DIRECTIONAL AND TEMPORAL VARIABILITY OF THE APAR/VI RELATIONSHIPS. THE CASE OF A SUNFLOWER CANOPY

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ABSTRACT

Detailed biomass and structure measurements as well as PAR balance and bidirectional and polarized reflectances in various wavebands from 450 nm to 1750 nm have been performed over a sunflower canopy in Montfavet, France, during July-August 1991. Preliminary results show that the vegetation indices (NDVI or TSAVI) computed from the red and near infrared reflectances exhibit strong directional and temporal (variation with the sun zenith angle) features. The relationship between the vegetation indices and the PAR fraction absorbed or intercepted by the canopy are likely to vary greatly with these factors. These experimental results will serve as a basis for further research involving the spectral, directional and polarization characteristics of the reflected light.

INTRODUCTION

The cartography and monitoring of the amount of carbon fixed by vegetation are important remote sensing objectives for the EOS era. Both at a large scale for the global carbon cycling, and at a more local scale for the management of agriculture, estimates of the biomass production or the carbon flux intercepted by vegetation are required. As a result of the photosynthetic activity, the biomass production can be approximated by energy conversion processes. The fraction of the solar incoming photosynthetically active radiation (400-700nm) (PAR), which is intercepted by the canopy is transformed into dry matter with an efficiency which is mainly controlled by climatic and edaphic factors. Under certain conditions, this conversion efficiency has been found to be constant when integrated over sufficient long time periods [1]. Researchers have shown both experimentally [2] and theoretically [3] that the PAR fraction intercepted (IPAR) or absorbed (APAR) by the canopy is strongly related to the radiometric response of the canopy. Evidence of the functionallity of this relationship is demonstrated by analyzing the processes governing the capability of a canopy to reflect or absorb the light [4]. The structure of the canopy (spatial arrangement of the vegetation elements) and the optical properties of the elements (leaf, stems, soil) are the only biophysical vegetation variables needed to describe photon transport in the canopy and so control both its reflectance and absorptance throughout the spectrum. Many scientific studies have related the APAR fraction to simple vegetation indices such as the normalized vegetation index NDVI [5] or the TSAVI [6]. However, the magnitude of the scatter in the experimental relationships as well as sensitivity analyses performed with canopy radiation transfer models [6] demonstrate that other factors might affect this relationship. This has been clearly demonstrated for the soil optical properties. But the geometry with which reflectance data are acquired (sun position, view direction) are other potential 'disturbing' factors. The objective of this research is to investigate the later problem, analysis of the large variations observed when comparing the relationships between APAR (or IPAR) and the corresponding vegetation indices (VI) acquired for various irradiance/view geometries. The research is based on experimental results collected during the 1991 summer over a sunflower canopy.

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MATERIAL AND METHODS

The canopy. Data were collected in Montfavet, France (4° 51'E; 43°55'N) in July-August 1991 on a level plot 100 m by 100 m. The relatively bright soil is classified as a calcarous fluvissol with about 30% clay. The sunflower canopy (cultivar Frankasol) was sown June 11 and emerged June 28. To minimize row effects which may complicate data interpretation, the canopy was sown in perpendicular regularly spaced rows 0.43m apart. The canopy was irrigated and fertilized so that no severe stresses were experienced.

Canopy biophysical characteristics. The plant density was evaluated after emergence on 5 randomly located 9.0 m^2 areas. Throughout the measurement period, three randomly located samples of 1.5m^2 were collected weekly. The average plant total above ground biomass (fresh and dry), leaf biomass, stem biomass and leaf area were measured as well as the plant height and, for each individual leaf layer, the shape, dimensions and height of the laminae. Throughout each of four days during the season, the leaf normal direction was measured on all leaves of 8-15 plants using a specially designed T shaped device called 'goniophyllometer'. At the bottom of the T, a 0.05m transparent disk allows the apparatus to be visually positioned normal to the leaf. A compass measures the azimuth angle of the leaf, and a clinometer connected to a data logger measures the leaf inclination angle. Spectral and directional leaf optical properties were evaluated. The directional/hemispherical reflectance and transmittance spectra of dorsal and ventral faces of 7 leaves were measured with a CARY D17 spectrophotometer on June 26. The spectral resolution varied between 1 and 3 nm, and the sampling step was 4 nm in the 400-800nm region and 10 nm in the 700-2500 nm region. The directional reflectance properties of 16 leaves were measured using the 'POLAR:I' system [7].

