Altitudinal variations of mountain forest phenology from SPOT/VEGETATION time series

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ALTITUDINAL VARIATIONS OF MOUNTAIN FOREST PHENOLOGY FROM SPOT/VEGETATION TIME SERIES

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ABSTRACT

The climate change is modifying phenology in a perceptible way. Thus, methods have been created to monitor phenology and its spatial dynamics at a broad scale for a low cost. This study focused in the Pyrenean forests using a PVI vegetation index provided by SPOT/VEGETATION sensors. The seasonal responses peculiar to deciduous broad leaved forest were obtained by disaggregating the signal for each land-use contained in each 1-km² pixel. Spatial distribution of the seasonal responses was consistent with elevation map. Ground phenological observations were used to calibrate a linear relationship which was then used to build a satellite-estimated budburst date map. Mean error between ground observations and budburst date estimated from satellite was smaller than a week. The budburst map showed great spatial consistency, thus, the method used was relevant for broad-leaved forests along the elevation gradient. These results pave the way for further research combining ground-based observations and remote sensing data in order to study temporal changes in the phenophases.

Keywords: Phenology, budburst, deciduous, forest, altitude, vegetation index, VEGETATION, disaggregation.

1 INTRODUCTION

Since 1976, climate has been undergoing a significant increase in temperature. Climate change can modify: the phenology and physiology of organisms, the species' geographic range, community composition and intra-community interactions, and the structure and dynamics of ecosystems. Among all vegetal species, tree traits – e.g. long life, low dispersal rate – are expected to be particularly sensitive. In this context, forested mountain ecosystems are well suited to understand and model adaptive processes, if any, resulting from climate change. Phenological modifications can be observed along the broad temperature gradient correlated to the large altitudinal gradient.

Ground observations are difficult to collect at a large scale as they are time consuming and costly (Menzel, 2002). In contrast, remote sensing medium resolution observations, which are suitable to study phenology on a large extent, have been available for some years now. These observations have mainly been used to conduct studies at the biome level on the continental scale (e.g. Zhou et *al*., 2001). New methods were developed to monitor the specific behaviour peculiar to each land use. The method of Cardot et al. (2004) is a promising one based on statistical spatial disaggregation of the radiometric signal of each pixel. Nevertheless, few studies have monitored spatial variations of phenology at a sub regional scale by incorporating the knowledge of local processes observable at ground.

The purpose of this study was to provide information about the spatial and seasonal dynamics of deciduous broadleaf forests in the French Pyrenees Mountains. Two issues are addressed: (1) analysing the spatial structure of phenological responses of deciduous broadleaf forests according to the altitudinal gradient from a multi-annual time series of VEGETATION/SPOT data (2) estimating and mapping the budburst date by calibrating budburst timing with ground based measurements in two valleys of the same area. Studies of temporal changes in the phenophases over a large range of elevations would then provide information about adaptation of forested areas in response to climate change.

2 MATERIALS AND METHODS

2.1 STUDIED AREA

The study area covers almost 10,000 km² of the Pyrenean region in South-West France (Longitude: 1.21°E – 0.24°W, Latitude: 42.6°N – 43.3°N). Forests cover a large range of elevation from 0 to 2,500 m. Oak (*Quercus sp*) and beech (*Fagus sylvatica*) are the main deciduous forest species.

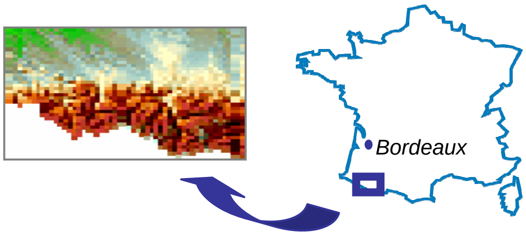

Figure 1. Location and relief of the study area

2.2 REMOTE SENSING DATA

A multi annual time-series of ten-day reflectance from 2002 to 2006 was used. It was produced from VEGETATION 1 and VEGETATION 2 daily data with the algorithms of Hagolle *et al.* (2004) which normalised the directional effects with Roujean's model (Roujean *et al.* 1992).

