

fAPAR (fraction of Absorbed Photosynthetically Active Radiation) estimates at various scale

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Abstract - This paper reviews the several methods available for estimating the fAPAR, both at local and large scale. The fAPAR definition is first discussed with regards to the directionality of the incident radiation. Then, the several techniques to estimate fAPAR from local ground measurements are reviewed with emphasis on the sampling strategy. We then describe methodologies to upscale fAPAR measurements over larger spatial domains. The several medium resolution fAPAR products available at the global scale are then presented. These products are intercompared over a sample of sites representative of the global domain. Finally, the accuracy of the products is evaluated against the fAPAR values derived from ground measurements. Conclusions are drawn on the suitability of the current products for vegetation monitoring and modelling and ways of improvement are proposed.

Keywords: Environment, Monitoring, Land, FAPAR, Scale, Product, Measurement

1. INTRODUCTION

The fraction of Absorbed Photosynthetically Active Radiation (400-700nm), $fAPAR$, is one of the 13 essential climate variables defined by the Global Terrestrial Observing System (GTOS). It is closely linked to canopy functioning processes such as canopy photosynthesis, carbon assimilation and evapotranspiration rates. $fAPAR$ should be restricted to the green photosynthetically active elements of the canopy.

As $fAPAR$ is a function of the incident radiation, it varies both with the sun position (characterized by its zenith angle θ_s , azimuth angle φ_s) and the atmospheric conditions. Similarly to albedo (Martonchik 1994), the total $fAPAR_T$ is therefore computed as the sum of the black-sky $fAPAR_{BS}$ (that depends on the direct component of the incident radiation and thus, sun position) and the white-sky $fAPAR_{WS}$ (that depends on the diffuse component of the incident radiation). Both components must be weighted by the diffuse to direct fraction (f):

$$fAPAR_T(\theta_s, \varphi_s) = (1-f) \cdot fAPAR_{BS}(\theta_s, \varphi_s) + f \cdot fAPAR_{WS}$$

If the diffuse radiation is assumed isotropic,

$$fAPAR_{WS} = \frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} fAPAR(\theta_s, \varphi_s) \cos\theta_s \sin\theta_s d\theta_s d\varphi$$

Finally, many applications require a daily integrated $fAPAR$ which is directly linked to net primary production (NPP) estimates (Gower et al. 1999). A simple approximation of the daily fAPAR is provided by:

$$fAPAR_{daily} = (1-f) \frac{\int_{\text{sunrise}}^{\text{sunset}} \cos(\theta_s) fAPAR_{BS}(\theta_s) d\theta_s}{\int_{\text{sunrise}}^{\text{sunset}} \cos(\theta_s) d\theta_s} + f \cdot fAPAR_{WS}$$

Depending on the way $fAPAR$ is estimated, it may correspond to one of the various quantities defined above.

The several techniques used for measuring $fAPAR$ at local scale are first presented. A methodology to upscale these local $fAPAR$ measurements at larger spatial domains is described. Then, the few available global $fAPAR$ products derived from medium resolution sensors are briefly described. Finally these

products are intercompared, and their accuracy assessed by comparison against ground measurements.

2. FAPAR MEASUREMENTS AT LOCAL SCALE

2.1 Instrument devices

There are basically four ways of quantifying $fAPAR$ at local scale. The first one consists in assessing directly $fAPAR$ through the use of quantum sensors that measure all the terms of the radiation balance (Gower et al. 1999):

$$fAPAR = 1 - \frac{PAR_r}{PAR_i} - (1 - r_s) \frac{PAR_t}{PAR_i}$$

Where PAR_i is the incoming radiation, PAR_r is the PAR reflected by the canopy towards the atmosphere, PAR_t is the PAR transmitted towards the soil background and r_s is the soil background reflectance. Note that all the fluxes are bi-hemispheric.