Photo 1. The tower (12 m high) used to perform the reflectance measurements

Radiative balance in the PAR domain. Two sets of sensors were used to monitor the radiative balance of the canopy. The first one is composed of LiCor quantum cells and linear sensors. One quantum cell measured the incoming radiation while two others placed at 0.5 m above the top of the canopy measured the reflected hemispherical flux. A fourth sensor, placed at 1.0 m height above a bare soil area 5m x 5 m from which all plants were removed, monitored the soil albedo. Two linear sensors were placed horizontally underneath the canopy in order to measure the hemispherical transmitted radiation. The second set of sensors consisted of SLAM sensors [8] specially designed to measure hemispherical fluxes in the PAR region. Six to 10 individual sensors, each approximately 0.04 by 0.08 m, were connected in a series electrical circuit. Twelve individual cells measured the incoming PAR radiation. Twenty cells placed along a 2.0 m transect located 2.0 m above the soil measured the hemispherical reflected flux. One hundred individual sensors were placed horizontally on the soil underneath the canopy to measure the transmitted hemispherical flux. All measurements were recorded on Campbell data loggers each fifteen minutes. All the sensors were intercalibrated and found to have a cosine response with sun zenith angle.

Radiometers name	Channels #	polarization	FOV	wavelength range (nm)
BARNES 108	5-7	Pol	1°	450-520
BARNES 104	1-3	Pol	1°	520-600
BARNES 108	1-3	Pol	1°	630-690
BARNES 105	1-3	Pol	1°	760-900
BARNES 108	5-7	Pol	1°	1150-1300
BARNES 104	5-7	Pol	1°	1250-1750
CIMEL ouest	1-3	Pol	12°	500-590
CIMEL est	1-3	Pol	12°	610-680
CIMEL zenith	1-3	Pol	12°	790-890
CIMEL sud	1	no Pol	12°	500-590
CIMEL108	2	no Pol	12°	610-680
CIMEL108	3	no Pol	12°	790-890

Table 1. Characteristics of the radiometers used in the experiment.

Radiometric measurement. A 12 m height tower, Phot. 1, was constructed in the center of the experimental field. At its top, bearings in a vertical post supported an horizontal beam (3.2 m long) which could be azimuthally rotated. Seven radiometers were mounted on an instrument platform fixed at one end of the beam. A wheel fixed at the other end allowed the instrument platform to be manually rotated in both azimuth and zenith angles. In order to estimate the polarized bidirectional reflectance factor of the canopy, polarized spectral data were collected in 9 wavelength bands (3 SPOT and 6 TM) with three Barnes MMR [9] and four Cimel [10] radiometers, Table 1. A string of spectral data was collected when the horizontal beam was oriented toward each of 10 azimuth angles: The 8 compass directions plus the principal plane and the perpendicular plane. Each string of data consisted of approximately 70 radiative measurements collected in approximately 2 minutes at 2° increments over a scan angle of ± 70° about nadir. For each radiometer, a sequence of data consisted of calibration measurements over a white, horizontal, painted barium sulfate panel, dark current measurements, 10 strings of canopy radiance measurements and a second calibration over the barium sulfate panel. Data from all radiometers were recorded on an Orion Schlumberger data logger. Each sequence took about 45 minutes to complete. Irradiance was monitored with a LiCor cell connected to the data logger and mounted at the top of the tower. Depending on the atmospheric conditions, 2 to 6 sequences were recorded throughout the day. All the data are later processed and calibrated into absolute bidirectionnal reflectances using the Barium sulfate spectral and directional characteristics measured prior to the experiment in a laboratory.

Atmospheric and Irradiance data. The atmospheric conditions during the radiometric measurements are evaluated using pyranometers and sunphotometers. After collection of each sequence of canopy radiometric data, two strings of sky data were collected with the radiometers oriented in the principal and perpendicular planes, allowing characterization of the incoming radiation flux both in direction and polarization.

RESULTS

Canopy structure and PAR balance. The Leaf area index (LAI) and total above ground dry matter show similar smooth patterns with time, Fig. 1. The intercepted PAR fraction (IPAR=1-T, where T is the transmitted PAR fraction) decreases drastically as IPAR reaches an asymptotic plateau after day 205, corresponding to an LAI value close to 2.5. The photosynthetic efficiency, the efficiency with which the canopy converts the intercepted PAR light into dry matter, is computed as the ratio between the increase in the total above ground biomass and the corresponding amount of PAR energy that the canopy has intercepted over the same time period (5 days in this case). The photosynthetic efficiency increases with canopy development from about 1.0 g.MJ^{-1} at the beginning to about 3.0 g.MJ^{-1} when the maximum leaf area index is reached. This efficiency increase might be partially due to the fact that plants allocate some photosynthates to developing their root systems, biomass which we ignored in estimating the photsynthetic efficiency. However, the values are in the range of previous results reported in the litterature. The leaf orientation exhibits a strong, well known heliotropic behavior described in a previous paper [11].