Perpendicular Vegetation Index (PVI, Richarson & Wiegand 1977) was calculated from red and near infrared reflectances, normalized at view zenith angle = 0° and at sun zenith angle at 10h30 UT. PVI was calibrated from soil line equation estimated by linear regression on the mean reflectance values per ten-day period during July and August over some pure bare rock pixels: PVI= 1.25NIR-0.75RED-0.07.

2.3 SPATIAL DISAGGREGATION

Because of its large size – nearly 1 km² – the VGT pixel includes generally several land-uses. As a result, the observed PVI ($X_i(t)$) is the combination of the ones specific to each land-use. To access the PVI seasonal variation linked to one particular cover type ($\rho_{ij}(t)$), the disaggregation of $X_i(t)$ is performed, based on the varying-time random effects model proposed by Cardot *et al.* (2004) (see Appendix).

Information on land use (π_{ij}) was provided by the geographical database Corine Land Cover CLC2000. On the studied area, 29 classes are represented. They were pooled together in 5 super classes: "No or sparse vegetation", "agricultural surfaces – i.e. crops, meadow – and transitional woodland", "Deciduous broadleaf forest", "Mixed forest" and "Coniferous forest". Only the results obtained for the broadleaf forest class were analyzed.

2.4 MONITORING OF A MEAN YEAR

To build a continuous phenological signal over the year, i.e. from the onset to the end of the vegetation growth, it was necessary to average the PVI of the 5 successive years per ten-day period. Due to the high cover of cloud and snow during winter and spring, the VGT time-series was incomplete at the early beginning and at the end of the mean year. Thus, the studied period was determined as March, 11 to November, 11. The pixels which are always cloudy or snowy in spring were removed; they were located mainly at elevation greater than 1,800 m in coniferous forests or in not forested areas.

The Cardot's algorithm was applied on the observed PVI of the mean year ($X_i(t)$). The parameters of B-spline functions were fixed as: interior knots number=5 and order=3. Figure 2 gives the order of magnitude of errors on the modelled individual responses and their seasonal variations. Residues are small between $X_i(t)$ and the modelled PVI ($\sum_{j=1}^{J} \pi_{ij} \rho_{ij}(t)$). Thus, the notion of mean year makes sense.

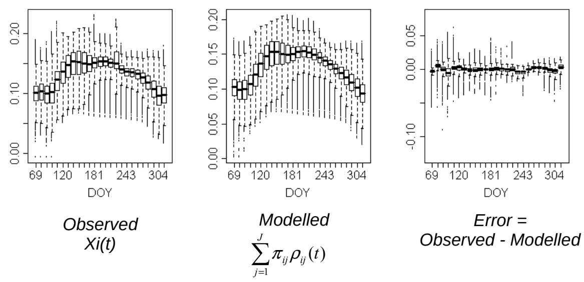

Figure 2. Error distribution on modelled individual responses of VGT pixels containing broad-leaved forest. Results for the mean year (2002-2006) with interior knots number=5 and order=3 for the B-spline functions. DOY=Day of the year

2.5 DIGITAL ELEVATION MODEL (DEM)

Elevation data at 90 m resolution coming from Shuttle Radar Topography Mission (USGS, 2005) were used to extract mean altitude of each VGT pixel.

2.6 PHENOLOGICAL OBSERVATIONS

Ground-based phenological observations were performed from 2005 to 2007 (see Vitasse, 2005 for methodology). Budburst dates were noted down every 10 days since early spring, over 31 plots located in two valleys (Luz and Ossau), on a gradient ranging from 100m to 1,600 m above sea level. Oak (*Quercus petraea*) is the species the most measured (i.e. 14 plots) along this gradient.