In the PAR domain, reflectance and transmittance are very small for green leaves, therefore, the term $\frac{PAR_r}{PAR_i}$ can be neglected and the term $\frac{PAR_t}{PAR_i}$ can be approximated by the gap fraction P_0 i.e. the transmittance assuming black leaves. Finally, the generally low value of the canopy soil background reflectance in the PAR domain ($r_s < 0.25$) allows considering that: $fAPAR \approx fIPAR = 1 - P_0$ where $fIPAR$ is the fraction of intercepted PAR (Andrieu and Baret 1993). These approximations are valid for green leaves and may fail in case of senescing leaves or bright background and presence of significant amount on non green vegetation elements. Indeed, Asner et al (1998) mentioned that $fIPAR$ underestimates $fAPAR$ by about 3-10% for canopies containing dense green materials while these underestimation raise up to 10-40% when considering shrublands and woodlands with LAI<3. Note that the measurements of the PAR balance terms must be continuously recorded along the day and along the vegetation cycle to be related to canopy functioning processes.

The second technique is based on instantaneous PAR transmittance measurements using devices such as ACCUPAR or ceptometers from which the instantaneous fIPAR is computed (Sims et al. 2005).

The third technique is based on directional transmittance measurements using LAI2000 (Hanan and Bégue 1995) or digital hemispherical photography or lidar systems (Chasmer et al. 2008). The directionality of measurements allow reconstructing the daily time course of $fIPAR$. Measurements must however be repeated along the growth cycle to account for the canopy structure development. Note that DHP when taken from above the canopy allow distinguishing between green and non green elements, providing a closer estimates of $fAPAR$.

The last technique consists in describing as realistically as possible the 3D canopy structure and optical properties of the elements, and then simulating $fAPAR$ (Widlowski 2011). Although very attractive, they are limited by the time required for such 3D characterization and accuracy with which canopy architecture may be described.

The selection among these techniques will mainly depend on the spatial and temporal extent of the experiment, as well as

on the accuracy targeted and human and devices resources available.

2.2 Sampling at the local scale

The local scale will be defined a 'patch' of vegetation with relatively homogeneous characteristics and called Elementary Sampling Units (ESU). The size of the ESU will depend on the canopy type and should be around 10 to 30 m for crops, grassland or shrubland and may cover larger areas (50-500 m) for forests depending on the tree crown size, distance between trees, as well as the heterogeneity at the stand level. Note that the ESU should be surrounded by a 'buffer' with characteristics similar to that of the ESU, to prevent PAR lateral advection or leaks (Widlowski 2011). The sampling strategy is defined both by the number and locations of individual measurements within the ESU. Using LAI2000 measurements acquired in crops and a pine forest, Weiss et al (2004) tested several sampling intensities for the characterization of an ESU. They concluded that between 5 to 15 individual measurements allowed getting good estimates of the gap fraction, and thus *fAPAR*. The general principle for optimally locating the sensor (quantum, LAI2000, DHP) within the ESU consists in getting measurements as independent as possible (Garrigues et al. 2002). This is achieved by spreading evenly the sensors within the ESU, i.e. maximizing the distance between neighboring photos. The best strategy is to follow a predefined sampling scheme such as that presented in **Error! Reference source not found.**, left, avoiding any possible selection of the locations depending on local conditions. In the case of row canopies, specific sampling schemes should be adopted, with the emphasis on getting a good representation of the row effect by organizing the measurements along small transects between rows (**Error! Reference source not found.**,right).

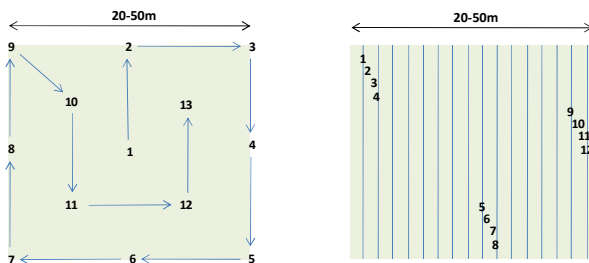


Figure 1. Typical sampling schemes within an ESU for random (left) or row (right) planted vegetation.

