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Estimation of leaf area index using ground-based remote sensed NDVI measurements: validation and comparison with two indirect techniques

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Abstract. This study took place in an evergreen scrub oak ecosystem in Florida. Vegetation reflectance was measured in situ with a laboratory-made sensor in the red (640–665 nm) and near-infrared (750–950 nm) bands to calculate the normalized difference vegetation index (NDVI) and derive the leaf area index (LAI). LAI estimates from this technique were compared with two other nondestructive techniques, intercepted photosynthetically active radiation (PAR) and hemispherical photographs, in four contrasting 4 m^2 plots in February 2000 and two 4 m^2 plots in June 2000. We used Beer's law to derive LAI from PAR interception and gap fraction distribution to derive LAI from photographs. The plots were harvested manually after the measurements to determine a "true" LAI value and to calculate a light extinction coefficient (k). The technique based on Beer's law was affected by a large variation of the extinction coefficient, owing to the larger impact of branches in winter when LAI was low. Hemispherical photographs provided satisfactory estimates, slightly overestimated in winter because of the impact of branches or underestimated in summer because of foliage clumping. NDVI provided the best fit, showing only saturation in the densest plot (LAI = 3.5). We conclude that in situ measurement of NDVI is an accurate and simple technique to nondestructively assess LAI in experimental plots or in crops if saturation remains acceptable.

Résumé. A l'aide d'un capteur réalisé au laboratoire, nous avons mesuré in situ la réflectance d'un peuplement bas de chênes à 655 et 825 nm pour calculer la NDVI et estimer le LAI. Ces estimations de LAI ont été comparées à celles obtenues par deux autres techniques non destructrices dans six placettes de 4 m^2, en février et juin 2000 : la mesure du PAR intercepté (rayonnement photosynthétiquement actif) et la technique des photographies hémisphériques. Pour calculer le LAI, nous avons utilisé la loi de Beer à partir du PAR intercepté et la fraction de trouées pour exploiter les photographies. Les feuilles de chaque placette ont été récoltées à la main après les mesures afin d'obtenir un LAI de référence et de calculer un coefficient d'extinction (k). La technique du PAR intercepté a été affectée par une importante variation du coefficient d'extinction, due à l'interception plus forte des branches en hiver lorsque le LAI était peu élevé. Les photographies hémisphériques ont fourni des valeurs de LAI satisfaisantes, légèrement surestimées en hiver à cause des branches et sous-estimées en été à cause de l'agrégation du feuillage. Le NDVI a fourni les meilleurs résultats, montrant toutefois une tendance à la saturation dans la placette la plus dense.

Introduction

Leaf area index (LAI) is a major parameter in ecosystem understanding and a relevant input to productivity models. Whatever the method used, LAI determination is time-consuming and somewhat inaccurate. At long-term experimental sites, LAI has to be determined routinely and nondestructively. A number of methods can be applied, each with advantages and disadvantages.

Allometric relationships can be used to predict plant leaf area from plant stem diameter, stem length, or stem volume index (Ceulemans et al., 1993). However, establishing robust, accurate relationships from representative samples can be time-consuming. Moreover, these relationships, determined on plants at a given phenological state or in a given season, may only be appropriate for the times during which they were generated.

Indirect methods, based on the coupling between light penetration and canopy structure, are a good alternative in homogeneous stands (see review by Norman and Campbell, 1989). Techniques based on reflectance in the red (R) and near-infrared (NIR) spectral bands are widely used in airborne and spaceborne remote sensing studies but are also promising at ground level. The normalized difference vegetation index

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(NDVI) is probably the most commonly used index for analyzing vegetation on a continental scale (Rouse et al., 1973; Gamon et al., 1995). This spectral index makes use of radiances or reflectances in NIR and R spectral regions because they enhance the contrast between soil and vegetation (Tucker, 1979). Such an approach should provide satisfactory estimates of LAI rather than plant area index (PAI) because only green parts are taken into account. This is highly relevant in photosynthesis and carbon balance studies. We designed a dual-band sensor to measure NDVI in the field and tested it together with other indirect methods at two periods (February and June 2000) in a low evergreen tree population in Florida.

