



## Ground-based Network of NDVI measurements for tracking temporal dynamics of canopy structure and vegetation phenology in different biomes

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### ARTICLE INFO

#### Article history:

Received 30 August 2011

Received in revised form 10 March 2012

Accepted 16 March 2012

Available online xxxx

#### Keywords:

Ground-based NDVI

NDVI time-series

Phenology

Evergreen and deciduous forests

Tropical rain forest

Herbaceous savanna

Crops

### ABSTRACT

Plant phenology characterises the seasonal cyclicity of biological events such as budburst, flowering, fructification, leaf senescence and leaf fall. These biological events are genetically pre-determined but also strongly modulated by climatic conditions, particularly temperature, daylength and water availability. Therefore, the timing of these events is considered as a good indicator of climate change impacts and as a key parameter for understanding and modelling vegetation–climate interactions. *In situ* observations, empirical or bioclimatic models and remotely sensed time-series data constitute the three possible ways for monitoring the timing of plant phenological events. Remote sensing has the advantage of being the only way of surface sampling at high temporal frequency and, in the case of satellite-based remote sensing, over large regions. Nevertheless, exogenous factors, particularly atmospheric conditions, lead to some uncertainties on the seasonal course of surface reflectance and cause bias in the identification of vegetation phenological events. Since 2005, a network of forest and herbaceous sites has been equipped with laboratory made NDVI sensors to monitor the temporal dynamics of canopy structure and phenology at an intra-daily time step. In this study, we present recent results obtained in several contrasting biomes in France, French Guiana, Belgium and Congo. These sites represent a gradient of vegetation ecosystems: the main evergreen and deciduous forest ecosystems in temperate climate region, an evergreen tropical rain forest in French Guiana, an herbaceous savanna ecosystem in Congo, and a succession of three annual crops in Belgium. In this paper, (1) we provide an accurate description of the seasonal dynamics of vegetation cover in these different ecosystems (2) we identify the most relevant remotely sensed markers from NDVI time-series for determining the dates of the main phenological events that characterize these ecosystems and (3) we discuss the relationships between temporal canopy dynamics and climate factors. In addition to its importance for phenological studies, this ground-based Network of NDVI measurement provides data needed for the calibration and direct validation of satellite observations and products.

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### 1. Introduction

Phenology is the chronology of phases of development of living species and it characterises the seasonal cyclicity of biological events such as, for plant species, budburst, flowering, fructification, leaf senescence and leaf fall. These biological events are genetically pre-

determined but also strongly modulated by environmental conditions (Schaber & Badeck, 2003; Zhang et al., 2005). For plant species, the main environmental drivers involved are temperature, daylength and water availability. Therefore, the timing of main phenological markers of thermally or water-constrained species is considered as a good indicator of the impacts of climate changes (Menzel, 2002) and as a key parameter for understanding and modelling vegetation–climate interactions (Crucifix et al., 2005).

Field observations (national phenological networks, phenological gardens, etc.), empirical or bioclimatic models (Delpierre, Dufrêne,

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et al., 2009; Delpierre, Soudani, et al., 2009; Schaber & Badeck, 2003, 2005) and remotely sensed time-series data (Fisher et al., 2006; Schwartz et al., 2002; Soudani et al., 2008; Zhang et al., 2003, 2006) constitute the three possible ways for monitoring the timing of plant phenological events.

Empirical and bioclimatic models are based on strong relationships between the timing of phenological events and different climatic factors. Nevertheless, they do not supplant the need for field observations because they are subject to uncertainties of varying magnitude, are species-specific and calibrated at local scales, and depend for their application on the availability of climate records used as input variables.

Field observations of vegetation phenology mobilise human resources, are expensive and time consuming and are subject to uncertainties due to operator bias (Siljamo et al., 2008; Soudani et al., 2008). Sampling protocols may also change over time and the reproducibility of observations made in different contexts is not guaranteed over the long period of time required by studies which specially focus on investigating the climate change impacts on plant species. Field observations are also punctual and provide only little information on the spatial variability of timing of phenological events.

Remote sensing has the advantage of being the only way of surface sampling at high temporal frequency and, in the case of satellite-based remote sensing, over large regions. Different markers can be derived from multi-temporal satellite data and linked to phenological events (Schwartz et al., 2002; Zhang et al., 2003). Nevertheless, some serious concerns related to remote sensing methodology are far from being completely resolved. Exogenous factors, particularly viewing geometry and atmospheric conditions, methods of data pre-processing and quality control (atmospheric correction schemes, spurious values removal and noise reduction in satellite data time-series) lead to some uncertainties on the seasonal course of surface reflectance and cause bias in the identification of vegetation phenological events (Hird & McDermid, 2009) or completely mask subtle changes in response to biotic and abiotic environmental perturbations (Verbesselt et al., 2010).

Taking advantage of the recent development of terrestrial environmental observatories, collaborative networks such as SpecNet (Gamon et al., 2006b) and more recently EUROSPEC (Balzarolo et al., 2011) were created. Their primary purpose was to explore the synergy between remotely sensed information on canopy structural and functional attributes and continuous eddy covariance measurements of carbon dioxide, water vapour and latent and sensible heat fluxes. In this context, near-surface remote sensing of vegetation phenology have attracted much interest and several studies have been conducted in the last years to track temporal dynamic of canopy structure from tower-based radiation and optical measurements (Ahrends et al., 2008; Huemmrich et al., 1999; Nishida, 2007; Richardson et al., 2007; Ryu et al., 2010; Wang et al., 2004).

Temporal patterns of canopy structure were well described by the seasonal course of the fraction of radiation absorbed by the canopy or the broadband Normalised Difference Vegetation Index (NDVI) calculated from upward and downward photosynthetically activity radiation (PAR) and global radiation measurements (Huemmrich et al., 1999; Wang et al., 2004).

Richardson et al. (2007), Nishida, (2007), Ahrends et al. (2008) and Wingate et al. (2008) suggested, using tower-based digital visible-light cameras, to monitor temporal and spatial variations of vegetation phenology. From this approach, canopy structure dynamic is monitored visually from downward-looking digital photos or based on indices calculated from the red, green and blue components of the colour image. Compared to approaches based on *in situ* radiation measurements, the main advantage of this technique is the greater spatial extent investigated and the possibility to account for spatial heterogeneity of phenology (Richardson et al., 2009). The major drawback is that images are acquired in the visible spectrum only,

excluding the near infrared portion which is much more sensitive to the amount of green vegetation. Indeed, it is well known that the high leaf absorption of radiation in the visible range of solar spectrum causes a rapid saturation of the reflected signal for a very low amount of canopy leaf area (Bégué, 1993; Soudani et al., 2006). The saturation effect reduces the dynamic range of the signal reflected by the canopy and increases the noise to signal ratio. Finally, in the absence of a grey card as a neutral reference to achieve a precise white balance directly at camera level or during the post-processing of images, optical greenness indices calculated using the colours of the visible light spectrum (Richardson et al., 2007) are noisy and strongly dependent on ambient light. These drawbacks may seriously limit the possibility of using this approach for the validation of satellite-based radiometric indices and estimates of phenological markers as suggested by Wingate et al. (2008) or in the PHENOCAM project (Richardson et al., 2007). However, *in situ* monitoring of individual plants and of vegetation cover dynamics using digital webcams at a daily time step offers the opportunity to document the full vegetation cycle of different species and over long time intervals. More recently, Ryu et al. (2010) developed and tested a novel NDVI sensor composed of two LEDs operating as detectors in the red and near infrared wavebands to monitor vegetation radiances above annual grassland. The results show the suitability of this sensor to monitor phenological events and to quantify canopy photosynthesis. The authors suggest the integration of this sensor into long-term ecological observatories monitoring network as a low-cost solution to capture temporal variations in canopy structure and functioning.

Since 2005, in the framework of the French network of long term measurements of carbon, water and nutrients fluxes, many forest sites have been equipped with laboratory-made NDVI sensors to monitor the temporal dynamics of canopy structure and phenology at an intra-daily time step. NDVI (Rouse & Haas, 1973) is determined from red and near infrared radiances measured above the canopy and is commonly used in remote sensing studies because it is sufficiently sensitive to capture small changes in the amount of photosynthetic vegetation. This action has been then extended to other herbaceous and forest ecosystems across the world. The long term objective must be to set up an effective worldwide network of sites representative of the majority of terrestrial biomes in different ecological and human contexts to document finely temporal and spatial variations of canopy structure and phenology. This monitoring network uses the same methodology for all sites and allows direct comparison with satellite data. It also takes advantage of pre-existing micrometeorological measurements at eddy covariance flux tower sites.