2.7. BUDBURST DATING

Budburst date of broadleaf forest was determined in two steps. First, an index of earliness (IE) was estimated. DOY_{Ref} denoted the mean budburst date observed for *Quercus* at ground. PVI_{Ref} denoted the PVI value on DOY_{Ref} on the average broad-leaved forest phenological curve ρ_j. DOY_{Ref} was equal to 116, i.e. April, 26. PVI_{Ref} was equal to 0.1297. Date for which individual PVI of the deciduous pixel (ρ_{ij}) equals PVI_{Ref} provided the IE of the pixel thanks to a linear interpolation between the 10-day periods. IE was normalized for varying from 0 to 1. In second step, linear regression between IE and ground-based budburst date, both averaged per altitude classes, was used for predicting the budburst date EbD. EbD was calculated over the study area and maps were produced.

3 RESULTS

3.1 MEAN PHENOLOGICAL CURVES.

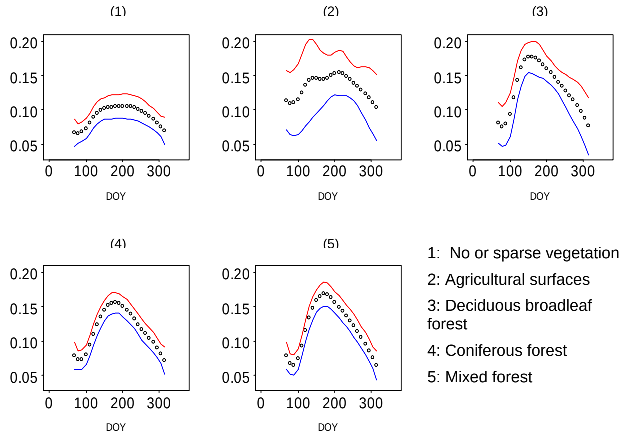

Figure 3. Estimated mean phenological curves (ρ_i) for each land cover type class ± 2 times instantaneous standard deviation, DOY=Day of the year

Figure 3 gives the mean phenological curves obtained for each land cover type class (ρ_j). “Deciduous broadleaf forest”, “Agriculture surfaces, and “Mixed forest” had the highest amplitude during the year. The greatest variability of PVI curves was observed with the two former classes, which regroup various crops, meadow kinds and forest species with different seasonal behaviours of the green leaf area. Coniferous had a low dynamics along the year. “No or sparse vegetation” seasonal variations had to be related to sun position, varying during the year.

3.3. INDIVIDUAL RESPONSES VERSUS ALTITUDE

K-means classification conducted over the deciduous forest allowed to pool individual phenological curves ρ_{ij} of similar shape (Fig 4). The obtained classes showed various phenological patterns. High altitude classes had the lowest PVI at beginning and at end of the cycle. Their seasonal amplitude was maximal. K-means classes located in plain had the highest PVI values at onset and end. The maximum value of PVI was reached earlier than in the cases of high altitude.

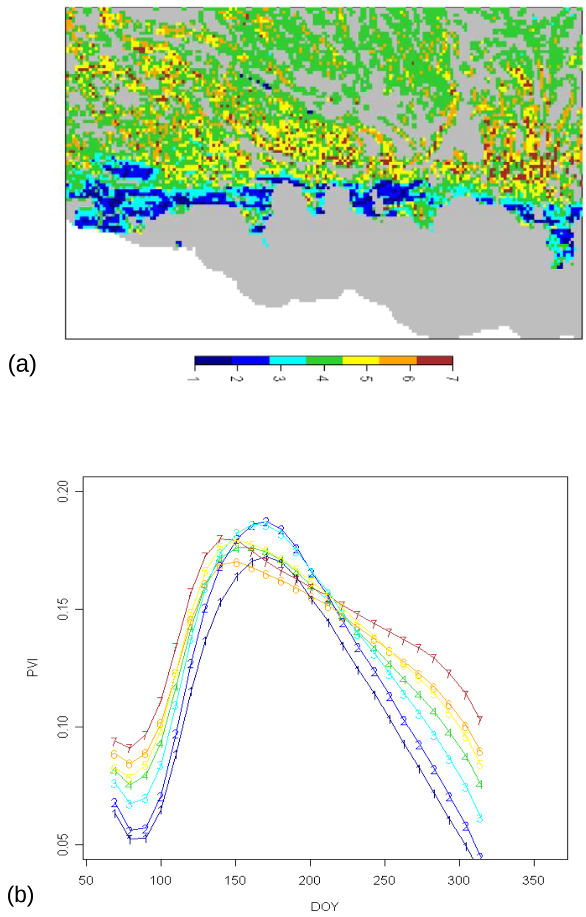

Figure 4. K-means classification of PVI phenological curves of deciduous broadleaf forest: (a) map of the 7 phenological classes. Grey: no deciduous forest or cloudy/snowy data. White: Spain (b) PVI phenological curves of class centres

