology. The properties of FAPAR thus concern a large number of users through such applications as forestry and environmental monitoring and can be used to identify the spatio-temporal patterns of vegetation dynamics over Europe.

In this study several metrics of vegetation phenology have been derived from FAPAR time series to characterize annualy the timing of the start, the end and the length of the growing season. The pertinence of these phenology metrics is evaluated through comparisons with historical records of in situ observations, recognizing that point measurements on the ground may not adequately represent the environmental variability generally present in areas of the order of 1 km^2. Such comparisons have been made against data obtained from two networks of field stations: PEP725 [5] and FLUXNET [6].

2. FAPAR-DERIVED METRICS

2.1 JRC-ESA-FAPAR

The FAPAR time series used in this study is derived from near daily observations of NASA/Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and ESA/Medium Resolution Imaging Spectrometer Instrument (MERIS) at spatial resolutions of 1.5 km and 1.2 km, respectively [7]. The FAPAR records have been re-sampled into grids of ~1 km (longitudinal sampling interval = 0.016°, latitudinal sampling interval = 0.011°). The same compositing algorithm [8] is applied to the products from both instruments to generate dekadal (sequences of nominally 10 consecutive days) estimates from the original (daily) values. In order to obtain a homogeneous dataset through the entire time period the observations from both sensors have been harmonized since simultaneous SeaWiFS and MERIS measurements revealed a small difference on FAPAR measurements between two sensors [9].

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2.2 Methods

Jung et al. [10] proposed a method that has been used to calculate four phenology indicators for each calendar year: maximum FAPAR, mean FAPAR, Growing Season Length (GSL), background (BG). In addition to these parameters, this study also presents a simple method to calculate the Start of Growing Season (SGS) and the End of Growing Season (EGS) (see Fig. 1).

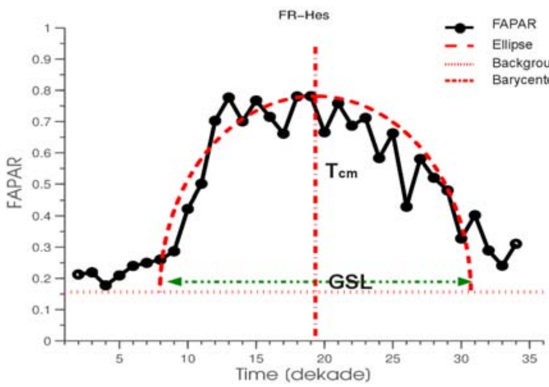

Figure 1. Illustration of the method used to retrieve the metrics from FAPAR over the FLUXNET site of Hesse Forest Sarrebourg (FR -Hes) during 2009.

The background value (BG) is first calculated as the 20% of the maximum value of the FAPAR time series for each pixel for each calendar year. FAPAR generally may not decrease to zero because of the vegetated background below the canopy. Hence BG value is typical for nongrowing season conditions. Note that originally (i.e. in [10]) the BG value was equal to the 10^{th} percentile of the annual FAPAR time series, and the value given here is the result of a sensitivity analysis that tested the effectiveness of this threshold.
Secondly, the length of the growing season (GSL) has been approximated by assuming that the FAPAR record is shaped like half of an ellipse (Eq. 1) and Fig. 1. Given the area of the ellipse (twice the cumulated FAPAR above the BG) and the major axis of the ellipse (annual maximum FAPAR minus BG), the minor axis of the ellipse– i.e. the growing season length - can be calculated.

$$GSL = \frac{4 \cdot CUM_{BG}}{\pi \cdot D} \qquad (1)$$

where CUM_{BG} is the sum of FAPAR records of a year after the subtraction of the BG value. D is the maximum FAPAR value of a year minus the background, GSL is the growing season length.
SGS is calculated as the difference between the timing of the centre of mass of the FAPAR profile, indicated by T_{cm} in Fig. 1) and half of the GSL (Eq. 2). The centre of mass is the point at which all the FAPAR can be "concentrated" for the purpose of calculating the "first moment". $FAPAR_i$ is the FAPAR value of the i^{th} dekade (i.e. ten days period), with i ranging from 1 to 36.