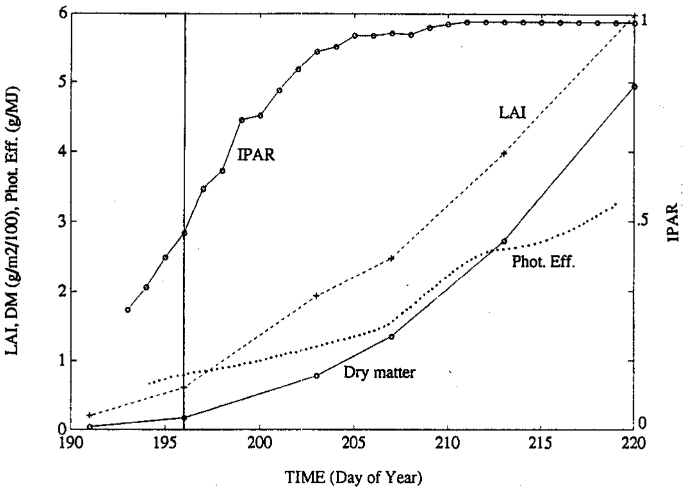

Figure 1. Leaf area index (LAI), biomass (Dry Matter, DM), intercepted PAR (IPAR=1-T, right scale) and photosynthetic efficiency (Phot. Eff.) estimated for the sunflower canopy during its development.

The reflectance and PAR, Fig. 2, data presented here were collected during July 16 when LAI =0.6, and the vegetation coverage was about 40% to 50%. The hemispherical reflectance does not change significantly throughout the day, remaining close to 0.1 as a function of solar zenith angle. The transmittance, on the other hand, is maximum at noon (θ_s=22°) and decreases significantly as θ_s increases. The PAR absorptance, estimated by balancing the PAR in the canopy, Fig. 2, exhibits an inverse behavior.

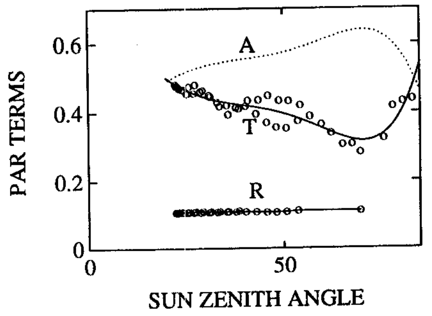

Figure 2. Reflected (R), transmitted (T) PAR terms measured with the "SLAM" cells during July 16 1991 as a function of sun zenith angle. The circles correspond to the data and the solid lines, to a polynomial fitting. The dashed curve represents the absorbed fraction (A=1-R-T(1-Rs), where Rs is the soil reflectance assumed here to be Rs=0.20 and lambertian).

Radiometric data. Fig. 3 presents data acquired in the sun principal plane for two contrasted wavebands (red (Barnes 108, Ch. 1-3)) and near infrared (Barnes 105, Ch. 1-3)). Because of the small field of view (1°) of the radiometers, the data have been smoothed using a moving "boxcar" window 7.5° wide. Figures 3a to 3c show an angularly broad hot spot, which is to be expected for a canopy containing leaves relatively large as compared to the canopy height. The specular componant, the difference between the total and the diffuse reflectances, is particularly low when observed around the sun position. However, even in the specular direction (θ_{view}=-θ_s), the specular componant is weak due to the low coverage of the vegatation. The heliotropism of the canopy, which might create a local maximum gap fraction for θ_{view}=θ_s-90° in