In this study, we present recent results obtained in several contrasting biomes in France, French Guiana, Belgium and Congo. These sites represent a gradient of vegetation ecosystems: the main evergreen and deciduous forest ecosystems in France (French CO<sub>2</sub> eddy flux tower sites), an evergreen tropical rain forest in French Guiana (Guyaflux experimental forest), an herbaceous savanna ecosystem in Congo (CarboAfrica site), and a succession of three annual crops in Belgium (Belgium CO<sub>2</sub> eddy flux sites). We present in this paper *in situ* NDVI measurements recorded in this new network to (1) provide an accurate description of the seasonal dynamics of vegetation cover in these different ecosystems (2) identify the most relevant remotely sensed markers from NDVI time-series for determining the dates of the main phenological events that characterize these ecosystems and (3) discuss the relationships between temporal canopy dynamics and climate factors.

## 2. Material and methods

### 2.1. Description of sites

The study sites are composed of eight sites covering three main bioclimatic regions (temperate, Mediterranean and tropical) and the

major plant functional types encountered in these regions: deciduous and evergreen broadleaf and coniferous forests, tropical moist evergreen forest, tropical savanna and crops (Table 1).

The three temperate deciduous forest sites are situated in the North of France. The main overstory species are: pedunculate and sessile Oaks (*Quercus robur* L. and *Quercus Petraea* (Matt.) Liebl) in Fontainebleau forest and beech (*Fagus Sylvatica* L.) in Hesse and Fougères forests. In France, pedunculate oak, sessile oak and beech are the three major species, covering respectively 18%, 16% and 13% of the area occupied by deciduous trees (60% of the total surface of French forests). In Europe, oaks occupy a wide range of bioclimatic regions from central Spain to Norway and beech occupies a vast territory in western and central Europe from southern France to Sweden in the north and to the Caspian Sea in the east.

The two evergreen forest sites are situated in Le Bray and Puéchabon regions in Southern of France. Le Bray forest is an even-aged maritime pine (*Pinus Pinaster* Ait.) with a dense understory of *Molinia caerulea* (L.) Moench. Le Bray is located in the Landes Forest, the largest man-made maritime pine forest in Europe which covers about 5% of total metropolitan French forest area. In France, maritime pine covers about 8% of total forest area and constitutes about 25% of the surface occupied by coniferous forests. The natural distribution of maritime pine includes the regions situated in the western Mediterranean and the Atlantic coast of South West Europe mainly in Spain, Portugal, France, Italy, Turkey and Greece. Puéchabon site is a holm oak (*Quercus Ilex* L.) evergreen broadleaf forest located on the northern Mediterranean coast. Holm oak is emblematic of Mediterranean sclerophyllous vegetation and is encountered in southern Europe and the Arab Maghreb region of northern Africa.

The tropical rainforest site is located in Paracou in French Guiana. More details about this experimental forest are given in Bonal et al. (2008). It is a mature forest with unknown human disturbance over the past centuries. Tree density (DBH > 10 cm) is about 600 trees/ha (of different ages). Average height is about 35 m but some trees reach 45 m. This forest is characterized by a high diversity with about 180 different tree species per ha (DBH > 10 cm), without clear dominant species. The most abundant species belong to the families of the Caesalpiniaceae, the Lecythidaceae, the Chrysobalanaceae and the Sapotaceae.

The tropical savanna site is located in Tchizalamou study site (North-North-East of Pointe Noire, Congo). This site is part of CarboAfrica flux site network. More details about this experimental site are given in Castaldi et al. (2010). It is composed of grassland savanna

dominated by *Loudetia simplex* (Nees, Hubb.), one of the most common species in this region of West Africa. This area is burned every year almost at same date (end of June).

The succession of crops is located in Loncée in the Belgian province of Namur. It is composed of a succession of annual crops over three years in the same location, of wheat (2007), sugar beet (2008) and wheat and mustard (2009). More details about this site and the farming operations undertaken are given in Aubinet et al. (2009) and in Dufranne et al. (2011). Briefly, in 2007, the wheat sowing was carried out in the middle of October of the previous year and the harvest was carried out during the first week of August (Doy 217). In 2008, the field was occupied by a sugar beet, sown at the end of April in the same year. The sugar beet was harvested at the beginning of November 2008 (Doy 308). In 2009, the field was occupied by the succession of two crops of wheat and mustard. The wheat was sown in November 2008 and the harvest was carried out at the first week of August. The mustard is a popular intercrop used as green manure. Mustard is also known to have insecticidal properties against nematodes. The sowing of mustard seeds was carried out at wheat stubble ploughing at the end of August. Mustard was buried into the soil before flowering, during the first week of December.

The main characteristics of all sites are summarized in Table 1. As underlined above, all sites are equipped with eddy covariance systems measuring net ecosystem carbon exchange. Mandatory and additional variables measured on this type of ecosystem research platforms are available (net carbon exchange, windspeed, temperature, rainfall, radiation, etc.). In addition, the seasonal dynamics of fallen litter is finely described in the tropical forest of French Guiana (Chave et al., 2010) and in the evergreen forests of Puéchabon (Limousin et al., 2008) and Le Bray (unpublished data). Litter biomass is measured separately for leaves, twigs, branches and fruits. Measurements were done weekly or monthly in 40 litter traps in the tropical forest, 26 litter traps in the Puéchabon forest and 20 litter traps in the Le Bray forest, and placed beneath the canopy in the footprint of the tower flux in every site.

## 2.2. NDVI sensor description and in situ NDVI measurements

NDVI sensors installed on the towers of different sites are laboratory-made according to Pontailier and Genty (1996) and Pontailier et al. (2003) design. The body of the sensor is made of Teflon® installed into a stainless steel cylinder having a diameter of 3.8 cm and a height of 9 cm. The upper part of the sensor body has a 5 mm thick acrylic diffuser (Altuglass® 740, Altulor, France). The body of the sensor is

**Table 1**  
Main characteristics of study sites.

Site name	Type of Biome	Lat/Long	Altitude (m)	Average temperature (°C)	Average precipitation (mm)	Main vegetation species	Age (years)	Maximum Leaf Area Index (m <sup>2</sup> /m <sup>2</sup> )
Fontainebleau	Deciduous broadleaf	48°28'35"N 2°46'48"E	120	102	720	Pedunculate and sessile Oaks ( <i>Quercus robur</i> L. and <i>Quercus Petraea</i> (Matt.) Liebl)	145	5
Hesse	Deciduous broadleaf	48°40'27"N 7°03'56"E	300	92	820	European beech ( <i>Fagus sylvatica</i> L.)	44	5.6
Fougères	Deciduous broadleaf	48°22'59"N 1°11'05"W	140	112	900	European beech	40	–
Puéchabon	Evergreen broadleaf forest	43°44'29"N 3°35'45"E	270	134	907	Holm Oak ( <i>Quercus Ilex</i> L.)	70	2.9
Le Bray	Evergreen needleleaf forest	44°43'2"N 00°46'9"W	61	132	972	Maritime pine ( <i>Pinus Pinaster</i> Ait)	42	1.7
French Guiana	Tropical rain forest	5°16'54"N 52°54'44" W	29	257	3136	150 species (DBH > 10 cm)/ha	–	7
Tchizalamou (Congo)	Herbaceous savanna	4°17'210"S 11°39'23"E	82	257	1150	<i>Loudetia simplex</i>	–	1.6
Loncée (Belgium)	Succession of crops	50° 33' 8"N 04° 44' 42"E	165	10	800	Succession Wheat/Sugar beet/ Wheat and mustard	–	–

equipped with two photodiodes having spectral sensitivity in red and near infrared bands, respectively centred on 640 nm and 720 nm. The red channel uses a large gallium arsenide phosphide photodiode (G1117 GaAsP, Hamamatsu Photonics, Hamakita, Japan) and a long-pass glass filter (RG 645, Schott Glaswerke, Mainz, Germany) allowing a sharp cut-off below 640 nm. The near infrared channel uses a silicon photodiode (S1226 44BK, Hamamatsu Photonics) and a long pass glass filter (RG 780, Schott Glaswerke) allowing a sharp cut-off below 770 nm. The two detectors were facing the diffuser. Their pins were directly welded onto a screened cable that linked the sensor to the central unit. Current was converted to voltage with shunt resistors. To provide a high sensitivity, the value of the resistors was selected as high as possible without affecting signal linearity (10 and 2 k $\Omega$ ). As a result, no amplification was necessary.