Material and methods

General context and field site

This work was a preliminary study to determine the best way to keep track of LAI in an elevated-CO_2 experiment in Florida within the National Aeronautics and Space Administration (NASA) Kennedy Space Center (28°38′N, 80°42′W), in a scrub–oak natural ecosystem. Although 27 species of plants occur in this ecosystem, up to 85% of aboveground biomass was composed of three rhizomatous evergreen scrub oak species, *Quercus myrtifolia* Willd., *Quercus geminata* Small, and *Quercus chapmannii* Sargent (Schmalzer and Hinkle, 1992). The vegetation was low in stature (~60 cm), as the site had been burnt in January 1996.

Measurements were done at two contrasting periods. Four 4 m^2 calibration plots (C1–C4) were marked out in February 2000, and two 4 m^2 calibration plots (C5 and C6) in June 2000. In these six plots, three indirect techniques to assess LAI were implemented: NDVI, intercepted photosynthetically active radiation (PAR), and gap fraction using hemispherical photographs. Immediately after these measurements the plots were manually defoliated, the area of a subsample of the leaves (approx. 0.1 m^2) was measured using an LI-3100 leaf area meter (LI-COR, Inc., Lincoln, Nebr.), and all leaves, including those subsampled, were dried to constant weight at 80°C and weighed. Actual leaf area of the calibration plots was determined by scaling from the leaf area and dry weight of the subsample to the dry weight of the complete plot. In the following text we refer to this green leaf area index as "true LAI".

NDVI measurement

We used a hand-held device that was a modified version of a sensor we designed previously to measure the zeta ratio (660 nm : 730 nm; Pontailler and Genty, 1996). The sensor was equipped with two photodiodes having a large photosensitive surface to ensure a high sensitivity. They measured radiances centred around 655 nm (R) and 825 nm (NIR). The R channel used a gallium arsenide phosphide photodiode (G1117, Hamamatsu Photonics, Hamakita, Japan) and a long-pass glass filter, providing a sharp cutoff below 640 nm (RG 645, Schott Glaswerke, Mainz, Germany). The NIR channel used a silicon photodiode (S 1226 8BK, Hamamatsu Photonics) and a long-pass glass filter (RG 780, Schott Glaswerke), providing a sharp cutoff below 770 nm. The characteristics of both detectors and filters are presented in **Table 1**. The body of the sensor was made of polytetrafluoroethylene (Teflon®) surrounded by a stainless steel housing (**Figure 1**). The upper part had a 5 mm thick acrylic diffuser (Altuglass® 740, Altulor, Courbevoie, France) glued to a black polycarbonate mount. The two detectors were facing the diffuser. Their pins were directly soldered onto a screened cable that linked the sensor to the display unit.

The sensor was then calibrated against a spectroradiometer (LI-1800, LI-COR, Inc.), considering bandwidths equal to 640–660 nm and 780–920 nm for R and NIR, respectively. 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. As a result, no amplification was necessary, contrary to similar sensors using silicon diodes and interference filters (Methy et al., 1987). Data were displayed on a 3 1/2 digits digital voltmeter (DPM 125, Lascar Electronics Ltd., Salisbury, U.K.).

Table 1. Characteristics of the two photodiodes and the two long-pass glass filters used in the NDVI sensor (manufacturer's specifications).

(a) Photodiodes

Model	Active area (mm^2)	Spectral range (nm)	Peak wavelength (nm)
Hamamatsu G1117	31.4	300–680	640
Hamamatsu S1226 8BK	33.6	320–1000	720

(b) Long-pass glass filters

		Wavelength (nm)		
Model	Thickness (mm)	1% transmission	50% transmission	95% transmission
Schott RG 645	3	635	645	670
Schott RG 780	3	760	780	825

Note: A set of diodes costs 230 euro, and a set of two 5 × 5 cm filters costs 100 euro.