$$SGS = \frac{\sum_{i=1}^{36} FAPAR_i \cdot i}{\sum_{i=1}^{36} FAPAR_i} - \frac{GSL}{2} \qquad (2)$$

Similarly the End of Growing Season (EGS) is estimated as the sum of the date of the centre of mass and half of the GSL (i.e. the ending point of the elliptical arc).
This method relies on the simmetry between the start and the end of the growing season with respect to the date of the barycenter and on the hypothesis of half-ellipsoidal shape of the profile. By employing this geometrical solution the issue of double peaks of FAPAR during the growing season has been skipped. As the presented method assumes that each vegetation cycle falls in a calendar year, specific improvement of this processing is therefore needed to track phenological timing globally (e.g. in the tropics).
Although not shown in this paper, a statistical analysis on uncertainties of phenological metrics has been carried out. Thus, for each metric, we also have the corresponding uncertainty in terms of time.

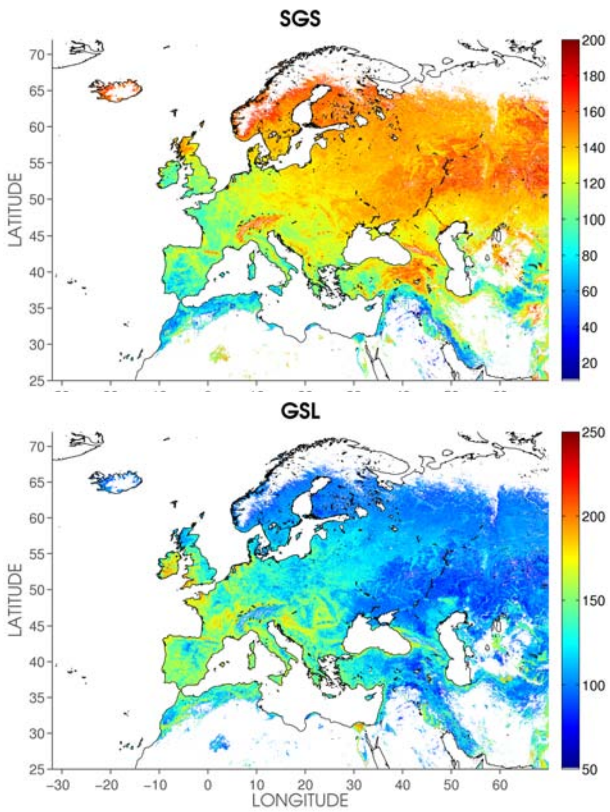

Figure 2. Spatial distributions of the climatological mean over 1998-2011 of the (top) SGS [day] and (bottom) GSL [day].

The three phenology metrics have been calculated for each year from FAPAR time series. Fig. 2, showing the climatological mean over 1998 - 2011, depicts the spatial patterns of the Start of Growing Season and the length of growing season.
The Start of the Growing Season typically falls between day 60 and 180 within the calendar year (early March to end of June), with high spatial variability. Growing seasons tend to start earlier than the European-wide average in southern and south-western Europe (in particular around the Mediterranean basin), and later than average in high-latitude or high altitude regions such as Scandinavia or the Alps. SGS exhibits a strong dependence on both latitudinal and longitudinal gradient. The Growing Season Length, a complementary measure to SGS, exhibits mean lengths of 150 days over Mediterranean regions, and 120 over eastern Europe.

3. GROUND-BASED OBSERVATIONS

3.1 PEP 725 Database

Field observations on phenological cycle are provided by the Pan European Phenology PEP725 project. PEP725 is a project funded by ZAMG (the Austrian ministry for science & research) and EUMETNET (the network of European meteorological services) to establish an open access database with plant phenology data sets for science, research and education.
This database provides observations acquired in Europe, although records are unevenly distributed. Central Europe has a rather well developed network of phenological stations, whereas the rest of the continent has generally only a few stations.
The dataset used for this study starts in 1998 and ends in 2011, and consists in 8092 stations. The Start of the Growing Season was defined as the leaf unfolding (defined as "code 11" in the PEP725 measurements' protocols), while the End of Growing Season was associated with the autumnal colouring (defined as "code 94" in the PEP725 measurements' protocols). Note that PEP725 measurements' protocols have been defined according to the BBCH scale (i.e. Biologische Bundesanstalt Bundessortenamt Chemische Industrie), which classifies phenology events on the base of a standardized system.