The sensor was calibrated against a spectroradiometer (LI-1800, LI-COR, Inc.), considering the whole bandwidth of 640–660 nm for the red band and 780–920 nm for the near infrared band. The calibration procedure is described in Pontailleur et al. (2003). Briefly, the NDVI sensor and the spectroradiometer were installed outdoors in an open area, looking upwards in overcast sky conditions. The coefficients of calibration in the red (R) and the near infrared (NIR) bands were then determined using simultaneous measurements acquired by the NDVI sensor and the LI-1800 spectroradiometer.

NDVI sensors were installed on towers, a few metres above the top of the canopy and looking downwards. They were generally inclined at about 20–30° from vertical and oriented towards South to avoid hotspot effects in canopy reflectance when the viewing direction is collinear with the solar direction. The field of view of the sensor was 100° in most study sites. The area observed varied from few tens to few hundred of square metres depending on site. Data were scanned every minute and recorded at half-hour time step in dataloggers. NDVI was computed for measured radiances reflected by the canopy. There was no second sensor pointing upwards measuring incident radiation to compute NDVI from reflectances. Such a sensor has to be cosine-corrected and must be frequently cleaned. As shown in Turner et al. (2003) and Fang and Liang (2003), the sensitivity of NDVI to leaf area index is very high for different processing levels of satellite data used in NDVI calculations, from digital counts, radiances or reflectances. Fang and Liang (2003) concluded that leaf area index can be estimated accurately from both reflectances and radiances but the radiance-based approach has the advantage of avoiding applying complex and time-consuming atmospheric corrections. Nevertheless, atmospheric effects have the effect of reducing the NDVI values leading to underestimation of the amount of green biomass and LAI–SVI relationships are generally stronger after atmospheric corrections. In this study, the effects of cloud cover are strongly reduced since only NDVI data acquired under clear skies or low cloud fractions are considered to construct NDVI time-series. Yet, residual noise may persist as shown by variations in NDVI signal at short-time scales but these variations are small in comparison to temporal changes of NDVI due to phenological events. Therefore, from an operational point of view, the use of a single sensor looking downwards constitutes an efficient solution for obtaining high-quality NDVI time-series that finely describe seasonal patterns of canopy greenness. This solution has the main advantages of being robust, maintenance-free and well adapted to routine measurements. However, the absence of a full atmospheric correction affects the accuracy of multi-temporal or multi-sites comparisons of NDVI time-series or when converting NDVI data into biophysical variables such as LAI, fraction of absorbed radiation or the fraction of vegetation cover.

### 2.3. NDVI data processing

The main step of NDVI data pre-processing was to remove values contaminated by clouds or snow, or acquired under conditions of low levels of radiation. We sought to develop an easy-to-use

quantitative method of noise reduction and spurious data removal based on the same criteria for all sites in order to obtain NDVI time-series comparable over time in the same site and between sites. This method is described below. At each site, incident solar radiation at the top of the atmosphere (TOA) was estimated using standard equations at the same time step as *in situ* NDVI measurements (30 min). From tower-based measurements of radiation in the Fontainebleau forest, direct and diffuse solar radiation components and sunshine duration per 30 min acquired by a Sunshine Sensor (BF3 – Delta-T Devices, U.K.) were used to determine a threshold separating between clear and cloudy sky conditions. Fig. 1 shows the relationship between solar path atmospheric transmittance, defined as the ratio between direct radiation measured at ground level and TOA solar radiation, and the ratio between global radiation measured at ground level and TOA solar radiation under different sky conditions.

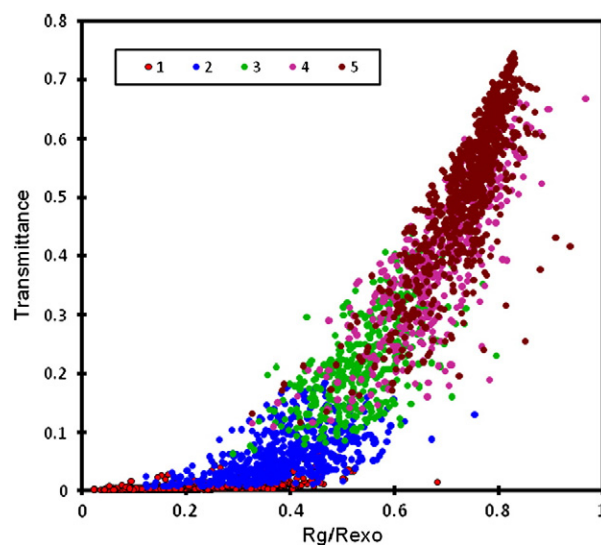
From Fig. 1, we observe that for totally clear skies (or with few clouds), global solar radiation at ground level to TOA solar radiation ratio is above 0.6. This value was used as a threshold to eliminate cloudy periods and assumed to be the same for all sites whatever the climate regime. In what follows, only daily average of NDVI measurements acquired under sky conditions corresponding to this threshold and between 10 and 14 h (UT) only, are considered in order to minimize the sun angle effects on NDVI data. Around solar noon, changes in sun angle are minimal, direct solar radiation reaching the top of canopy reaches high values and the effects of shadow on NDVI are minimized. This protocol is commonly used to sample seasonal changes of reflectance above canopies (Gamon et al., 2006a; Miller et al., 1997; Styliniski et al., 2002).

## 3. Results

### 3.1. Temperate deciduous broadleaf forests

The results shown below (Figs. 2, 3 and 4) present NDVI time-series measured in the two beech forests in Hesse (Fig. 2) and Fougères (Fig. 3) and in the oak forest in Fontainebleau (Fig. 4).

These NDVI time-series describe with high temporal precision the intra-annual patterns of canopy structure in deciduous broadleaf forests in temperate climate zone. The phenology of these species is strongly dependent on temperature and is characterized by two phases: the leafy season from mid spring to October and the



**Fig. 1.** Relationship between path direct solar transmittance and global radiation at ground level ( $R_g$ ) to top of atmosphere solar radiation ( $R_{exo}$ ) for year 2009 (Fontainebleau forest) for five levels of sunshine duration per period of 30 min (1: 0 min – overcast sky, 2: 1–10 min, 3: 11–20 min, 4: 20–29 min, 5: 30 min – clear sky).



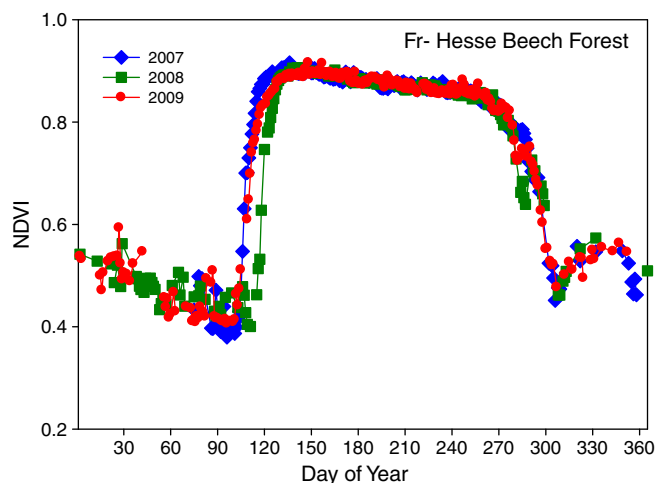


Fig. 2. Ground-based NDVI time-series over Hesse beech forest.

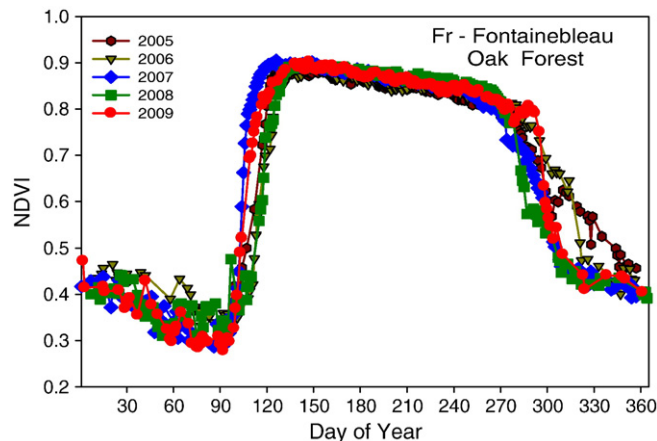


Fig. 4. Ground-based NDVI time-series over Fontainebleau Sessile Oak forest.

dormancy season during late autumn and winter. These main phases are separated by two short phases delimited by two major phenological events: a first phase of budburst, leaf development and maturation in spring and a second phase of onset of yellowing, senescence and leaf fall in autumn.