As *fAPAR* is a sum of fluxes, the ESU *fAPAR* simply corresponds to the average value of the individual measurements. The same applies for *fIPAR*.

3. UPSCALING ESU MEASUREMENTS TO AREAS OF FEW KM²

At the kilometer scale, Weiss et al (2001) proposed to estimate *fAPAR* in two ways:

(1) Using an ancillary image, acquired close to the date of measurements, with a spatial resolution near or higher than the size of the ESUs, and containing a signal related to *fAPAR*. A transfer function between the ESUs reflectances and measured *fAPAR* is first fitted and then applied to the whole image to upscale ESU measurements to the whole area of interest. This methodology was applied successfully in land product validation projects such as VALERI (<http://w3.avignon.inra.fr/valeri/>) and BigFoot (<http://www.fsl.orst.edu/larse/bigfoot/index.html>).

(2) The upscaling can also be achieved through geostatistical methods (e.g ordinary kriging) that require variogram estimation (Wackernagel 2003). In that case, the sampling scheme must take into account all the distances between ESUs, and particularly for the short (20-50m) to medium ones (100-500m) which are the typical ranges of most landscape heterogeneity (Garrigues et al. 2006).

Weiss et al (2001) showed that ordinary kriging is not applicable (unless for some very homogeneous landscapes) since it requires in many cases too many ESUs to provide accurate *fAPAR* estimates. They also tested collocated kriging that combines the use of an ancillary image and variogram (Wackernagel 2003) and showed very little improvements brought by the geostatistics. We therefore consider that the determination of a transfer function between the image reflectance and ESUs measurements is the best method to upscale ground measurement to areas of few square kilometers. In the following, we describe how to design the sampling scheme to improve upscaling performances, and then how to calibrate the transfer function to extrapolate the measurements to the area of interest.

3.1 Design the sampling scheme for a few km² area

The location and number of ESUs should be defined as a function of the variability of land cover types and state within the area of interest. Additionally, ESUs should be spread over the domain to better capture the variability induced by other factors (such as topography, soil distribution ...) that otherwise would not be necessarily well sampled. The sampling intensity should be adapted to the abundance of each cover type and state.

To better design the way ESUs should be located, the use of ancillary information is mandatory. This could be achieved either by using a high spatial resolution image at a date close to the experiment, a land cover map, or more simply, an image derived from Google earth (<http://earth.google.fr>). In addition, when selecting the location for an ESU, it is also important to include practical considerations such as the ESU accessibility to ease the sampling and to consider the required buffer around it. To represent well an area of few square kilometers, 10 to 50 ESUs are generally required, depending on the heterogeneity of the scene at a resolution close to that of the ESUs (typically few hundred of square meters). Each ESUs must be geolocated thanks to a GPS system.

3.2 Selection and calibration of the transfer function

For a given image and set of measurements, the transfer function consists in calibrating semi-empirical relationships between the ground measured *fAPAR* and the radiometric signal of the corresponding ESU. There is no need to apply atmospheric correction before fitting the transfer function since the atmospheric effects generally do not vary in space over few kilometers. Conversely, attention must be paid to the image registration and orthorectification is recommended to well match ESUs locations. Finally, the image must be acquired within ± 1 week around the ground measurement date to prevent possible change of canopy structure.

Several semi-empirical model can be fitted, from simple linear regressions up to more sophisticated ones. During the VALERI project, these transfer functions have been tested over around 50 sites corresponding to a range of canopy type (Table 1). Once the relationship is calibrated, it can be applied to the whole area of interest. As the area represented by the ESU is small as compared to the area of interest, the fitted model must be robust when used for interpolation within the definition

domain (e.g the convex hull defined with the ESU radiometric space) and may show unreliable results when applied outside the definition domain.