3.2 FLUXNET

An additional evaluation of the phenology metrics is conducted by comparing remotely sensed (hereafter RS) start and end of season with phenological metrics extracted from CO_2 flux data time series. FLUXNET dataset has been used to this purpose. Using the method proposed by [11] and [12], the start and end of the growing season have been retrieved from the CO_2 fluxes.
First of all, eddy covariance measurements of Gross Primary Productivity (GPP) have been standardized, gap-filled and partitioned. Later, daily GPP measurements have been scaled, such that the 5^{th} percentile is equal to zero and the 95^{th} percentile is equal to one.
Then, cubic smoothing splines have been fitted to the time series of daily GPP. Finally, from the smoothed daily data, day of year (DOY) corresponding to the start (end) of the season have been identified as the day at which the scaled GPP exceedes (drops below) 20% of the peak of the scaled GPP. It should be noted that the phenology metrics from FLUXNET are based on CO_2 flux measurements, which in turn provide spatially integrated data that are in turn diagnostic of ecosystem phenology. The comparison of FLUXNET retrievals with RS observations has been limited to the FLUXNET sites with the highest degree of spatial homogeneity in order to minimize the effect of the scale mismatch. Following the method proposed by [13], high resolution images have been used to evaluate site spatial homogeneity and inspect the representativeness of the tower footprint in the SeaWiFS/MERIS pixel.
After removal non homogeneous sites, the resulting dataset consists of 42 sites: 5 for deciduous broadleaved forests (DBF), 13 sites for Evergreen Needleleaved Forests (ENF), 7 for Cropland (CRO), 3 for Evergreen Broadleaved Forests (EBF), 14 for Grasslands (GRA).
The dataset used for this study starts in 1998 and finishes in 2006. Note that the FLUXNET dataset is shorter than the FAPAR timeseries, due to the lack of CO_2 flux measurements enabling the production of phenological variables.

4. COMPARISONS

Performances of start and end of growing season are evaluated by comparing them against ground observation. Fig. 3 shows the scatter-plots and histograms of differences between satellite-derived and direct records from PEP725 database.
A perfect matching would collapse all points on the 1:1 line. The bin number in both axes is equal to five days. The colour scale on the left plot indicates the occurrence of the two distributions; the blue colour corresponds to a limited number of measurements whereas the red colour indicates the maximum number. Each panel in these figure also reports the sample size (N), the mean absolute (δ) and the standard deviation (σ) of the differences between RS and in situ records, whereas the histogram of all measurements differences [day] is plotted on the right.
Top panel of Fig. 3 shows the comparisons between the in-situ records and RS Start of Growing Season observations. δ between the values given by RS and in situ is equal to 7.9 days.

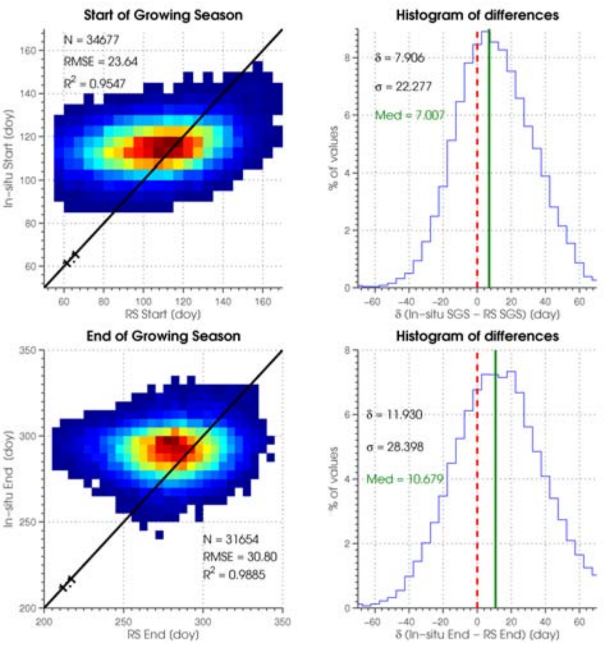

Figure 3. Scatter-plot and histogram of differences for (top) Start and (bottom) End of Growing Season acquired between 1998 and 2011 using PEP725 in-situ measurements and RS-derived products.