Canopy foliage biomass dynamics are similar for oaks and beech. NDVI decreases monotonely but slightly during the whole winter and reaches its minimum value before budburst in early spring. This temporal pattern is observed for both species, at the three sites and every year. The monotonic decrease of NDVI observed during winter and also during summer may be due to seasonal variations in sun angle and changes of optical properties of soil background and canopy elements. During winter, the canopy is open and the temporal variations of the optical properties of the soil due to litter decomposition may have significant effects on NDVI signal as shown in previous studies (Nagler et al., 2000; Van Leeuwen & Huete, 1996).

When averaging NDVI measurements over all available years, the timing of budburst determined from the position of NDVI minimum increase is observed in Doy 105 ( $SD \pm$  standard error of the mean of 3 days) in the Hesse forest, in Doy 105 in the Fougères forest and in Doy 92 ( $\pm 1$ ) in the Fontainebleau Forest. NDVI continues to increase until it reaches its maximum value late in spring at Doy 131 ( $\pm 3$ ) in the Hesse forest, in Doy 135 in the Fougères forest and in Doy 128 ( $\pm 4$ ) in the Fontainebleau forest. For the two beech forests, leaf expansion period at spring, calculated from the date of NDVI minimum increase to the date of maximum NDVI, lasts between 26 and 30 days.

For the oak forest, leaf expansion duration varies between 28 and 40 days.

During summer, which constitutes the main season of growth in temperate deciduous forests, NDVI is almost at its maximum level despite a slight monotonic decrease during this period. A steep decrease in NDVI is then observed in early autumn at the beginning of leaf yellowing and then at leaf fall. This decrease in NDVI starts in Doy 271 ( $\pm 2$ ) in the Hesse forest, in Doy 285 ( $\pm 8$ ) in the Fougères forest and in Doy 278 ( $\pm 5$ ) in the Fontainebleau Forest. In the two beech forests, the date of the end of NDVI decrease is located in Doy 305 ( $\pm 1$ ). In the oak forest of Fontainebleau, the date of the end of NDVI decrease is difficult to determine in particular for the year 2005. We could for instance observe very long senescence phases for years 2005 and 2006 in Fontainebleau forest.

On average over all years, the length of the leafy season, from the date of budburst in the early spring to the end of the period of NDVI plateau, is little bit shorter in Hesse forest ( $167 \pm 4$  days) than in Fougères Forest (185 days). In the Fontainebleau forest, the length of growing season is about 186 days on average ( $\pm 5$  days).

### 3.2. Evergreen needleleaf and broadleaf forests

Figs. 5 and 7 show the seasonal variations of NDVI measured over the two forests of maritime pine in the Le Bray forest (Fig. 5) and in the Mediterranean holm oak in the Puéchabon forest (Fig. 7).

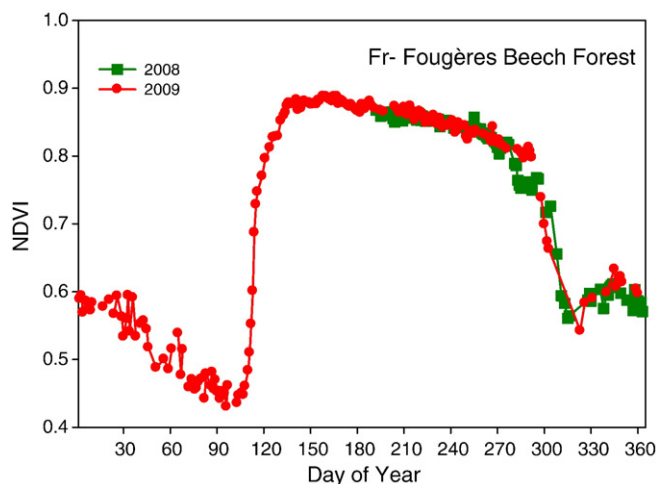


Fig. 3. Ground-based NDVI time-series over Fougères beech forest.

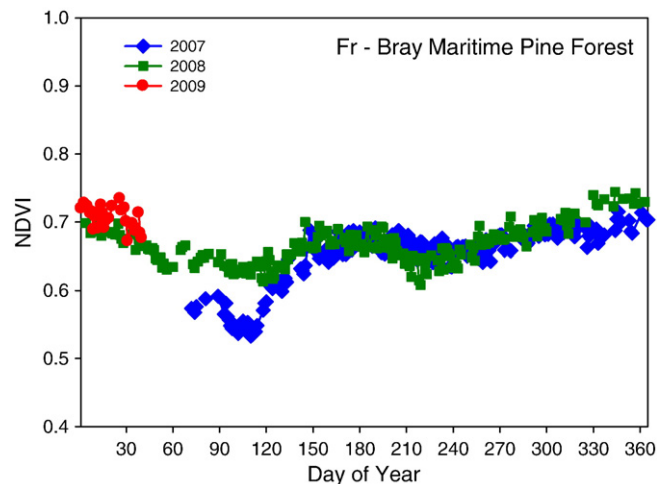


Fig. 5. Ground-based NDVI time-series in the Le Bray maritime pine forest.

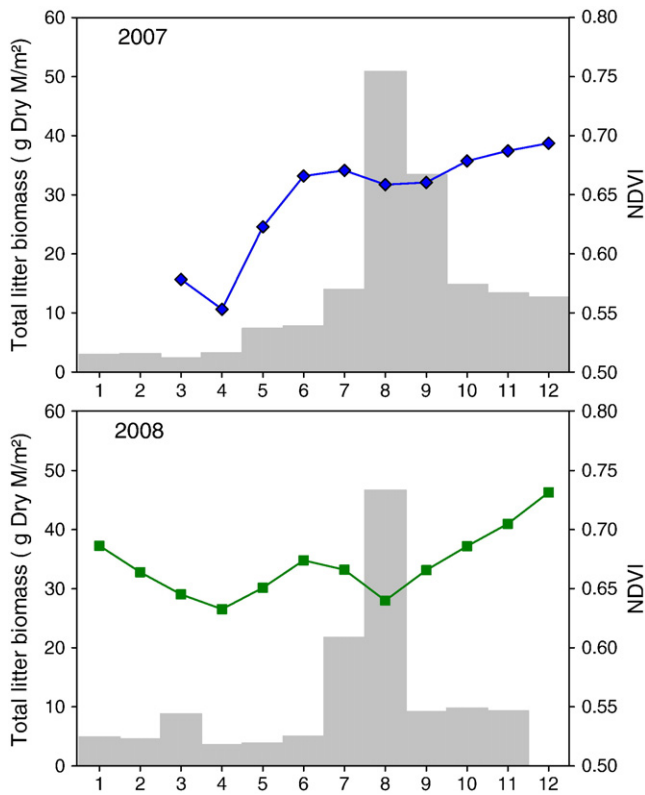


Fig. 6. Seasonal variations of foliar litter biomass and NDVI in the Le Bray maritime pine forest.

Note that the interruption of NDVI measurements in the Le Bray forest in 2009 is due to the extensive damage caused by an exceptional storm called Klaus that ravaged mainly the south-west of France on January 24. In the Puéchabon forest, an unexplained dysfunction of the sensor explains the gap in NDVI measurements during the autumn of the year 2008.

The seasonal dynamics of NDVI measured on both evergreen forests show much lower amplitude of variation than that measured on deciduous forests. The minimum NDVI is higher and there are no clear phases of leaf emergence in spring and of leaf fall in autumn. This pattern is explained by the partial renewal of foliage every year.

Over the maritime pine forest in the Le Bray forest (Fig. 5), NDVI decreases during the winter and reaches its minimum value at the beginning of spring. NDVI starts to increase in late April, which

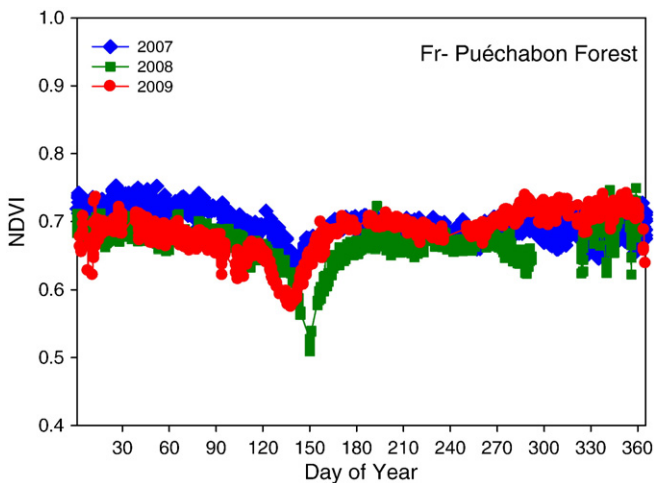


Fig. 7. Ground-based NDVI time-series over Puéchabon Holm Oak forest.

coincides with the onset of budburst of pine trees and the development of new shoots and needles. NDVI peaks in June/July. In July/August, we observe a slight decrease of NDVI, more pronounced in 2008 than in 2007 but which lasts only a few weeks. This temporary decrease in NDVI was earlier in 2008 than in 2007. This pattern is consistent with the needle litter fall (Fig. 6) whose maximal values were reached in July–August 2008 and August–September in 2007. During autumn and early winter, NDVI is approximately at the same level than the maximum values reached in the middle of the summer.