#1	$fAPAR = w_0 \sum_{i=1}^n w_i \cdot S_i$
#2	$fAPAR = w_0 \sum_{i=1}^n w_i \cdot \log(S_i)$
#3	$fAPAR = w_0 \sum_{i=1}^n w_i \cdot S_i + w_{n+1} \cdot \prod_{j \in [L, W]} S_j$
#4	$fAPAR = w_0 + w_1 \cdot NDVI$
#5	$fAPAR = w_0 + w_1 \cdot SR$
#6	$fAPAR = w_0 + w_1 \cdot \log(NDVI)$
#7	$fAPAR = w_0 + w_1 \cdot \log(SR)$

Table 1. Typical transfer functions used to relate $fAPAR$ ground measurements to the satellite signal (S) in the n bands i . $NDVI$ is the normalized difference vegetation index $NDVI = (S_{nir} - S_{red}) / (S_{nir} + S_{red})$ and SR is the simple ratio ($SR = S_{nir} / S_{red}$). w_i are the calibration coefficients of the transfer function

4. FAPAR AT REGIONAL OR GLOBAL SCALE

Larger spatial domains from the region up to the continent or the globe are required for a wide range of applications including climate, bio-geo-chemical cycles investigations or species distribution. In practice, the calibration of an empirical function to extrapolate ground measurements to a larger area is not possible beyond few square kilometres. For larger spatial domains, the only way is to use remote sensing products derived from airborne or satellite sensors.

Since the end of the 1990s, several medium resolution sensors were launched and few $fAPAR$ products are now available to the user community. We present here the principal ones and propose to compare their performances in terms of temporal and spatial consistency, as well as against ground measurements. This is achieved by using the framework proposed in the CEOS context by Garrigues et al (2008) and Weiss et al (2007). The products are evaluated over the BELMANIP2 and VALERI ground validation sites (3kmx3km area) in the plate-carrée projection.

4.1 Used products

The used products are (i) CYCLOPES (CYC:1999-2007): the retrieval algorithm is based on neural networks trained on a 1D radiative transfer model simulation. The compositing is achieved at the Top Of Canopy reflectance level. The reflectance is normalized using a kernel driven BRDF model inverted over a 30 day period (Baret et al. 2007) (ii) MODIS collection5 Terra $fPAR$ (MOD: 2000-2010). The retrieval algorithm relies on a 3D radiative transfer model which ingests red and near infrared bidirectional reflectance factor values, their uncertainties, view-illumination geometry, and eight biome land cover types (Myneni et al. 2002). The model is inverted with a Look-Up-Table specific per biome type. MODIS LAI value corresponds to the maximum daily $fAPAR$ value in an 8-day compositing period. (iii) the JRC $fAPAR$ (JRC:1997-2006). The algorithm consists in two-steps where the spectral reflectances are, first rectified to minimize atmospheric and angular effects and, second, combined together as a spectral vegetation index to estimate the green $fAPAR$ at the time of the satellite overpass (Gobron et al. 2006). Note that for 2006, the product derived from MERIS (Gobron et al. 1999) was used while the SeaWiifs one was used for the other years. The 3 products correspond to instantaneous $fAPAR$ at the satellite overpass. The comparison is performed over the period common to all the products: 2000-2006.

4.2 Product evaluation

$fAPAR$ results from incremental bio-physical processes and should provide smooth variations in time (except in extreme situations such as human intervention). The smoothness of the temporal profiles was evaluated by computing the difference δ between the $fAPAR$ product value at date t , and the mean value of the same $fAPAR$ product at date $t - \Delta t$ and $t + \Delta t$. Low δ values indicate a smooth product (Weiss et al. 2007). Figure 2 shows that CYC is the smoothest product. The “shakiest” product is the JRC $fAPAR$ mainly due to the fact that there is no compositing algorithm for this product which is provided daily. Further, MOD (8 days) is composited by selecting the maximum $fAPAR$ value over the period of the synthesis. On the other hand, the compositing in the CYC algorithm is performed over a 30 days window. Highest values of δ are generally obtained in case of residual cloud contamination. Note that this happens more frequently with JRC and MOD than with CYC.

