MODIS EVI, NDVI, WDRVI, DAILY AND COMPOSITE: LOOKING FOR THE BEST 1 CHOICE TO ESTIMATE PHENOLOGICAL PARAMETERS FROM DECIDUOUS FORESTS

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MODIS EVI, NDVI, WDRVI, DAILY AND COMPOSITE: LOOKING FOR THE BEST CHOICE TO ESTIMATE PHENOLOGICAL PARAMETERS FROM DECIDUOUS FORESTS

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ABSTRACT

Surveying forest phenology through time helps evaluating climate change effects on ecosystems; Vegetation Indices (VIs) time series (TS) from MODIS imagery are key instruments to this. The objective of this work was to find the best combination of VI and MODIS data to estimate starting of season (SOS) dates on broad-leaved, temperate forests. We generated TS of EVI and NDVI and four WDRVI implementations using daily reflectances from MOD09GQ/MOD09GA products and 16-day composite VIs from the MOD13Q1 dataset from 2001 through 2012. MODIS-based SOS estimations were compared with phenological ground observations from the 50 broad-leaved plots of the RENECOFOR French forest network. Results showed that the use of composite TS led to estimations as good as daily TS. EVI, NDVI and, sometimes, $WDRVI_{0.20}$, were the best estimators of advanced SOS; moreover, SOS best matched ground observations respective to EOS in all comparisons.

Index Terms— MODIS, phenology, daily vs. composite TS, acquisition dates, EVI - NDVI - WDRVI.

1. INTRODUCTION

Phenology has been defined by the United States International Biological Program Committee as the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species [1]. Accurate monitoring of large areas' phenology allows to evaluate how climate change is affecting vegetation and biogeochemical cycles' dynamics. Phenological field surveys demonstrated that phenological phases in temperate forests can begin and totally develop in a few days (7 to 33 days, according to various authors, e.g. [2],[3],[4],[5],[6]). In addition, the inter-annual variability of phenophases' timing is very low if evaluated along prolonged temporal periods (-0.2 to -5.1 days per decade on average, i.e. -0.7 to -17.8 days as absolute difference from the average bud burst day over 35 years in boreal forests [7]).

These and other field data set an important objective to the remote sensing (RS) phenology-oriented scientific community, i.e. the estimation of the timing of phenophases with algorithms and data precise and accurate enough to generate results comparable with those from ground surveys. To achieve this objective, a number of methods has been developed.

The most common algorithms are based on least-square fitting of vegetation indices (VIs) time series (TS). According to several authors, the best results are obtained based on least-square fitting of logistic functions to VIs TS ([8],[9]), since vegetation phenology is responsive to cumulate daily temperature, that can be represented by a logistic function ([10] [11] [12]). A number of logistic functions have been developed ([13] [14] [15] [16] [12]) and the main differences among them is the number of fitting parameters (four to eight). Hmimina et al. [15] improved the function proposed in Soudani et al. [16]; such a function is based on the equation proposed by Zhang et al. [12] and is similar to the one presented in Fisher et al. [14] [16]. Usually, Start of Season (SOS) and End of Season (EOS) dates can be extracted from the fitted function as the left and right inflection point, respectively, and a good agreement with ground data can be obtained [15] [16].

MODIS imagery's most interesting feature is its daily temporal resolution. Because of this, MODIS data are supplied as both daily reflectances and composite VIs (Normalized Difference Vegetation Index (NDVI) and

Enhanced Vegetation Index (EVI)). Daily data are supposed to have greater temporal resolution, but they are noisier than composite data. The noise in daily TS and lack of values during critical phases (i.e. spring and summer) could affect the estimation of phenological metrics, making composite data potentially more suitable to forest monitoring. On the other hand, Testa et al. [17] found that a theoretical error of ± 7 days in the estimation of SOS and EOS could affect a significant number of pixels if 16-day composite data were not properly aligned in time based on acquisition dates.

Dynamic Range Vegetation Index (WDRVI, [14] [15]) has been proposed to linearize the NDVI-LAI relationship. It has not yet been widely tested to forest phenology monitoring since it was born for agricultural purposes. It is calculated as [18]:

$$WDRVI = \frac{\alpha \cdot NIR - red}{\alpha \cdot NIR + red} \tag{1}$$

or, directly from NDVI [19], as:

$$WDRVI = \frac{(\alpha + 1) \cdot NDVI + (\alpha - 1)}{(\alpha - 1) \cdot NDVI + (\alpha + 1)} \tag{2}$$

with α = [0.05, 0.10, 0.15, 0.20] [14] [15]. α is the coefficient that reduces the contribution of NIR to the VI's value, making the LAI-NDVI relationship close to linear [14].