Over the holm oak stand in the Puéchabon forest, temporal variations of NDVI over the three years are similar (Fig. 7). The temporal pattern shows a significant decrease of NDVI, reaching minimum values around Doy 135 in 2007, Doy 139 in 2009 and Doy 150 in 2008. Then, NDVI returns to the level measured in early spring almost one month after, around Doy 165 in 2007 and 2009 and Doy 180 in 2008. During the autumn of 2008, unusual signal NDVI variations made the interpretation of the measurements difficult. However, it may be noted as a slight decrease from the end of September (Doy 270). This temporal pattern of NDVI over three years is consistent

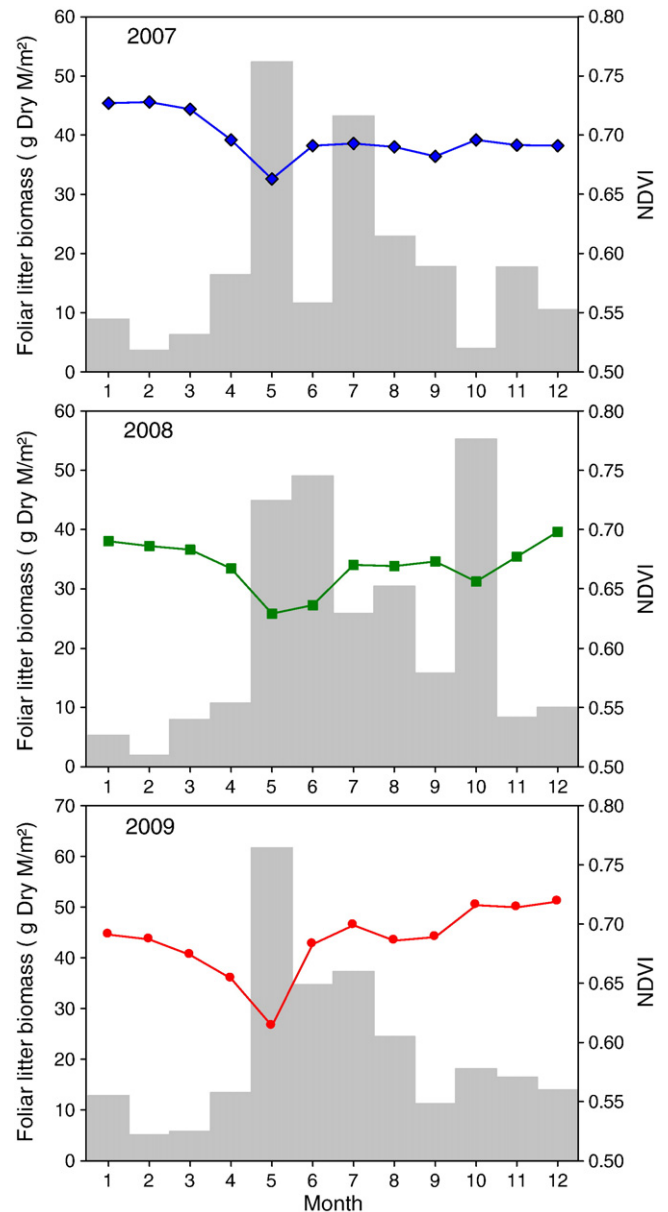


Fig. 8. Seasonal variations of monthly foliar litter biomass and NDVI in the Puéchabon forest.

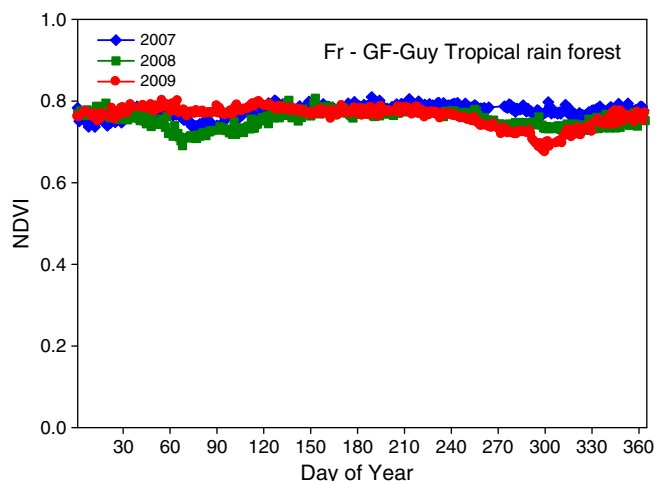


Fig. 9. Ground-based NDVI time-series over French Guiana tropical rain forest.

with the seasonal rhythm of litter biomass collected in traps (Fig. 8). Periods corresponding to the minimum values of NDVI are concomitant with the main periods of litterfall. Also, in agreement with the pattern of NDVI, maximum litterfall is reached earlier in May for the years 2007 and 2009 and in June 2008.

### 3.3. Tropical rain forest

At this site, NDVI values show little variation throughout the year (Fig. 9). Nevertheless, we observe two periods characterised by a decline in NDVI of variable magnitude. NDVI values reached a minimum around Day 70 (middle of March) for the first period and around days 300–320 (October) for the second period. For the first period, the decline in NDVI is clearly visible in 2007 and 2008. For the second period, the decline in NDVI is particularly pronounced in the 2009. The first period of NDVI decline was much shorter than the second one. The second decline was less pronounced for 2008 and very weak for 2007. These two periods of NDVI decline are concomitant with a period of lower rainfall and higher solar radiation (Fig. 10). The decrease

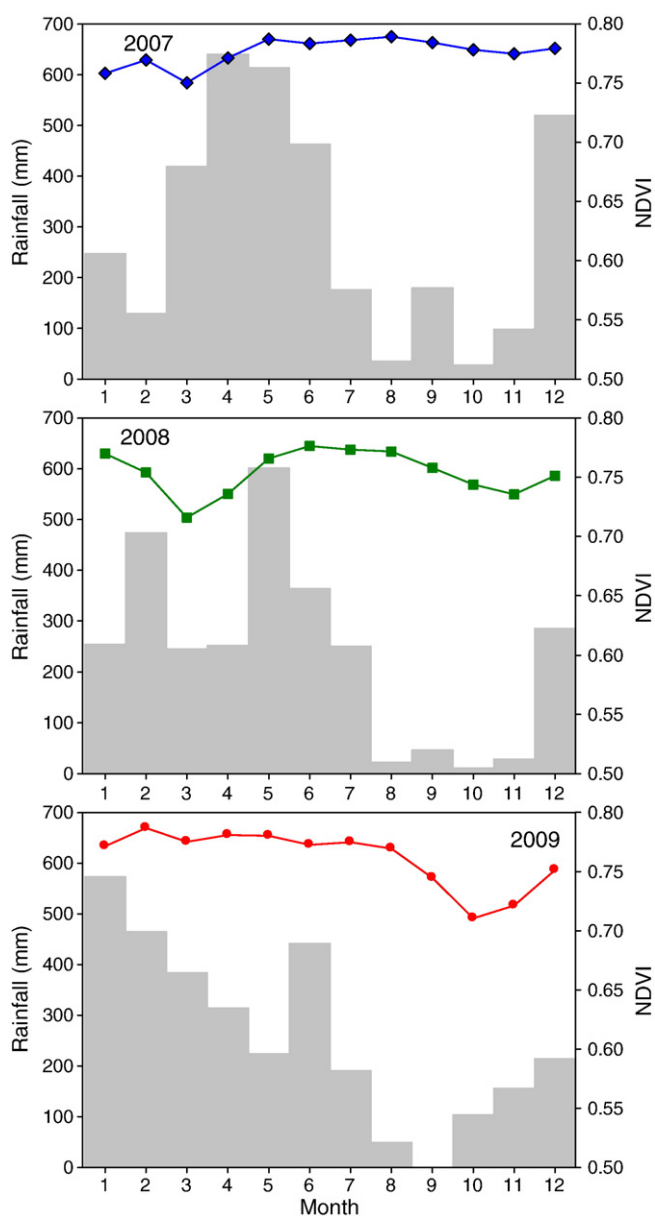


Fig. 10. Seasonal variations of monthly rainfall and NDVI in the French Guiana tropical rain forest.