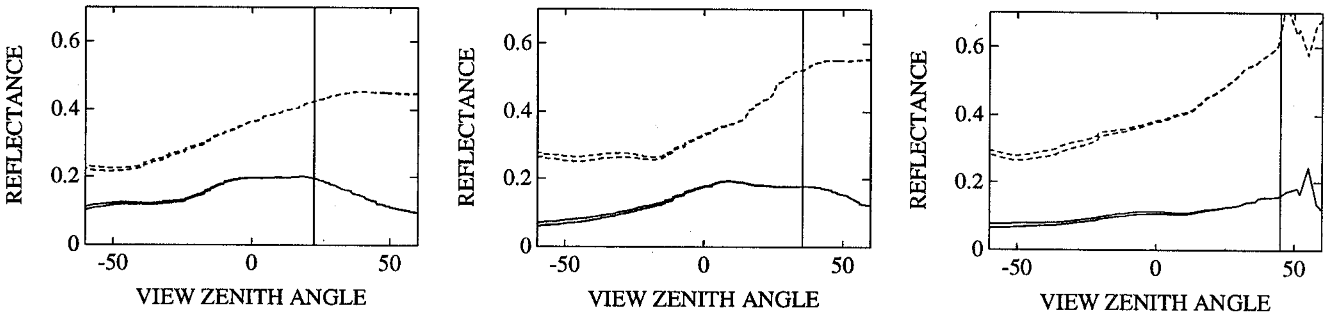

Figure 3. Directionnal variation of red (solid lines) and near infrared (dashed lines) reflectances observed on July 16 1991 for θ_s=22.5° (a), θ_s=35.5° (b), θ_s=45° (c). The data are presented in the sun principal plane, the sun position at the time of the measurements being indicated by the vertical line. Both the total and diffuse components of the reflectance are separated for each channel.

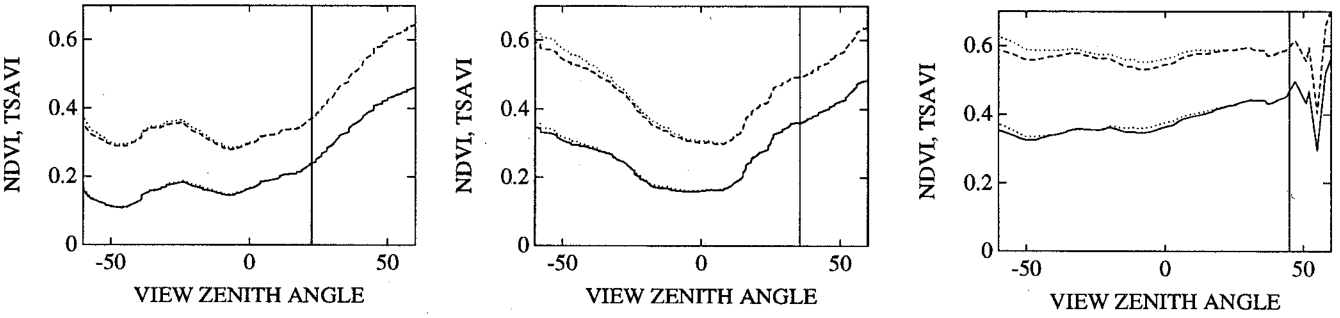

Figure 4. Directional variation of NDVI (dashed lines) and TSAVI (solid lines). This figure correspond to the data presented in Fig 3. The dotted lines are the vegetation indices evaluated using only the diffuse component of the reflectance.

the principal plane is not very obvious on both the diffuse and the specular componants. Further analyses are required, taking into account the soil optical properties, to demonstrate these particular features. However, both view direction (θ_{view}) and time of the measurement (associated with θ_s) induce large variations in the reflectance observed.

DISCUSSION AND CONCLUSION

Most relationships between the fractions of intercepted (IPAR) or absorbed (APAR) PAR and the canopy radiometric response are based on the use of some vegetation indices. The variations with the view position and the time of the measurements are shown on Fig. 4 for the normalized difference vegetation index (NDVI) and an alteration of this index which minimizes the soil background effects, the TSAVI (transformed soil adjusted vegetation index) vegetation index [6]. In this case, the weak contribution of the specular componant induces a tiny decrease in the vegetation indices. However, both spectral indices are significantly affected by the view angle as well as the time of the measurement (θ_s). These factors may change the values of the vegetation indices by more than 20% and introduce scatter into their relationship with the daily integrated PAR absorbed (or intercepted) by the canopy. In the same way, the relationships that might exist between these vegetation indices and instantaneous APAR - if both were estimated from coincident data - are likely to change from one view configuration to an other.

These preliminary results demonstrate the need to develop alternative techniques to relate more precisely the PAR balance terms to the specular and diffuse reflectances sensed in various wavebands and under various sun/view configurations. In developing these alternative techniques, it will be necessary to employ not only the traditional spectrally based vegetation indices, but also to utillize information extracted from the directional variation of the canopy polarized reflectance from which the specular component may be calculated. One important objective of this research is to investigate problems related to reflectance model inversion to evaluate the PAR balance. However, any improvements in our ability to estimate PAR have to be evaluated over time periods larger than the day or the week and over spatial scales compatible with various satellite capabilities.

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