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Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables

GTOS

Essential Climate Variables

GTOS 65

FAPAR

Fraction of Absorbed Photosynthetically Active Radiation

WMO UNESCO UNEP ICSU FAO FIAT PANIS

T10

Assessment of the status
of the development of the standards for the
Terrestrial Essential Climate Variables

FAPAR

Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)

Author:
Nadine Gobron and Michel M. Verstraete

ECV reports coordinator: Reuben Sessa (gtos@fao.org)

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GTOS Secretariat
NRC, Food and Agriculture Organization of the United Nations (FAO)

Viale delle Terme di Caracalla, 00153 Rome, Italy
Tel.: (+39) 06 57055547
Fax: (+39) 06 57053369
E-mail: gtos@fao.org

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List of Acronyms

ASDC	Atmospheric Science Data Center
AVHRR	Advanced Very High Resolution Radiometer
BBL	Beer-Bouguer-Lambert
BRF(s)	Bidirectional Reflectance Factor(s)
CALVAL	CALibration VALidation
CART	Canopy Architecture Radiative Transfer
CEOS	Committee on Earth Observation Satellites
CNES	Centre National d'Etudes Spatiales
EC	European Commission
ECV(s)	Essential Climate Variable(s)
EOS	Earth Observing System
ESA	European Space Agency
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
GEM	Global Environment Monitoring
G-POD	Grid Processing on Demand
IES	Institute for Environment and Sustainability
INRA	Institut National de la Recherche Agronomique
IVOS	Infrared and Visible Optical Sensors
JRC	Joint Research Centre
LAI	Leaf Area Index
LP DAAC	Land Processes Distributed Active Archive Center
LSA SAF	Land Surface Analysis Satellite Applications Facility
LTER	Long Term Ecological Research
LUT	Look-Up Table
MERIS	Medium Resolution Imaging Spectrometer
MISR	Multiangle Imaging SpectroRadiometer
MOD12Q1	MODIS Land Cover Product
MODAGAGG	MODIS Surface Reflectance Product
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
PAR	Photosynthetically Active Radiation
R&D	Research and Development
RAMI	RAdiation transfer Model Intercomparison
RDVI	Renormalized Difference Vegetation Index
RT	Radiation Transfer
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
TIP	Two-stream Inversion Package
TRAC	Tracing Radiation and Architecture of Canopies
VITO	Vlaamse Instelling voor Technologisch Onderzoek (Flemish Institute for Technological Research)
WGCV	Working Group on Calibration and Validation
WMO	World Meteorological Organization

Executive Summary

The Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) plays a critical role in the energy balance of ecosystems and in the estimation of the carbon balance over a range of temporal and spatial resolutions. Spatially-explicit descriptions of FAPAR provide information about the relative strength and location of terrestrial carbon pools and fluxes. It is one of the surface parameters that can be used in quantifying CO_2 assimilation by plants and the release of water through evapotranspiration. The systematic observation of FAPAR is suitable to reliably monitor the seasonal cycle and inter-annual variability of vegetation photosynthetic activity over terrestrial surfaces.

The solar radiation reaching the surface on the 0.4-0.7µm spectral region is known as the photosynthetically active radiation (PAR). FAPAR refers to the fraction of PAR that is absorbed by a vegetation canopy. FAPAR is difficult to measure directly, but is inferred from models describing the transfer of solar radiation in plant canopies, using remote-sensing observations as constraints. In environmental applications, absorption of radiation by leaves is of greater concern than of other plant elements (trunks, branches, etc.). Ground-based estimates of FAPAR require the simultaneous measurement of PAR above and below the canopy as well as architecture information to account for the non-leaves absorption. FAPAR assessments are retrieved from space remote sensing platforms by numerically inverting physically-based models. Most of the derived products represent only the fraction absorbed by the live green part of the leaf canopy. Being the ratio of two radiation quantities, FAPAR is a dimensionless variable.

Space agencies and other institutional providers currently generate and deliver to the scientific community various FAPAR products at different temporal (from daily to monthly), and spatial resolutions over the globe. Over ten years of space-derived FAPAR data are now available from different institutions.