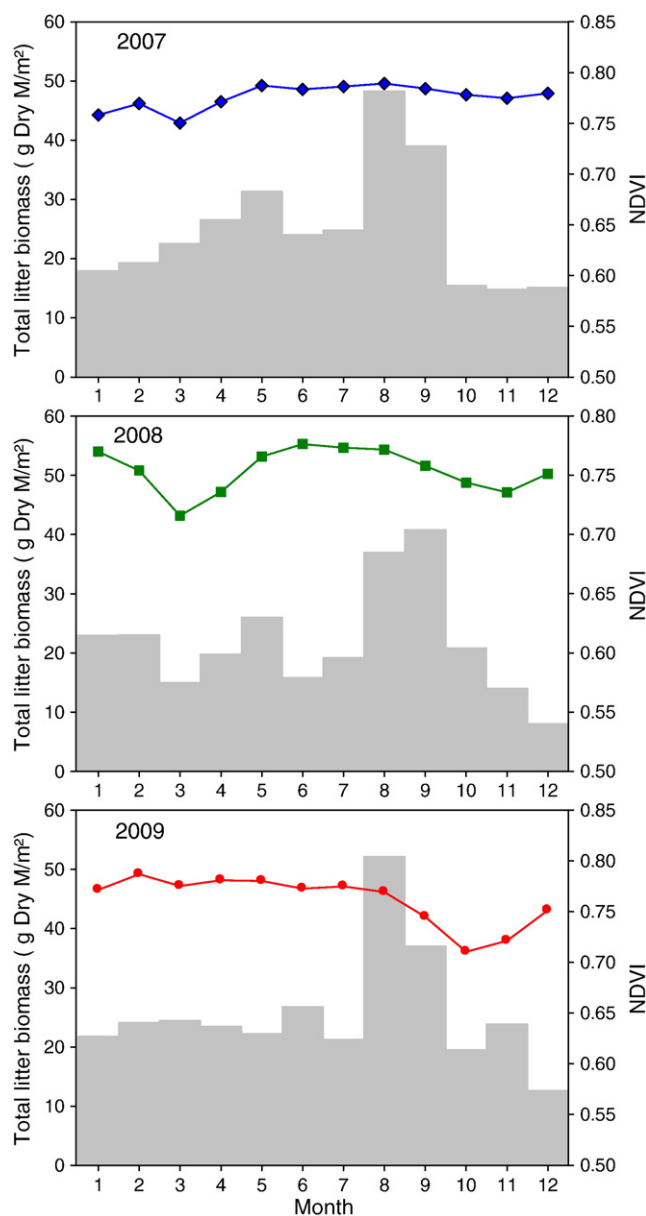


Fig. 11. Seasonal variations of monthly litter fall biomass and NDVI in the French Guiana tropical rain forest.

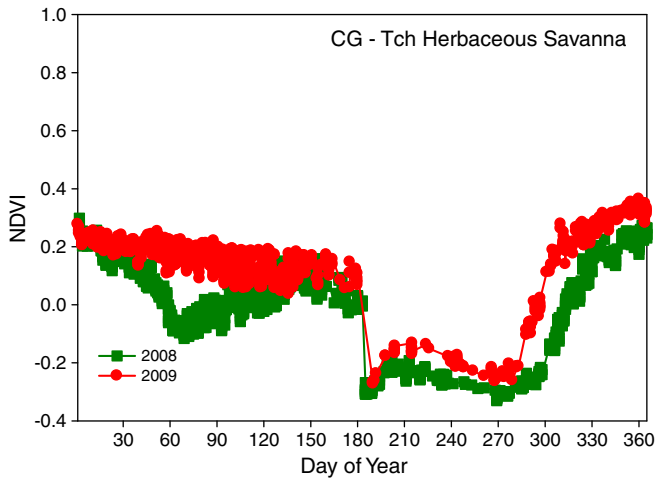


Fig. 12. Ground-based NDVI time-series over Congo African savanna.

of NDVI observed from the beginning of the second dry period also coincides with the period during which the maximum of litterfall is reached (Fig. 11).

### 3.4. African tropical savanna

At the beginning of 2008, NDVI is at its maximum and coincides with the wet season. Then, NDVI decreases in parallel with a decrease of rainfall and reaches a first minimum during a short dry period in February (Fig. 12). With the return of rain, NDVI increases and reaches a new maximum in mid-May at the end of the wet season. Then, NDVI decreases gradually with the beginning of the main dry season and suddenly drops as a consequence of fire in late June.

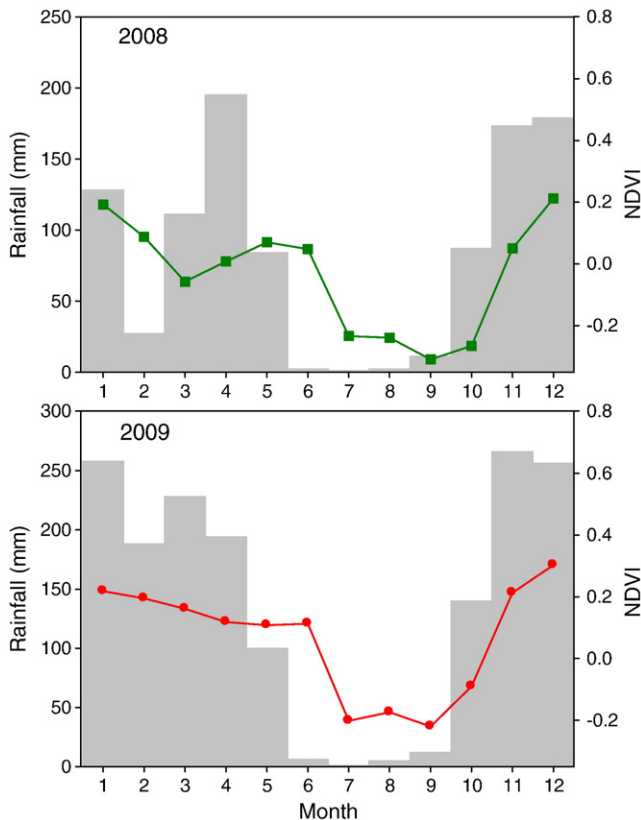


Fig. 13. Seasonal patterns of monthly rainfall and NDVI in the grassland savanna (Tchizalamou, Congo).

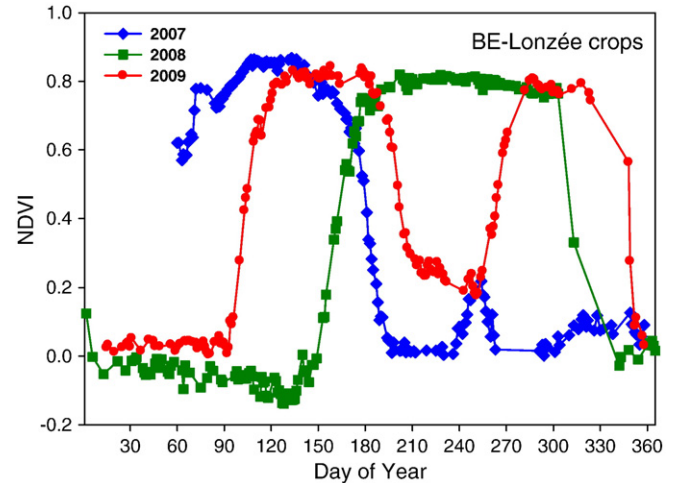


Fig. 14. Ground-based NDVI time-series over a succession of crops in Lonzée (Belgium). Winter wheat (2007), sugar beet (2008) and winter wheat and mustard (2009).

After the fire, soil is covered with ash and burned clumps of grass, inducing negative NDVI values. During the whole dry season, NDVI remains negative and increases steadily when the vegetation development starts actively at the beginning of the wet season in early October (approximately 100 days after the fire). In 2009, the temporal pattern of NDVI is quite similar to that observed in 2008 with the exception that NDVI remains high during February and March. Fig. 13 shows that this temporal pattern is mostly driven by rainfall and fire.