As a test area and validation dataset, we used the records of the Réseau National de suivi à long terme des ECOsystèmes FORestiers (RENECOFOR) network. In particular, we focused on the 50 out of 102 plots covered by deciduous forests of *Quercus robur* L. (pedunculate oak, 9 plots), *Quercus petrae* (Matt.) Liebl. (sessile oak, 19 plots); and *Fagus sylvatica* L. (beech, 20 plots). In two plots, pedunculate and sessile oaks are mixed (Figure 1).

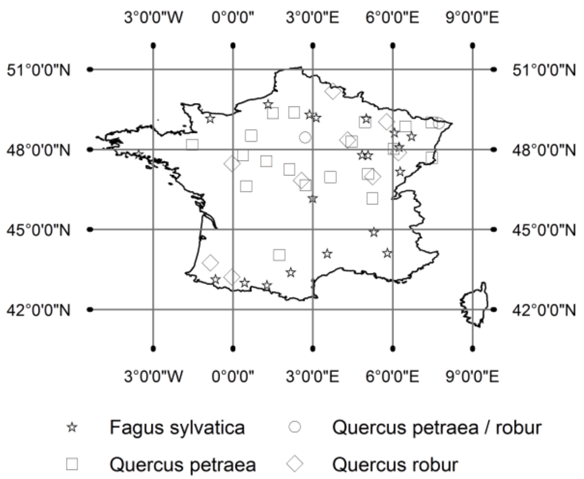

Figure 1. Species and geographic position of the 50 RENECOFOR plots we considered in this work.

In every plot, 36 same-species and almost coetaneous trees are fenced and monitored. For every plot, two SOS metrics and two EOS metrics are recorded, weekly, corresponding to the dates when 10% and 90% of each plot's trees have buds open or yellow leaves over at least [...] and 4 EOS metrics.

The first objective of this work was to find the best combination of VI and MODIS data to estimate SOS dates compared with ground observations. Secondly, we tested a procedure that allowed us to initialize the fitting parameters avoiding any arbitrary initialization that could potentially lead to erroneous estimations, making, moreover, different fitting algorithms reliably comparable one each other.

2. MATERIAL AND METHODS

In this study we generated 2001 through 2012 TS of MODIS Terra 250 m daily and 16-day composite NDVI, EVI and WDRVI. Daily NDVI and EVI were obtained from MOD09GQ daily reflectances; EVI's blue bands were extracted from MOD09GA 500 m dataset. TS were pre-cleaned removing low-quality and spurious values, according to quality assurance flags (different for daily and composite data). Daily and composite WDRVI TS were implemented from NDVI TS (Equation 2). For each case, we generated four WDRVI TS with α = [0.05, 0.10, 0.15, 0.20]. As shown in Figure 2, the lower is α, the stretched and low-shifted is WDRVI. Moreover, because of the slightly different slope of the fitted function during increasing and decreasing phases, shifting-in-time of inflection points is expected. Such a shift potentially affects SOS and EOS estimations.

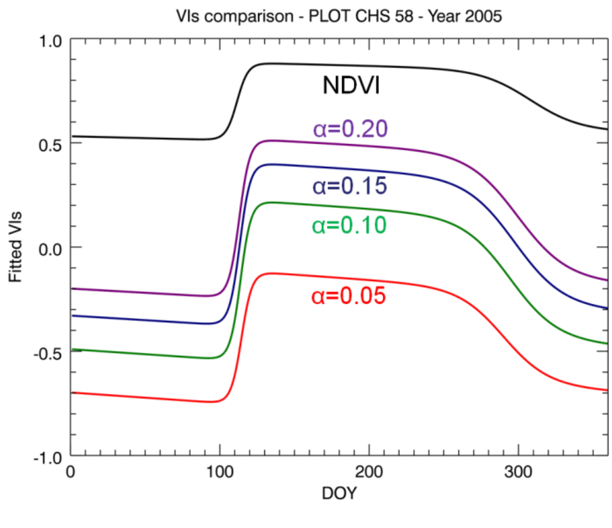

Figure 2. NDVI compared to the four WDRVI implementations. The

Composite TS were tested in four different forms: a) as they were after stacking (16-day $_{RAW}$); b) with values placed to actual acquisition dates (values not equidistant along TS, 16-day $_{AD}$)); c) corrected for acquisition dates but with equidistant values, as described in Testa et al. (16-day $_{AD-E}$) [17]; and, d) "projecting" each 23-images-long composite pixel/year into a 365 (366) days-long pixel/year, placing

$_{\text{DAILY}}$). This last case will be hereafter referred to as composite to daily. The median moving filter was not applied to this last case.