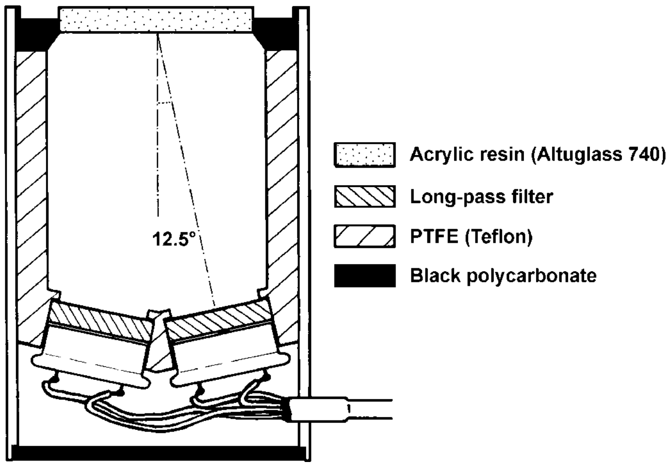

Figure 1. Longitudinal section of the NDVI hand-held sensor (length 55 mm, diameter 42 mm).

The two analog outputs could also be connected directly to dataloggers or chart recorders.

The relative spectral response of both channels was monitored using a halogen-stabilized light source and a monochromator (H10, Jobin Yvon Inc, Longjumeau, France), combined with simultaneous energy measurement with a pyranometer (CE 180, Cimel Electronique, Paris, France). The two sensors presented a maximum sensitivity at ~655 and ~825 nm, respectively (**Figure 2**). The R spectral band was narrow (640–665 nm), whereas the NIR spectral band was much wider (750–990 nm), which is allowable because many authors consider as relevant all wavebands between 750 and 1000 nm (Elvidge and Chen, 1995).

The sensor was placed immediately above the canopy top (~50 cm), looking downwards. A black hood was placed on the head of the sensor to restrict the field of view to 60° to discard oblique radiation that may come from outside the examined plot. The area of plant canopy viewed by the sensor was about

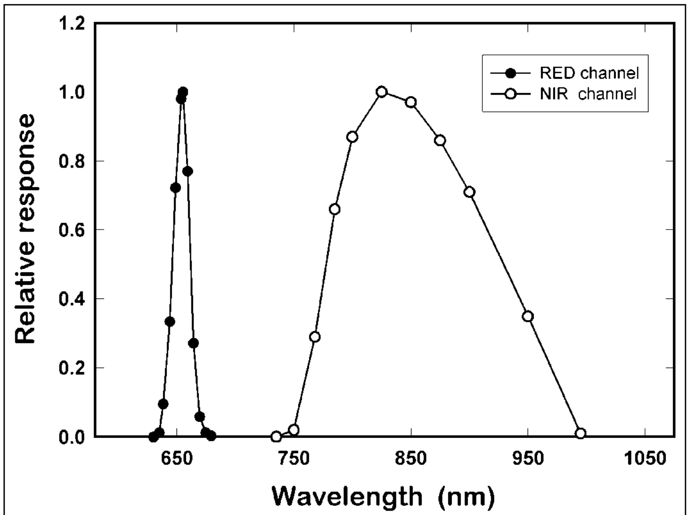

Figure 2. Relative spectral response of the two channels of the NDVI hand-held sensor.

1 m^2. Thirty-six (3 × 12) measurements were made on each plot and on a bare soil with litter (after total harvest).

Measurements were performed on sunny days (to provide highest resolution) and at a constant sun elevation of 40–45° (i.e., at solar noon in February and 3.5 h before or after noon in June). Reference measurements were made for incident light, showing a fairly stable ratio of R to NIR, ranging from 1.53 ± 0.05 in February to 1.67 ± 0.08 in June. This variation resulted from two phenomena: higher interception in the NIR range in summer because of increased water vapour content of the air, and temperature sensitivity of the sensor.

NDVI was expressed as

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}} \tag{1}$$

where NIR and R are the radiance in the near-infrared and red range, respectively, in the field of view of the instrument, according to the bandwidth specifications of the instrument.

Intercepted PAR

LAI can be determined by performing radiation measurements above and below the canopy. Use of the PAR spectral range (400–700 nm) was preferred because one can expect better resolution than that using global radiation (300–2500 nm) because leaves absorb about 85% of incident PAR and only 25% of incident NIR radiation (Gates, 1962; Wooley, 1971). Overcast sky conditions were preferred to direct sunlight because information from various angles of incidence is then averaged.