The histogram shows a near Gaussian distribution of differences centered on a value of 7 days. σ takes value of 22.3 days, whereas R^2 is equal to 0.95. Bottom panel of Fig. 3 shows how the End of Growing Season compares according to the method described before (i.e. , autumnal colouring). δ is equal to 119 days, while σ amounts to 28.4 days. R^2 is equal to 0.98.

The analysis of the scatter-plots reveals that all the performance indicators of the Start of Growing Season, when compared with those of the End of Growing Season, are better with the exception of R^2.

Evaluation of phenology metrics is also carried out over FLUXNET sites (hereafter GPP or FLUXNET-derived metrics). In this case - for synthesis purposes - figures showing how the phenology compares according to the methods described before (i.e., scatterplot and histogram of differences between RS-derived and FLUXNET-derived metrics) have been omitted, whereas the corresponding statistics have been presented in the following paragraph. It is worth noting the small dimension of FLUXNET dataset. Indeed, the number of measurements provided by the PEP725 is two orders of magnitude larger than those provided by FLUXNET.

The Start of Growing Season exhibits the best correlation, while the End of Growing Season generally provides the worst performances. δ varies in the two cases from -0.7 days (SGS) to -4.5 days (EGS). The corresponding standard deviation of differences (σ), takes value from 27 days (SGS) to 32.6 days (EGS), respectively. R^2 goes from 0.91 (SGS) to 0.98 (EGS).

The number of measurements over FLUXNET sites, definitely smaller than those from PEP725, allows a different visualization of the results: Fig. 4 shows phenology comparison across different Plant Functional Types (PFT).

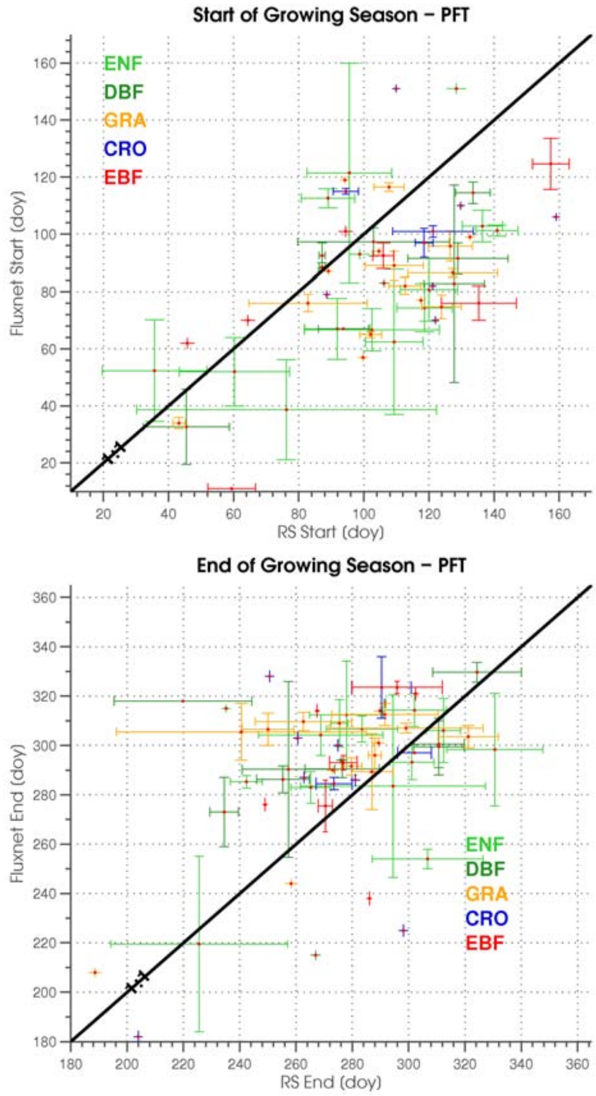

Figure 4. Scatter-plots with error bar of FLUXNET and RS product for (top) Start and (bottom) End of Growing Season over different Plant Functional Types (PFT).