### 3.5. Crops and herbaceous species

At the agricultural site in Lonzée (Fig. 14), NDVI measurements started in 2007 at the end of March during the growth of winter wheat. From this date, we observe an increase of NDVI during spring, reaching a peak at the end of April. Then, NDVI decreases, slowly until mid-June and faster in July, up to a minimum value a few weeks before harvest done at the beginning of August. After harvest, NDVI increases again and reaches a small and narrow peak centred on Day 247 (first week of September) due to a significant re-growth of wheat and weeds. From Day 260, NDVI decreases after ploughing of wheat stubble. In 2008, a few days after the sowing of sugar beet, NDVI increases and reaches its maximum at the end of June. NDVI remains almost at the same level during the summer until harvest at the beginning of November (Day 308). It may be noted that the decline of NDVI is not immediate after harvest but takes a few days. In 2009, NDVI time-course within the year is bimodal, reproducing the temporal variation of above ground biomass of wheat and mustard, respectively. We note that in 2009, winter was exceptionally cold, delaying wheat growth and tillering of few weeks.

## 4. Discussion

Ground-based NDVI measurements were filtered using a simple screening procedure to obtain time-series which finely reflect the temporal dynamics of canopy structure. This process eliminates days of medium and high cloudiness. In conditions of low cloud cover, the noise present in NDVI time-series is generally small on all sites with the exception of NDVI measurements achieved in the tropical savanna. The higher noise of NDVI measured on this site can be, at least partially, explained by the very strong fluctuations of incident solar radiation that characterize the radiation regime in tropical climates (Soubdhan et al., 2009). These fluctuations occur within short periods, generally a few seconds, depending on size, number and speed of clouds and introduce more noise in NDVI data.



Nevertheless, this noise does not affect significantly the shape of the temporal pattern of vegetation greenness in this site of African savanna described by NDVI time-series.

In temperate deciduous forests (Figs. 2, 3 and 4), estimates of the timing of phenological events derived from *in situ* NDVI time-series are generally in agreement with field observations. On average (period 1997–2006) and over the French Permanent Plot Network for the Monitoring of Forest Ecosystems (RENECOFOR) composed of 102 deciduous and evergreen permanent stands (Lebourgeois et al., 2010), the beginning of budburst occurs on Doy 112 for beech and on Doy 100 for sessile and pedunculate oaks. Generally, the onset of green-up of beech appears one to two weeks later than for oaks (Lebourgeois et al., 2002; Lebourgeois et al., 2010; Soudani et al., 2008). The beginning of leaf colouring occurs on Doy 275 for beech, Doy 284 for sessile oak and Doy 283 for pedunculate oak (Lebourgeois et al., 2010). On the other hand, the duration of leaf expansion period estimated using NDVI time-series (about 30 days in beech forests and 36 days in the oak forest of Fontainebleau) is also in agreement with observations made in previous studies, in Hesse forest (Granier et al., 2000) and in other temperate deciduous forest stands (Aubinet et al., 2002; Bequet et al., 2011; Breda et al., 1995; Gond et al., 1999).

The good agreement between observed and predicted phenological events leads us to conclude that the temporal pattern of *in situ* NDVI in temperate deciduous forests during the spring is mainly dependent on the temporal dynamics of leaf area index despite changes in biochemical composition of leaves such as water and chlorophyll contents, concomitantly with vegetation development. This confirms findings in previous studies (Blackburn & Milton, 1995; Kodani et al., 2002) showing strong dependency relationships between NDVI and LAI despite temporal variations of chlorophyll content.

In spite of this generally good agreement between predictions and field observations, the use of date of NDVI minimum increase in early spring as an estimate of the budburst date may be less appropriate marker because it varies little from year to year and may not reflect small inter-annual variations in the phenological timing of leaf budburst. The date of NDVI minimum increase is also difficult to determine with sufficient accuracy due to high noise-to-signal ratio. For example, in 2007, the period extending from autumn 2006 to spring 2007 was exceptionally warm and led to a very early onset of phenological spring phases observed from *in situ* phenological records (Delpierre, Dufrêne, et al., 2009; Delpierre, Soudani, et al., 2009; Luterbacher et al., 2007; Rutishauser et al., 2008). Our results (Figs. 3 and 4) respectively for Hesse and Fontainebleau forests, show that, during the spring of 2007, the start of NDVI minimum increase did not occur earlier than on other years, but the leaf expansion period was faster, leading to an earlier full canopy foliage development and, as a result, a longer growing season. The date of maximum NDVI at the end of the spring also seems less dynamic and varies little from year to year. Indeed, the date at which the maximum NDVI value occurs is both dependent on total leaf surface area and on changes of biochemical, geometrical and physiological properties of leaves during the phase of leaf area development. It is known that NDVI becomes less sensitive at high leaf surface area (Bégué, 1993) which may limit the performance of the date of maximum NDVI as a phenological marker to characterize the beginning of the vegetation leafy season. As a result, the timing of half-amplitude of NDVI during the leaf expansion phase appears more relevant to characterize budburst in deciduous forests. This conclusion is consistent with the results obtained in Soudani et al. (2008) which showed that the best predictions of the date of budburst in temperate deciduous forests are obtained using the date of the inflection point of NDVI during leaf expansion period, largely better than the use of dates of NDVI minimum increase or maximum NDVI. On the other hand, it is more difficult to derive a phenological marker from NDVI time-series that characterizes the end of the growing season in the

temperate deciduous forests. The decrease of NDVI is slower and more variable from year to year. This can be explained by the multitude of biological and physical phenomena taking place during this period (leaf yellowing, browning, leaf fall, marcescence, and mechanical influence of wind and precipitations). This is particularly noticeable in the NDVI time-series measured in autumn 2005 in the Fontainebleau forest (Fig. 4). The decrease of NDVI was very slow and noisy, which makes difficult a precise determination of a phenological date that characterizes this period. The date where NDVI starts decreasing appears to be the most relevant phenological marker to characterize the end of the growing season because it is less dependent on the biotic and abiotic factors cited above.

In evergreen forest ecosystems, ground-based NDVI time-series are, to our knowledge, the first complete data sets measuring finely subtle temporal variations in canopy leaf area in evergreen forests (Figs. 5, 7 and 9). In the forest of maritime pine at Le Bray (Fig. 5), the temporal variations of NDVI are consistent with the phenology of this species (Kramer et al., 2000; Loustau & Cochard, 1991). For this site, the onset of budburst usually occurs in late April (Lebourgeois et al., 2002). Leaf area index increases, due to the development of a new needle generation. It reaches a peak in June–July and then decreases (Kramer et al., 2000) due to the fall of the oldest needle generations (3 and 4 year old). The foliage fall reaches a peak in summer and remains relatively high in autumn, and then is quite weak and stable during the rest of the year (Fig. 6). However, under water stress conditions, the foliage fall is accentuated (Delzon & Loustau, 2005). Overlap of both processes – growing of new needles, fall of the oldest needles – could explain the complexity of the seasonal course of NDVI in Le Bray site. Moreover, the NDVI temporal variation is probably influenced by understory species mainly composed of *Molinia*. The first leaves of this perennial grass appear in March–April concomitantly with the budburst of maritime pine. Leaf area index increases significantly in May and reaches its peak in June–July (Yauschew-Raguenes et al., 2008). The leaf area index decrease of *Molinia* is observed in late October at the beginning of withering which ends in November (Loustau & Cochard, 1991; Yauschew-Raguenes et al., 2008). On this site, maximum leaf area index of both *Molinia* and maritime pine is of the same order of magnitude (Duursma et al., 2009). The contributions of these two vegetation strata to the overall NDVI are difficult to deconvolute. Furthermore the large field of view of the sensor likely minimizes the relative contribution of the understory to NDVI signal, since a large view angle reduces the gap fraction within and between the trees viewed by the sensor. It may be noted that during autumn, the NDVI signal does not appear to be influenced by the yellowing of the herbaceous vegetation stratum of *Molinia*.

In the Puéchabon forest of holm oak (Fig. 7), NDVI measurements are consistent with the phenology of this species which is mainly characterized by two major events: the sprouting of leaves and shoots, the shoot elongation and flowering in spring from March to the middle of June and occasionally in autumn (exceptionally and only on a few trees on the Puéchabon forest), and the shedding of leaves, particularly important during the phase of leaf sprouting in the spring and occasionally in autumn (La Mantia et al., 2003). The mean leaf longevity of holm oak at the Puéchabon site from leaf emergence to leaf shedding is about 484 days ( $\pm 29$  days) on average over the years 2003 to 2009 (unpublished data). Thus, the decline of NDVI curve observed in spring is the result of two biological phenomena: the sprouting of leaves and shoots and the shedding of old leaves. The inter-annual variations of NDVI are also consistent with the direct phenological observations achieved in this site (unpublished data). These observations reveal a temporal shift in the timing of leaf budburst between 2008 and the two other years. In 2007 and 2009, the date of sprouting of young leaves is Doy 129 (May 8 and May 9 in 2007 and 2009 respectively) and one week later, Doy 135 in 2008. Litterfall dynamics investigated from litterfall traps collected monthly also show a shift between 2008 and the two other years

(Fig. 8). In 2007 and 2009, the maximum litter biomass is recorded on May while in 2008 the maximum is recorded in June. Inter-annual variations in the occurrence of phenological phases are frequently observed on this species and are strongly controlled by spring and summer rainfall (Misson et al., 2011). When the conditions are favourable, leaf fall is delayed. In 2008, the spring was wet but the summer was dry, promoting a second phase of leaf fall from the end of September to the end of November, as shown by field observations. This second phase of leaf fall could explain, at least partially, the decrease of NDVI during this period.