We used two laboratory-made sensors to measure the PAR above and below the canopy. The sensors had a different shape but were both equipped with similar detectors, namely gallium arsenide phosphide photodiodes (G1116, Hamamatsu Photonics) combined with a blue filter (FG6, 2 mm, Schott Glaswerke). The spectral response of this combination ranged from 390 to 680 nm (Pontailler and Genty, 1996) and was well adapted to those measurements because of the absence of sensitivity above 700 nm. A cosine-corrected sensor was installed 2.5 m above the canopy, and a 35 cm long sensor, using 25 diodes, was placed at ground level at eight different locations successively. The two sensors were connected to a CR23x datalogger (Campbell Scientific Inc., Logan, Utah), and data were recorded for 5 min at every location (averaged from raw data at 6 s sampling interval).

LAI can be calculated using Beer's law as follows:

$$\mathrm{LAI} = -\frac{1}{k}\ln\left(\frac{I}{I^{\mathrm{o}}}\right) \tag{2}$$

where I is the transmitted radiation, I^{o} is the incident radiation, and k is the extinction coefficient. This approach requires a reliable estimation of k, mainly related to leaf optical properties, distribution, and orientation. In this experiment, we could use true LAI values to determine k.

Hemispherical photography

This technique of hemispherical photography has been widely used in crops and forests for 40 years (Evans and Coombe, 1959). The analysis of a circular image, taken upwards at ground level with a fisheye lens and covering 180°, enables the calculation of LAI by measuring canopy gap fractions at various angles. Recently, the development of digital photography made this technique easier, faster, and cheaper. As in the intercepted PAR method, both leaves and branches are taken into account. This method requires overcast sky conditions to avoid scattering light. It is not applicable to very low crops or canopies. Another problem with this method is that foliage clumping, which causes important underestimations in LAI determination, is difficult to determine with a good accuracy.

Four photographs were taken in each plot using a digital camera (CoolPix 950, Nikon Corporation, Tokyo, Japan) fitted with a fisheye adapter lens (Nikon FC-E8). Images were 24-bit TIFF files (uncompressed) with a resolution of 1600 × 1200 pixels. Pictures were analyzed (conversion into a binary (1 bit) image according to a user-defined threshold, gap fraction determination, and LAI calculation) with Gap Light Analyzer software (Frazer et al., 2000). LAI was derived from gap fractions in five concentric rings covering zenith angles of 0–75° (Welles and Norman, 1991).

Results

NDVI

The best fit between true LAI and NDVI was obtained using a negative exponential function (**Figure 3**). Measurements performed in June (S5 and S6) did not differ significantly from those performed in February. As expected, some saturation occurred when LAI increased.

Using this negative exponential relation, we could estimate LAI and compare these values with reference values (true LAI). We obtained a satisfying linear relation (r^2 = 0.958) with a slope less than 1 and a non-negligible intercept (**Figure 4**).

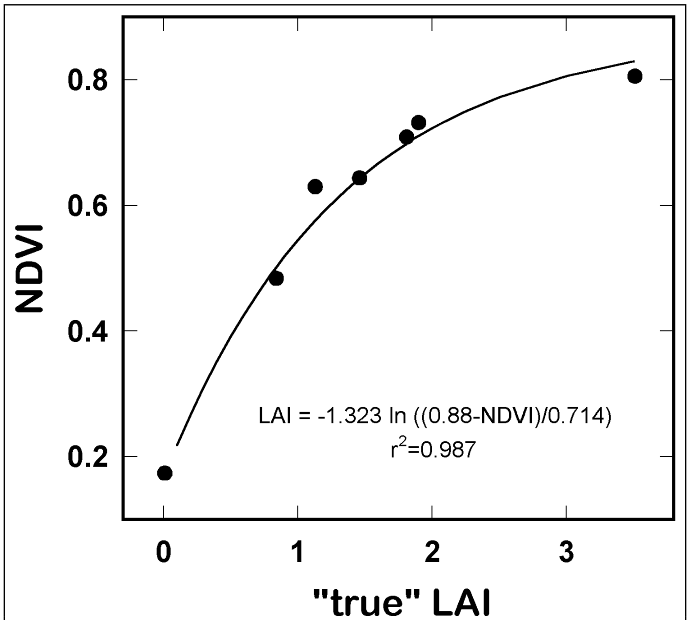

Figure 3. Relationship between NDVI and true LAI (from destructive sampling) on seven contrasting plots, including a bare soil.