For each site the dot represents the time average, while the error bar represents the temporal standard deviation of both RS observation and GPP-derived measurements. Each PFT is represented with different colour. The different number of measurements for the SGS and for the EGS (i.e. 124 for SGS and 144 for EGS) is associated to the presence of outliers in FLUXNET-derived metrics. In particular, SGS (EGS) measurements beginning in the first (last) dekade (i.e.

10-day period) of the year have been discarded (these values are the results of a analysis - not shown here - that assessed the efficacy of FLUXNET-derived metrics).

Table 1: Performance statistics (RMSE, R^2 and Bias) of Start of Growing Season and End of Growing Season for different Plant Functional Types (PFT).

PFT	Start of Growing Season		
	RMSE [day]	**R^2**	**Bias [day]**
ENF	37.392	0.840	-20.793
DBF	24.188	0.921	-18.145
GRA	29.798	0.880	-21.421
CRO	34.178	0.891	-17.093
EBF	32.640	0.848	-17.946
	End of Growing Season		
	RMSE [day]	**R^2**	**Bias [day]**
ENF	32.129	0.988	-9.994
DBF	36.288	0.985	0.890
GRA	21.312	0.995	-1.306
CRO	44.423	0.976	-8.743
EBF	52.241	0.965	-16.962

Tab. 1 shows the performance statistics (RMSE, R^2 and Bias) of start and end of growing season for different PFT. The best results come from Deciduous Broadleaved Forest that presents the best ensemble of performance statistics. Conversely, Evergreen Needleleaf Forest andEvergreen Broadleaf Forest have among the worst results for SGS and EGS respectively. These results are consistent with previous findings [14].
The statistics also suggest a strange behaviour of grassland (GRA): this PFT maintains reasonably good results with the EGS, conversely, SGS' statistics are very poor. Relative to grassland it is reasonable to assume that the fragmentation and the richness of different species within the same site emphasizes the mismatch between FLUXNET and satellite footprint. Cropland on the one hand got reasonably good results for SGS, on the other hand got notably poor results for EGS, probably due to different "cutting schedule" within the same site.
Results from these evaluation exercises suggest that the PEP725 records are comparable to remotely sensed phenology. Comparing statistical indicators of Fig. 3 and 4 and Tab.1 it is possible to observe that generally PEP725 exhibits the highest correlation, conversely, FLUXNET the lowest one although the spatial homogeneity in MERIS/SeaWiFS pixel. This difference is mainly due to the methodology: PEP725 database is made up exclusively of direct observations, whereas FLUXNET metrics rely on “threshold”. This implies that the "threshold" method inherent in FLUXNET-derived phenology may be the major limitation.

5. CONCLUSION

In the present study, one of the the most extensive Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) dataset derived from SeaWiFS and MERIS sensors has been analyzed to quantify the spatial and temporal vegetation dynamics over Europe for the period 1998 –- 2011.
Various metrics on vegetation phenology have been derived from the FAPAR time series. The pertinence of these phenology metrics is evaluated through comparisons with historical records of in situ observations. Comparable phenology from both PEP725 sites and from FLUXNET CO_2 measurements have been retrieved, although the numerous and strong hypothesis behind the methodology.
The results, hence, stress the convenience of developing a protocol to link ground phenological observations to satellite measurements, as pursued by the Phenology Focus Group of the Committee on Earth Observation Satellites (CEOS).
This paper incorporates issues already discussed in [15], where spatio-temporal variability of vegetation dynamics has been studied (including the identification of the spatial patterns in phenological metrics and the corresponding trends).
Similar studies with the FAPAR derived from the future Ocean and Land Color Instrument (OLCI) on board Sentinel-3 and from the past Advanced Very High Resolution Radiometer (AVHRR) sensor will serve for continuously monitoring the phenology.
The results obtained from this study can be extended to the future studies of global environmental change.

6. ACKNOWLEDGEMENTS

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