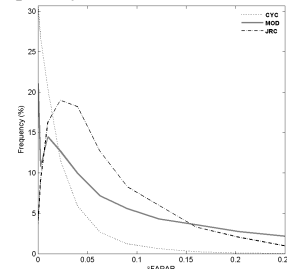


Figure 2. δ value histograms for different products, over BELMANIP2 sites.

$fAPAR$ histograms were then compared for the 4 main biome types (Figure 3). For non forest including grassland, shrubland, cropland and bare soils, the three products show similar patterns, with the exception of MODIS for which $fAPAR$ for pixels classified as bare soil were not computed and where here assigned a 0 value. This explains the discontinuity observed for low values (around 0.05) for MODIS over non forest biomes. For forest biomes, the JRC $fAPAR$ distribution is systematically shifted to the low $fAPAR$ values as compared to the two other products. For evergreen broadleaf forest, MODIS and CYC show similar distributions, showing a sharp peak for the high $fAPAR$ values as expected. The main differences are observed for evergreen needleleaf forest for which MODIS presents an expected high amount of very low $fAPAR$ values, which may be due to cloud mis-detection.

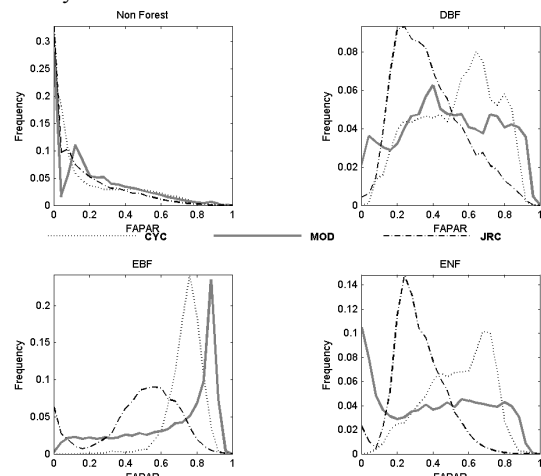


Figure 3. $fAPAR$ histograms over BELMANIP2 as a function of biome type (DBF= Deciduous Broadleaf forest, EBF= Evergreen broadleaf forest, ENF= Evergreen Needleleaf forest).

Comparison with ground measurements (Figure 4) confirms that JRC is systematically underestimating *fAPAR*. CYC and MOD show similar performances. However, MOD appears to slightly overestimate very low *fAPAR*, as observed on the histograms, while CYC seems to underestimate the highest values. Note also that the bad performances observed for two MOD ENF points are probably due to cloud mis-detection.

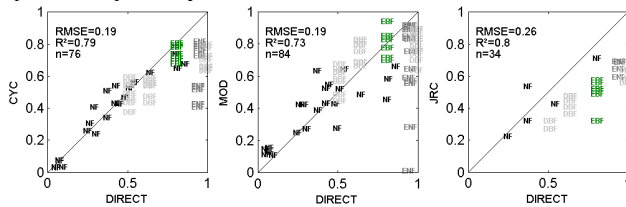


Figure 4. Product performances against ground measurements (*n* is the number of points) for the different biomes (ENF, EBF, DBF, non forest)

5. CONCLUSION

This paper proposes a brief review of *fAPAR* estimation from the local to the global scale. At the local scale, improvements are required to provide instruments at low cost, able to acquire data during the full vegetation cycle, over a proper spatial extent. Further, attention must be paid to the *fAPAR* definitions (green/non green elements, diffuse fraction, ...) and their compatibility with canopy functioning model requirements. This applies also at the regional and global scales. Efforts should also be conducted to improve satellite products. Indeed, it is necessary to provide *fAPAR* archive, temporally consistent from one sensor to another for vegetation monitoring over decades. This will be achieved through the GEOLAND2 (<http://www.gmes-geoland.info/>) and LTDR (Long Time Data Record, <http://www.gmes-geoland.info/>) projects. Finally, to ensure the quality of these products, it is required to extend ground measurement networks over the various biome types and during the whole vegetation cycle.

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