PAR is monitored as part of the standard protocol at ecological and radiation research sites (e.g. FLUXNET, LTER, SURFRAD), but few sites generate all the necessary reliable measurements to derive the canopy FAPAR needed for the validation of satellite products. Community efforts are underway to document the accuracy of available space-derived datasets while ground-based networks, coordinated by CEOS-WGCV, perform measurements relevant to these validation exercises.

Recommendations

- For use in diagnostic or prognostic climate models, FAPAR products should ideally allow users to infer the values associated with various external conditions such as direct versus diffuse incoming radiation as well various Sun zenith angles.
- FAPAR datasets should be provided with detailed information on the spectral and architectural properties of the targets of interest, to help properly interpret the ground-based measurements.
- Protocols for validation should indicate the type of vegetation radiation transfer regime applicable, as well as the ambient conditions prevailing at the time of the in-situ measurements.
- Space agencies and data providers should ensure that when a RT model is used in the operational retrieval of FAPAR that these models undergo exhaustive testing and benchmarking, for instance by participating in RAMI (Widlowski *et al.*, 2007).
- Free access to daily products at the sensors' native spatial and temporal resolution is essential for comparisons purposes on validation sites (prior applying time-composite or remapping technique).
- Time series of ground-based estimates is more informative than point measurements.
- Currently the CALVAL portal is only dedicated to calibration of Infrared and Visible Optical Sensors (IVOS). It should be extended to validation of ECVs.

1. Introduction

Vegetation follows its own dynamics (phenology); including the diurnal cycle of plant photosynthesis and respiration, growth, and differentiation with the seasons. FAPAR is a primary variable controlling the photosynthetic activity of plants, and therefore constitutes an indicator of the presence and productivity of live vegetation, as well as of the intensity of the terrestrial carbon sink. FAPAR varies in space and time due to differences between species and ecosystems, weather and climate processes, and human activities. It is a key variable to document the intensity of the terrestrial carbon cycle and thus to assess of greenhouse gas forcing. Spatially-detailed descriptions of FAPAR provide information about carbon sinks and can help to verify the effectiveness of the Kyoto Protocol's flexible-implementation mechanisms.

Biosphere models typically use higher temporal resolution than land cover/change maps (produced every 5 years) and require additional dimension of temporal changes. This type of model may use local CO_2 fluxes measurements as drivers although they often do not offer an adequate sampling of spatial coverage. Long time series of FAPAR at global scale therefore provide the needed information to monitor plant phenology. FAPAR can also be used to assess the a priori fractional cover of plant functional type inside each model grid cell and to help quantify the available radiation useful for carbon assimilation. About 10 years of FAPAR products are now available, and the climate as well as carbon cycling communities have started to exploit these to constrain their simulations or to study changes of land properties (Potter *et al.*, 2003; Tian *et al.*, 2004; Gobron *et al.*, 2005, Wenze *et al.*, 2006; Knorr *et al.*, 2005, 2007; Galy-Lacaux *et al.*, 2008; Jung *et al.*, 2008; van der Werf *et al.*, 2008 etc.).

Last but not least, changes in FAPAR have been used as indicators of desertification and to monitor the productivity of agricultural, forest and natural ecosystems, for instance.

Current operational remotely sensed FAPAR products are mainly derived from medium-resolution satellite observations instruments (e.g. MERIS, MODIS and MISR) to provide regional and global operational FAPAR products at a variety of spatial (from hundreds meters to half degrees) and temporal (from daily to monthly) resolutions. In addition to these operational space agency products, various national and international projects, like JRC-FAPAR, GLOBCARBON and LANDSAF, to name but a few, provide additional collections of products using data streams derived from other sensors (such as SeaWiFS, ATSR, VEGETATION or SEVIRI) over up to several years, at the continental or global scale. Comparisons between the actual FAPAR products derived by the various space agencies or projects reveal discrepancies: they are mainly due to the different strategies in the retrieval methodology but also to the quality of inputs variables. Recent evaluation exercises during the last two years have helped reduce and understand better the reasons for the discrepancies. This has been possible thanks to substantial data re-processing efforts, which included improvements in calibration as well.

PAR is monitored as part of the standard protocol at ecological and radiation research sites (e.g. FLUXNET, LTER, SURFRAD), but few sites generate reliable measurements of FAPAR that can be meaningfully used for validation of the satellite products. Community efforts are underway to document the accuracies of available space-derived datasets while ground-based networks, coordinated by CEOS-WGCV, perform measurements relevant for validation exercises.