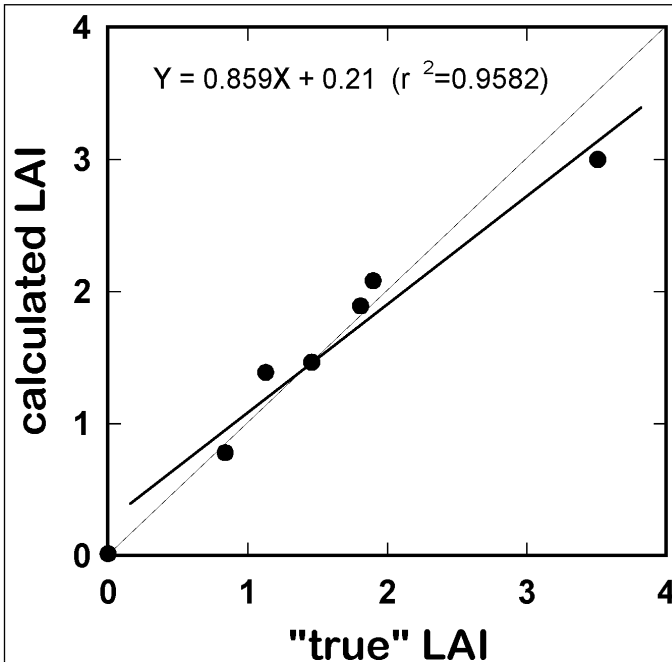

Figure 4. Relationship between true LAI (from destructive sampling) and calculated LAI. Calculated LAI was derived from the negative exponential relationship shown in **Figure 3**.

Intercepted PAR

Values of k calculated using Beer's law were high and extremely variable, ranging from 0.74 to 1.22. Values observed in February were higher than those observed in June (**Figure 5**). Thus it seemed unrealistic to use a mean extinction coefficient in this study. We assumed that light intercepted by branches and stems was relatively less important in summer as LAI increased, so we used a variable k based on the transmission value as shown in **Figure 5**

This calculation mode greatly improved the correlation between calculated and true LAI (**Figure 6**): $Y = 0.5967X + 0.602$ ($r^2 = 0.935$) for constant k, whereas $Y = 0.9569X + 0.098$ ($r^2 = 0.957$) for variable k. In particular, the slope of the relation for variable k is much closer to 1.

Hemispherical photographs

Of the three techniques implemented in this study, LAI determination using hemispherical photographs was the only one requiring no calibration.

We obtained a satisfactory fit between true LAI and LAI derived from hemispherical photographs (**Figure 7**). The five plots with LAI less than 2 showed some overestimation,

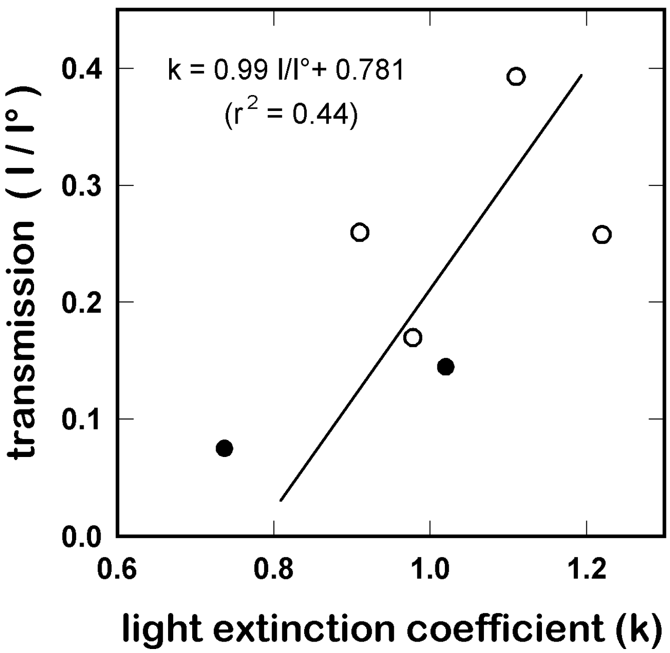

Figure 5. Relationship between PAR transmission and light extinction coefficient in six contrasting plots at two different periods. Solid symbols denote June 2000, and open symbols February 2000.