In the tropical rainforest in French Guiana (Fig. 9), NDVI varies little over the year, as one would expect in evergreen moist forests. The interpretation of these small variations is complex because they were not consistent over the three studied years. We observed a clear decrease of NDVI in 2007 and 2008 during the short dry period in early spring (February–March), followed by an increase corresponding to the arrival of the first rains in April, but this pattern was not observed in 2009, while a relatively dry period was also observed in April–May (Figs. 9 and 10). The seasonal pattern of litterfall measured in this forest (Fig. 11) does not completely explain the decline of the NDVI signal during the short dry season. Indeed, litterfall is quite stable during winter and spring until the end of June and usually peaks in August/September before observing a decrease later. On the contrary, litterfall seasonal pattern may explain part of the slight NDVI decline observed during the second (main) dry season from the end of August to the end of October (Figs. 10 and 11). During the end of the main dry season and in synchrony with the return of rainfall and lower incident radiation, NDVI increases. This NDVI pattern may be explained by peaks in leaf fall and leaf flushes at the onset of the dry season and during dry to wet season transition period, respectively, as suggested in other studies. Morellato et al. (2000) reported that leaf flush patterns of Atlantic rain forest trees were significantly seasonal and concentrated at the beginning of the wettest seasons. The same conclusions were reported in tropical montane rain forests by Koptur et al. (1988) and Funch et al. (2002). However, these findings must be treated with caution, particularly as other studies did not reveal clear peaks in leaf flushing and showed that the phenology of tropical vegetation does not seem to be influenced by rainfall regime (Medeiros et al., 2007). Indeed, phenological patterns in tropical forests are very complex, due to the high diversity of tree species which express a wide range of phenological patterns under the control of various biotic and abiotic factors (Sakai, 2001).

As underlined above, the litterfall regime (Fig. 11) does not fully explain the seasonal variations in NDVI observed in this tropical rainforest site, and other factors thus contribute to these variations. Among these factors, seasonal variations in flowering may also contribute (Sakai, 2001), as it has been found that flowering may affect the remote sensing signal (Sánchez-Azofeifa et al., 2011) over tropical forests. Large interspecific variations in flowering periods have been found in the tropical rainforest of French Guiana (Loubry, 1994), and may thus contribute to this effect. Another factor influencing seasonal variations in NDVI could be solar radiation and its influence on the greenness of these forests. During the three years of measurements, the strongest decline in NDVI is observed during periods characterised by dry conditions and high solar radiation (from September to November and around March) (Fig. 9). This decrease can be interpreted as a slight decrease in the greenness of the studied area during these periods of low rainfall and high solar radiation.

Besides, the decrease of NDVI during the dry season is not in accordance with previous findings, based on satellite data, of Xiao et al. (2006), Huete et al. (2006) and Saleska et al. (2007) who concluded to an increase of canopy greenness during dry periods. Xiao et al. (2006) observed a maximum of canopy greenness (using MODIS Enhanced Vegetation Index EVI) at the end of the dry season or early in the wet season and concluded that the phenology of evergreen tropical forests is not controlled by rainfall but by the amount of solar

radiation regime and herbivores. For three consecutive years, we do not observe any peak of NDVI in the dry season; On the contrary, the maximum values are observed during the wet season (Fig. 10). Huete et al. (2006), using time-series of five years of MODIS EVI data over Amazon rainforests, observed a significant increase in canopy greenness from the beginning to the end of the dry season (July–November) and concluded that this increase is not in agreement with predictions of ecosystem models that highlight the role of water limitation on canopy photosynthesis in tropical rain forests during the dry season. Saleska et al. (2007) using EVI MODIS data showed similar results during 2005 drought in the Amazon. They observed an increase of canopy greenness during the peak of the drought from July to September. However, this conclusion was contradicted by Samanta et al. (2010) who concluded that Amazon forests did not green-up during the 2005 drought and explained this discrepancy by the quality of the MODIS EVI data set used. Huete and Saleska (2010) tested many procedures for the noise reduction and reconstructing of MODIS EVI time-series and confirmed the green-up of Amazon forests during the 2005 drought. This controversy is still unresolved and highlights the difficulty of interpretation of the satellite signal in the absence of ground reference measurements. Our results, based on ground-based NDVI time-series measured in the tropical rainforest in French Guiana contradict the conclusions of an increase of canopy greenness during dry seasons. Nevertheless, because of the low spatial representativeness of single tower-based NDVI measurements, further studies are required to confirm our conclusions.

In the tropical savanna site, NDVI time-series reflect the strong control that rainfall has on the growth and the structure of the herbaceous vegetation of *Loudetia simplex* (Figs. 12 and 13). In this region, climate is characterized by a wet season from October to May and a dry and cloudy season from May to October. Seasonal vegetation dynamics are mainly controlled by precipitation and fire regimes as demonstrated by other previous works in nearby similar grassland ecosystem (Laclau et al. 2002) and in other African ecosystems (Merbold et al., 2009). NDVI time-series show that the maximum NDVI is practically reached five months after burning and two months after the beginning of the wet season. Then and throughout the wet season and even in the absence of a short dry season in March, NDVI decreases slowly. This pattern is in accordance with the dynamics of green biomass observed on this site (unpublished data) and in Laclau et al. (2002). The maximum NDVI corresponds to the maximum amount of living biomass and the NDVI decay starts concomitantly with the appearance of the first senescent leaves, four months after burning.

At the agricultural site in Lonzeé, time-series of NDVI reflect seasonal changes in leaf and canopy properties (Fig. 14). In wheat crops, the decrease of NDVI observed from the middle of June in 2007 and from the middle of July in 2009 until harvest is due to leaf yellowing during the senescence process as shown in Dufranne et al. (2011) in this field and as shown in previous studies (Adamsen et al., 1999; Broge and Mortensen, 2002). In 2008, we may also note that the harvest of sugar beet does not result in an immediate drop of NDVI but in a gradual decline of around four weeks due to the crop residues that decompose slowly. In conclusion, NDVI measurements in the succession of crops highlight the strong dynamics of vegetation and offer a quantitative way of understanding of temporal variations of carbon exchanges over agricultural crops. We could for instance observe that in 2007 and after wheat harvesting, the re-growth of wheat and weeds at the beginning of autumn is also observed through GPP measurements which show a significant increase during this period (Aubinet et al., 2009).

## 5. Conclusion

*In situ* NDVI sensor constitutes a low-cost ( $\approx$ two hundred US dollars per unit) and efficient tool to track temporal variations of

canopy structure and phenological events. NDVI time-series provide effective estimates of photosynthetic biomass and constitutes accurate estimates of dates of main phenological events such as budburst and leaf yellowing. This sensor can replace and surpass visual observations and can be used as an *in situ* metrology tool to enhance the capabilities of phenology observatory networks. It can also provide information of great importance on the dynamics of vegetation covers to better understand the temporal variability of the carbon and water exchanges between the vegetation and the low atmosphere gathered in carbon flux measurements network. This new ground-based Network of NDVI measurements also provides data needed for the calibration and direct validation of satellite observations and products. Finally, time-series gathered in this ground-based NDVI network over various vegetation cover types may be considered as temporal vegetation signatures that could be used to interpret signal variations at sub-pixel scale and to unmix coarse spatial resolution satellite data.

## Acknowledgements

This study is financed by the F-ORE-T “Observatoires de Recherche en Environnement (ORE) sur le Fonctionnement des Écosystèmes Forestiers” ECOFOR, INSU, Ministère de l'Enseignement Supérieur et de la Recherche, France. We would like to express our profound gratitude to Daniel Berveiller and Laurent Vanbostal for their help in the manufacturing NDVI sensors and measurements. We also thank all those involved in the data collection process on all study sites. We are very grateful for thorough and helpful comments from reviewers of the manuscript.

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