2. Definition and units of measure

FAPAR estimates result from an analysis of multiple measurements with the help of a radiation transfer model in plant canopies using remote sensing observations as constraints.

'Total' FAPAR (absorbed component) is computed as the balance between sources and sinks, with positive inputs corresponding to:

- Incoming PAR at the top of the canopy (direct and/or diffuse);
- Incoming PAR from propagating horizontally (mostly important at very high spatial resolution)
- Light reflected by the underlying ground (soil and/or understory)

and losses corresponding to:

- Outgoing PAR reflected by the canopy (top and bottom)
- Outgoing PAR propagating horizontally

Leaves-only FAPAR refers to the fraction of PAR radiation absorbed by live leaves only, i.e., contributing to the photosynthetic activity within leaf cells. This quantity is lower than 'total' FAPAR because it does not include PAR absorption by the supporting woody material (in forest) or by dead leaves (in crops). In particular, the retrieval method assumes that the leaves are alive and photosynthesizing, hence the name 'green' FAPAR.

While FAPAR is typically based on an instantaneous measurement, for climate change applications representative daily values are required. They are obtained through direct measurements, or by assuming variation with the cosine of the solar zenith angle to obtain the daily leaves-only FAPAR.

The definition of FAPAR products as a balance of multiple fluxes remains dependent on the atmospheric conditions prevailing at the time of the measurements. In particular, estimates can be generated using direct, diffuse, or global radiation inputs. Knowledge on the type of incoming solar radiation fluxes is essential to properly interpret the data. Similarly FAPAR can also be angularly integrated or instantaneous (i.e., at the actual sun position of measurement).

As is the case for the surface albedo, one can define FAPAR estimates for a variety of atmospheric conditions and integrated in angles, space and times as needed.

3. Existing measurement methods, protocols and standards

No standard has been defined yet regarding the procedure to compute FAPAR and in particular to agree on the selection of environmental conditions and inputs datasets to use. However, use of physically-based approach is now the main methodology to retrieve the FAPAR products from ground-based measurements and space data.

3.1 *In situ*

FAPAR, as well as other related ECVs (LAI, biomass, and surface albedo) is much harder to measure in tall (and especially heterogeneous) forest environments than for crops or grasslands. Only a small subset of all existing land cover types (and only on few climatic zones) has been adequately characterized. The methods used to estimate FAPAR are often closely related to those required to determine LAI (see examples in Table 2).

FAPAR *in situ* determination requires simultaneous measurements of PAR above and within the canopy.

The latter may be taken at various heights, thus establishing a FAPAR profile within the canopy. To circumvent the complications arising from the different geometries of direct and diffuse sunlight, FAPAR measurements are typically taken under overcast conditions. The basic measurement requires the use of pyranometers (WMO, 2006) but various commercial instruments have been built which may used for ground-based FAPAR measurements (e.g. Leblanc *et al.*, 2005; www.licor.com/env/Products/Sensors/rad.jsp).

In the vast majority of cases, these ECVs are measured within the context of research programs. But there is a need to acquire these values more systematically in space and in time, taking into account the heterogeneity and 3-D structure of canopies in different ecosystems.

Such measurements are required to support long-term global climate investigations for two reasons. One is to ensure that all key biomes are properly and consistently sampled. This will allow the details of natural vegetation changes and carbon stocks to be carefully monitored in key locations. The other is to generate the field data required for validation of satellite-based measurements, thereby enabling the calculation of these variables on a global scale.

Comparing remote sensing products retrieved at medium spatial resolutions (spatial sampling frequency of about 1 km or more) with *in situ* measurements implies addressing a number of issues and trade-offs. For instance, the uncertainty in the exact location of particular pixel coordinates on the Earth geoid when remapped, suggests averaging the values over an area containing multiple pixels to ensure that the resulting time series relates to a relatively clearly defined geophysical system. For their part, the protocols for acquiring local ground measurements must be conceived so as to minimize undesirable effects related to the different spatial resolutions between the retrieved remote sensing products and the ground-based measurements. Specifically, ground measurements should optimally take into account the three-dimensional (3-D) spatial variability of the canopy attributes, and in particular estimate the radiant fluxes existing inside the (relatively low resolution) sampled domain (Knyazihin *et al.*, 1997, Widlowski *et al.* 2006 and 2008).