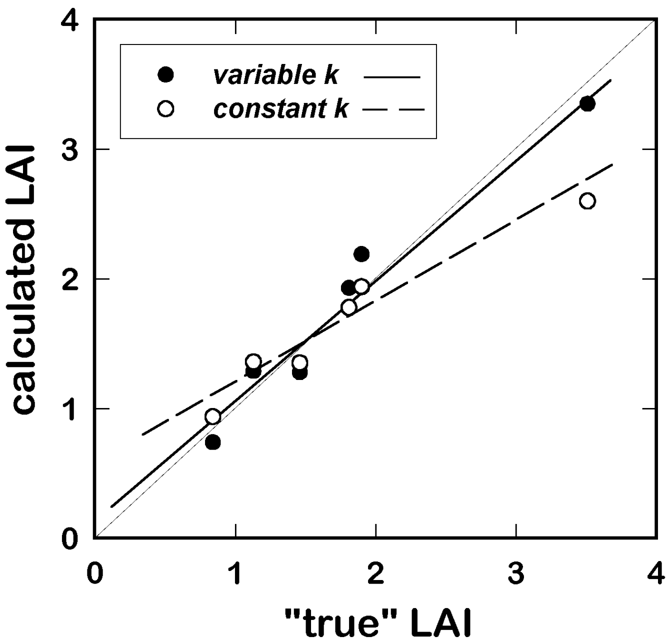

Figure 6. Relationship between true LAI (from destructive sampling) and LAI estimated from PAR transmission measurements, using a mean extinction coefficient (0.996) and a variable extinction coefficient (from the equation in **Figure 5**).

probably because of the presence of woody branches and stems in the images. By contrast, the plot with the highest vegetation coverage showed an underestimated LAI value, probably owing to foliage clumping. This data point had an important

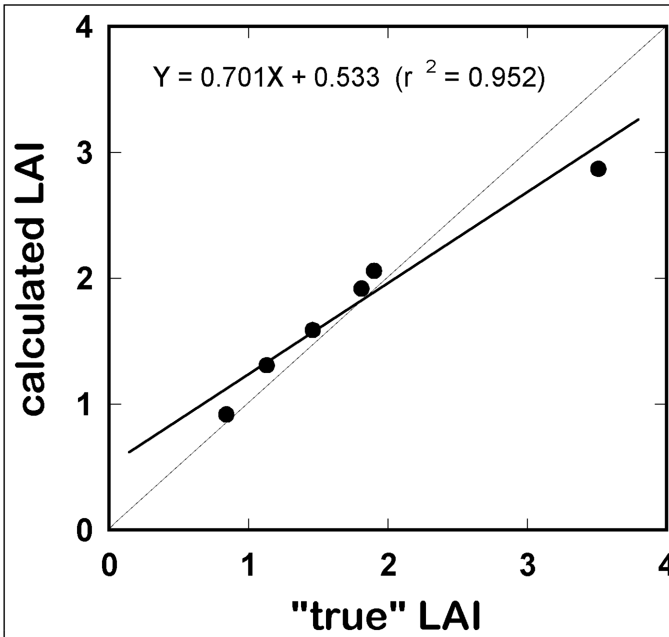

Figure 7. Relationship between true LAI (from destructive sampling) and estimated LAI, using hemispherical photographs.

weight and significantly lowered the slope of the regression line (0.7).

Discussion and conclusions

The three methods used in this study exhibited advantages and drawbacks. The intercepted PAR method was relatively easy to implement but suffered because of the large impact of branches and stems on light interception and the difficulty in estimating a reliable light extinction coefficient (k). We could calculate k in our plots because we assessed a true LAI value from time-consuming destructive sampling. We found that the value of k was surprisingly high and variable (0.74–1.22). This was probably due to the presence of numerous branches and stems in the scrub oak, which have a considerable impact on light transmission. The value of k was overestimated because it was computed from a transmission value considering all aboveground organs (leaves, branches, and stems) and from a true LAI considering leaves only (Equation (2)). The value of k was variable because the relative impact of branches varied throughout the season, being lower after the setting up of a new flush of leaves. Values of k greater than 1 were occasionally mentioned in the literature: Baldocchi et al. (1984) reported a high value (1.06) in a leafless oak forest. The lower value observed in this experiment (0.74) is in agreement with values usually mentioned in summer for closed canopies (Norman, 1980; Baldocchi et al., 1984).