For each pixel/year, for each of the six VIs and for each TS case (i.e. filtered daily, 3 cases composite filtered, 3 cases composite not filtered, and composite to daily not filtered) we performed least-square fitting of the logistic function proposed in Hmimina et al. [15] and extracted SOS and EOS as the left and right inflection point, respectively. Hmimina et al. [15] proposed to estimate NDVI as follows:

$$NDVI_t = p \cdot t + (a + c) + \frac{1}{2}(a - c) \cdot tanh[b \cdot (t - \mu)] - \frac{1}{2}(a - e) \cdot tanh[d \cdot (t - u)] \quad (3)$$

where μ and u are the left and right inflection points respectively, that should best represent the SOS and EOS dates [15]. The left inflection point of the fitting function (assumed to represent the SOS date) corresponds to the maximum of its first derivative, while the right inflection point (EOS) corresponds to the first derivative's minimum and, both, to half of the increase above spring and autumn minima. Because of this, the two inflection points are equivalent to 0.50 thresholds in TIMESAT.

Fittings were performed according to a new procedure we developed. It makes the estimation of phenological parameters independent from user's initialization. We defined two temporal searching windows, one for SOS and one for EOS, both 135 days long (SOS: day of year (DOY) 50 through 185; EOS: DOY 210 through 355). Each value of each searching window (stepping by 3) was used to initialize a new fitting, ensuring that every SOS initialization was coupled with each EOS initialization. A total of (135/3)2 = 2,025 fitting were performed for each pixel/year. The fitting resulting in the minimum RMSE respective to the raw TS it was based on was selected to extract the inflection points dates.

SOS estimations were finally compared with the each of the 4 SOS parameters recorded within RENECOFOR in terms of average error (μ) and RMSE. In particular:

$$\mu = \frac{\sum_{i=1}^{n}(P_{ei} - P_{oi})}{n} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_{oi} - P_{ei})^2}{n - 1}} \quad (5)$$

where P_{ei} and P_{oi} represent the values of the parameters observed and estimated respectively for the i pixel/year and n was the number of available values. If $\mu < 0$, then MODIS-derived parameters were anticipated, else if $\mu > 0$ then estimates were delayed respective to ground.

from MODIS were instead those from the understory. We considered the theoretical precision of RENECOFOR data to be 7 days ±3.5 on average (corresponding to weekly sampling [16]).

3. RESULTS

Due to length constrictions, results cannot be extensively reported here. In general, MODIS-based estimations best agreed with the main species 90% flushing metric. EVI and NDVI performed generally better than WDRVIs, achieving the best agreement in all comparisons referred to the above-cited ground parameter. NDVI-based estimations were biased less than 1 day in all comparisons with RMSEs ranging 12 to 14 days. EVIs showed 1 to 3 days biases but lower RMSEs (10 to 12 days). Excluding daily and composite to daily implementations, $WDRVI_{0.20}$ performed similarly to EVI in terms of biases (3 days) and RMSEs (10 to 12 days). In daily and composite to daily TS, $WDRVI_{0.20}$ achieved RMSE as good as those from EVI TS, but with slightly higher biases. Table 1 reports μ and RMSE from the 5 datasets with reference to EVI, NDVI and $WDRVI_{0.20}$ referred to the Main Species Flushing 90% parameter.

Table 1. Average errors (μ) and RMSE achieved by our procedure respective to Main Species Flushing 90% dates from the RENECOFOR dataset.

TS	EVI		NDVI		$WDRVI_{0.20}$	
	μ	RMSE	μ	RMSE	μ	RMSE
Daily	3	11	1	13	5	11
16-day $_{\text{RAW}}$	2	12	0	12	3	11
16-day $_{\text{AD}}$	3	12	0	14	3	12
16-day $_{\text{AD-E}}$	2	11	0	12	3	10
16-day $_{\text{DAILY}}$	1	10	0	12	4	12

4.CONCLUSIONS

In general, our test could not achieve the theoretical precision of the RENECOFOR observation, as demonstrated by RMSE values greater than 7.

In our test area, the use of daily data did not lead to better results than composite data. In general, MODIS 16-day composite NDVI can be reliably used to investigate SOSs if TS are corrected with acquisition dates without making them equidistant, allowing a very reduced effort of computation time and data size respective to daily TS.

The use of composite, raw TS (16-day $_{\text{RAW}}$) is not orthodox since the temporal error introduced by omitting acquisition dates ranges 0 to 16 days: despite the slightly better average results 16-day $_{\text{RAW}}$ TS achieved in our tests, at the single plot/year scale performances may be much worse due to the above-cited temporal errors.

Good results for SOS estimation were obtained generating daily TS from composite data, but the little seconds to hours in our 50 pixel by 12 years case study).

The temporally corrected and equidistant 16-day $_{AD-E}$ TS, generated according to the procedure proposed by Testa et al. [17], allowed the best performances with all VIs based on 23 VI values per year. Considering the little computational amount the alignment-in-time procedure required, together with the good results achieved, we suggest the use of such a procedure in works aimed at forest phenology investigation, or, alternatively, the use of 16-day $_{AD}$ TS, that does not require additional pre-processing operations.

NDVI was the only VI that allowed unbiased estimations respective to ground phenological observations, but it scored 1 to 4 days-higher RMSEs respective to EVI or $WDRVI_{0.20}$.

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