3.2 Satellite

Satellite data measured by optical remote sensing sensors are the most appropriate for monitoring the FAPAR by vegetated surfaces. The proper interpretation of these data hinges on understanding the various physical processes that have influenced the properties of light while it travelled through the atmosphere and the canopy.

This understanding is embedded in the radiative transfer models that simulate remote sensing data. Inversion methods to retrieve vegetation parameters from remote sensing data require the development of mathematical tools that minimize the effects due to the scattering by atmospheric particles, the brightness of soils and the changing geometry of illumination and observation.

Various methodologies of current products are summarized below and Table 1 summarizes current input spectral data, output products, methodology and references of the main data providers.

Top of Atmosphere Inputs

- JRC SeaWiFS FAPAR & ESA MERIS FAPAR
  The JRC generic FAPAR algorithm can be tailored to any sensor acquiring at least three spectral bands in the blue, red and near-infrared regions of the solar spectrum. This algorithm capitalizes on the physics of remote sensing measurements and addresses the many operational constraints associated with the systematic processing and analysis of a large

amount of data. Basically, the useful information on the presence and state of vegetation is derived from the red and the near-infrared spectral band measurements. The blue spectral band, which is very sensitive to aerosol load, is ingested to account for atmospheric effects on these measurements. The details of this physical based method have been extensively described in the literature and specific algorithm have been generated for the main sensors concerned (e.g. Gobron *et al.*, 2000 2002, 2007). In practice, the generic FAPAR algorithm thus implements a two step procedure where the spectral BRFs measured in the red and near-infrared bands are, first, rectified in order to ensure their optimal decontamination from atmospheric and angular effects and, second, combined together to estimate the FAPAR value.

Top of Canopy or Surface Albedo Inputs

- NASA FAPAR
  MODIS: The MODIS LAI/FPAR algorithm consists of a main procedure that exploits the spectral information content of MODIS surface reflectances at up to 7 spectral bands. A three dimensional formulation of the LAI/FPAR inverse problem underlies this procedure. Should the main algorithm fail, a back-up algorithm is triggered to estimate LAI and FAPAR using vegetation indices. The algorithm requires a land cover classification. Therefore the algorithm has interfaces with the MODIS Surface Reflectance Product (MODAGAGG) and the MODIS Land Cover Product (MOD12Q1) (Knyazihin et al. 1998b; Myneni et al. 2003).
  MISR: A look-up table (LUT) approach is used to rapidly model the radiative transfer process of complex canopy/soil models to determine the matching modelled reflectances and the associated values of LAI and FAPAR. For efficiency in execution of the algorithm, all necessary radiative transfer parameters have been pre-computed and stored in the Canopy Architecture Radiative Transfer (CART) file (Knyazihin et al. 1998a; Hu et al. 2003, 2007).

- GLOBCARBON
  LAI and instantaneous FAPAR are derived using a constrained model-based look-up table (LUT) as described in Deng et al. (2006). This relies on relationships between LAI and reflectances of various spectral bands (red, near-infrared, and shortwave infrared). These relationships have been established for different types of vegetation types using a physically based geometrical model complete with a multiple scattering scheme (denoted Four-Scale by Chen and Leblanc, 2001). FAPAR is derived from the smoothed LAI value using a modified Beer-Bouger law (Plummer et al. 2007).

- CYCLOPES
  The algorithm is based on a neural network approach trained over radiative transfer model simulations. The FAPAR products correspond to a sun zenith angle at 10:00 local solar time under direct illumination only. The retrieval is applied on top of canopy reflectances after smoothing the VEGETATION data for removing outliers (Baret et al., 2007).

- LANDSAF
  The retrieval of daily FAPAR from SEVIRI data without any prior knowledge on the land cover used the statistical relationship developed by Roujean and Bréon (1995). The principle of the algorithm is based on simulations of visible and near-infrared spectral reflectance values in optimal angular geometries identified based on numerical experiments for AVHRR. A pre-established relationship between Renormalized

Difference Vegetation Index (RDVI); less sensitive to background reflectance variability; computed in an optimal angular geometry in the solar principal plan, and daily FAPAR is used (http://landsaf.meteo.pt).