We could improve the calculation of LAI by varying the value of the extinction coefficient as a function of PAR transmission, but this method is probably not applicable to all stands. Unfortunately, there is no simple way to estimate the extinction coefficient. If one uses mean values from the literature, substantial errors can occur in the calculation of LAI.

As a conclusion, the intercepted PAR method must be considered with caution when tracking LAI over a relatively long period or in plots including different species because the extinction coefficient is variable and difficult to assess.

The technique using hemispherical photographs is easier to implement since the availability of digital photography. It is not applicable to dense grass stands because the camera modifies the surrounding canopy. It is also not recommended in high forests with small leaves (when a leaf is smaller than 1 pixel). This technique was the only one that required no calibration; however, the resulting LAI depends on the way the photographs and data are processed. Among the processing steps, the choice for a threshold when converting the 24-bit image to a binary image is critical because it is partly subjective. The data-processing technique suggested by Welles and Norman (1991) is widely used because it is implemented in numerous pieces of software and is more or less compatible with the operating mode of the LAI-2000 plant canopy analyzer (LI-COR, Inc.). The ring arrangement and the number of azimuth sectors, however, may have a considerable impact on the final result (Planchais and Pontailler, 1999; Dufrêne and Bréda, 1995).

For photographs, the relation between true and estimated LAI was affected by a large discrepancy in the densest plot (**Figure 7**). We supposed that this was mainly caused by foliage clumping. When calculating LAI using this method, leaves are supposed to be randomly distributed, which is not always the case. This causes an underestimation of LAI. This is also observed with commercial devices using optical methods (Fassnacht et al., 1994). By contrast, this technique, as in the previous one, considers leaves, branches, and stems together, which may lead to an overestimation of LAI, especially in sparse plots of woody species.

In situ NDVI measurement is not a new technique (Pearson et al., 1976; Tucker et al., 1979), but it has not been widely used to date. This is probably due to the lack of a simple portable instrument. However, the results are very encouraging, as shown by the very good fit between NDVI and LAI according to a negative exponential function ($r^2 = 0.987$; **Figure 3**). The sensor we developed is cheap and easy to tool, requiring no knowledge of electronics. It enables fast and easy measurements, making numerous replications possible. Contrary to other indirect field techniques, NDVI measurement senses mainly green plant parts and ignores branches or woody stems. It is well adapted to low canopies where other techniques may be difficult to implement. In situ NDVI measurement is less affected by atmospheric conditions than spaceborne NDVI measurement.

As expected, we observed some saturation effect. Saturation is moderate in the range of values determined here, making it possible to obtain reliable estimations of LAI up to 3 or even greater. The explanation for this is that, even if the canopy reflectance in the red band reaches an asymptote at LAI values of 2–3, its reflectance in the near infrared continues to increase with an increase in leaf area (Peterson and Running, 1989). Nevertheless, the accuracy of this technique decreases when LAI increases. NDVI is also affected by background materials when LAI is low. New "hybrid" indices such as the renormalized difference vegetation index (RDVI) proposed by Roujean and Breon (1995) are supposed to minimize the drawbacks of NDVI in both low and high vegetation coverages.

This technique requires a calibration because the NDVI–LAI relationship varies according to species, canopy geometry, and soil optical properties. It appears more adapted to examination of the long-term evolution of canopies or analysis of the spatial variability of heterogeneous or discontinuous covers. By contrast, it will not be easy to implement this method over mature forests, but it has been shown that it is possible to derive LAI from transmittance measurements (in the R and NIR bands) performed at ground level (Jordan, 1969). Although a laboratory-made sensor used in this study was especially designed for this purpose, radiation sensors operating in two user-defined bands are also commercially available (Skye Instruments, Llandrinod Wells, U.K.).

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