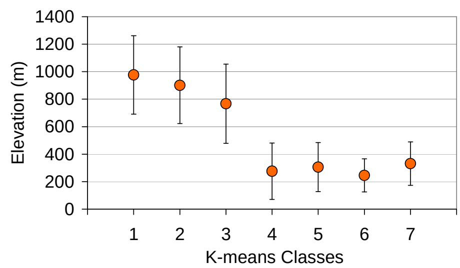

Figure 5. Distribution of elevation of K-means classes for broadleaf forest.

For each pixel, DEM altitude and K-means class resulting from yearly classification were compared. Average and standard deviation of altitude for each K-means class were calculated and plotted (Fig. 5.)

K-means classification revealed strong effect of elevation on spatial distribution of the seasonal dynamics of the PVI of deciduous forest.

3.5. BUDBURST DATE

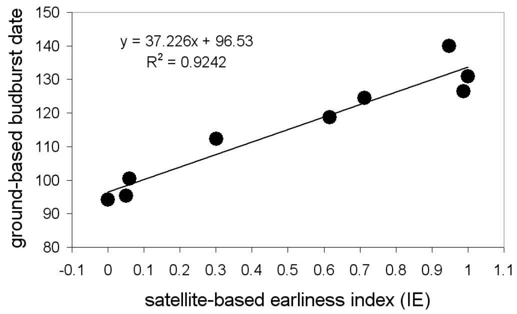

Figure 6. Linear regression between the satellite-derived index of earliness (IE) and the ground-based budburst date, both averaged per altitude classes.

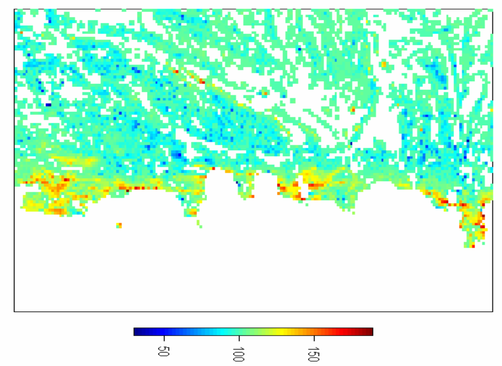

Figure 7. Satellite-based budburst date (EbD, day of the year) of broadleaf forest for the mean year (2002-2006)

A very strong linear relationship between IE and ground-based budburst date was found (Fig. 6). This regression was used for predicting the budburst date EbD. Its equation was: EbD= 37.226*IE+96.53. RMSE equalled 4.2 days. The spatial variability of the retrieved budburst date using this relationship is given in Figure 7.

4 DISCUSSION

Building a mean year in order to fill gaps can be criticized. The number of missing data per 10-day periods was variable in spring and may have a strong impact on a 5-year mean value. Despite this, the mean year appeared well modelled by the algorithm of Cardot *et al.* (2004) – i.e. with low errors between modelled and mean "observed" year–. A 5-to-10-year fluctuating mean can be a good compromise to balance interannual variability over many years, especially atypical years, and to study long term change on phenology.

The studied pixels were selected according to the number of cloud or snow free data available for calibrating the Roujean's model. As high altitudes were more frequently hidden by cloud and snow, the pixels located in high mountains were excluded. Maximum altitude on the studied area was 3,100m, whereas the maximum altitude after selection was 1,800m. But broadleaf forest was mostly located below this altitude and budburst ground-based observations were made from 100 m to 1,600m, so the amount of data lost in high mountains was acceptable.

As expected, seasonal variations of PVI, related to the green leaf area dynamics, was stronger for deciduous forests than for forests including evergreen species (i.e. coniferous). For deciduous forest, elevation explained a large part of the spatial distribution of PVI phenological responses. Shortening of vegetative season length through altitude found expression in the delay of the PVI increase in spring and the advance of its decrease in fall. Plain and hill forests showed phenological patterns quite different from mountain ones, particularly with a greater earliness of PVI maximum likely to be due to the earlier growth of leaves. The geographic range of species and spatial variability of the vegetation structure – i.e. trees and undergrowth- could explain the patchy pattern of spatial distribution of phenological responses in the north part of the region. These results agreed with conclusions of Vitasse (2005) based on ground observations, which showed that the budburst dates are mostly determined by altitude and species and their interaction.

The map of remote sensing estimated budburst date EbD for broadleaf forest performed a spatialization of the budburst date measured at ground. The expected error on the estimates given in the map is about 4 days. It was very satisfactory compared with the range of variation which was equal to 34 days for a gradient of 1,000 m. However the range of retrieved dates is larger than for the observed ones. Moreover some pixels at low elevation had the remote-sensed budburst beginning before DOY 70, i.e. before the first 10-day period of the available VGT time-series. A detailed validation will be needed from a large independent dataset i.e. from ground observations spread over the whole area. The available ground data determined the choice of *Quercus sp.* as model species. Ground-based observations on beech, a species well represented in plain, showed that budburst is delayed until one month compared to *Quercus sp.* at

100m (Vitasse, 2005). The time-lag between the two species progressively decreased as forest altitude increased. An improvement could be brought by taking into account the altitudinal distribution of the two species.

5. CONCLUSION

This study permitted to test the use of remote sensing time-series at medium resolution like those provided by VEGETATION/Spot sensors for monitoring phenology over mountain forests. The impact of the altitudinal gradient on phenology was clearly observable, with high spatial and temporal consistency. The spatial disaggregation of 1-km² pixels made easier the analysis of the phenological behaviour specific to the deciduous forest which is quite fragmented. Although obtained from satellite data averaged on 5 years, the produced maps completed well ground-based monitoring – carried out on precise observational sites – by informing about the phenological diversity over the large altitudinal gradient at the regional scale. Applying a running-window over many decades should then be a promising method to follow the impact of changing climate on phenology.

The study focused here on budburst date. But it could be adapted to other phenophases such as senescence date and by extension to the length of growing season. Ground-based data availability is crucial to know the timing of phenophases and to calibrate and validate its estimation from the radiometric signal. Thus, further studies in phenology will require increased coherence in time and space between satellite data and ground-based monitoring for reaching the best accuracy.

APPENDIX : CARDOT'S MODEL

The Cardot's model (Cardot et *al*., 2004) is:

$$\begin{cases} X_i(t) = \sum_{j=1}^{J} \pi_{ij}\rho_{ij}(t) + \varepsilon_i(t) \quad t \in \{t_1, \ldots, t_p\} \\ \rho_{ij} \sim \mathcal{N}(\rho_j, \Gamma_j),\ j = 1, \ldots, J \end{cases}$$

where p = number of 10-day periods

$X_i(t)$ = Observed response of the pixel i at the t 10-day period

π_{ij} = Proportion of area of the land-use j within the pixel i

$\rho_{ij}(t)$ = Response of the land-use j within the pixel i

$\rho_j(t)$ = Expectation of the random function $\rho_{ij}(t)$

Γ_j = Covariance matrix with the following elements:

$$[\Gamma_j]_{l,l'} = \mathrm{cov}(\rho_{ij}(t_l), \rho_{ij}(t_{l'})), \quad l, l' = 1, \ldots, p.$$

The estimation procedure by maximizing the likelihood provides $\rho_j(t)$ and Γ_j. The Best Linear Unbiased Prediction (BLUP) formula allows obtaining the prediction of each individual response $\rho_{ij}(t)$. The two steps include an approximation to the phenological curves with B-Splines functions.

ACKNOWLEDGEMENTS

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