- JRC-TIP
The main goal of this approach is to help bridge the gap between available remote sensing products and large-scale global climate models. To ensure consistency between various surfaces fluxes and to facilitate the assimilation of space remote sensing products in these models, Pinty et al (2007, 2008) recently proposed an advanced methodology that capitalizes on automatic differentiation techniques to generate the adjoint and Hessian code of a cost function. This software package, named JRC-TIP, inverts the two-stream model of Pinty et al. (2006) in a numerically accurate and computer efficient manner. It delivers extensive statistical information on the results, allowing the user to evaluate in quantitative terms the quality of the retrievals.

Projects/Institution	Input data	Output product	Retrieval Method	References
JRC-FAPAR ESA MERIS-FAPAR	Top of Atmosphere (TOA) BRFs in blue, red and near-infrared bands	Instantaneous green FAPAR based on direct incoming radiation	Optimization Formulae based on Radiative Transfer Models	Gobron *et al.* (2000, 2006, 2008)
NASA MODIS LAI/FPAR	Surface reflectance in 7 spectral bands and land cover map.	FAPAR with direct and diffuse incoming radiation	Inversion of 3D Model versus land cover type with backup solution based on NDVI relationship)	Knyazikhin *et al.* (1998b)
NASA MISR LAI/FPAR	Surface products BHR, DHR & BRF in blue, green, red and near-infrared bands + CART	FAPAR with direct and diffuse incoming radiation.	Inversion of 3D Model versus land cover type with backup solution based on NDVI relationship)	Knyazikhin *et al.* (1998a)
GLOBCARBON	Surface reflectance red, near infrared, and shortwave infrared	Instantaneous FAPAR (Black leaves)	Parametric relation with LAI as function as Land cover type.	Plummer *et al.* (2006)
CYCLOPES	Surface reflectance in the blue, red, NIR and SWIR bands	FAPAR at 10:00 solar local time	Neural network	Baret *et al.* (2007)
LANDSAF	Visible and Near-Infrared bands	FAPAR	Parametric relation	Roujean and Breon (1995)
JRC-TIP	Broadband Surface albedo in visible and near-infrared bands.	FAPAR & Green FAPAR for direct & diffuse incoming radiation	Inversion of two-stream model using the Adjoint and Hessian codes of a cost function.	Pinty *et al.* (2007)

Table 1: Inputs data and retrieval methods of the main FAPAR product providers.

3.3 Intercomparison and validation

No comprehensive inter-comparison of ALL available and current FAPAR products (described above) has been published yet. Such an evaluation might be very difficult to accomplish because existing products diverge as far as time-compositing period and algorithm, spatial resolution as well as remapping techniques. In any case, future inter-comparisons should be carried out using products at the closest to the native spatial and temporal resolution of the sensors (i.e. ~ 1 km), on time periods long enough to document the inter-annual variability of vegetation.

Differences in definition and environmental conditions assumed to estimate FAPAR will also need to be taken into account, such as relying on direct or/and diffuse sources of illumination, instantaneous or angularly integrated value, and on the assumption on the leaves' colour.

Three benchmarking exercises of FAPAR products have nevertheless been carried out:

- Gobron *et al.* (2006, 2008) inter-comparer SeaWiFS and MERIS FAPAR products at about 1 km over various EOS validation sites where ground-based FAPAR field estimates were mainly derived from LAI measurements.
- Bacour *et al.* (2006) compared various products over few daily measurements with limited ground-based estimates of FAPAR.
- Hu *et al.* (2007) inter-compared MISR and MODIS FPAR results over one year using the most probable LAI and FPAR retrieved values.
- More recently, FAPAR products derived from the JRC-TIP package using MODIS and MISR surface albedo as inputs have been compared against official NASA MODIS and MISR products as well as with JRC SeaWiFS and ESA MERIS FAPAR over various sites of validation (Pinty *et al.* 2007, 2008).

4. Summary of requirements and gaps

- Different FAPAR products are based on different definitions and assumptions. This has hindered their comparison.
- These products are also derived using different radiation transfer models, which is perfectly acceptable provided those models are themselves carefully benchmarked, for instance in the context of RAdiation transfer Model Intercomparison (RAMI). See: http://rami-benchmark.jrc.ec.europa.eu/HTML/Home.php).
- Access to daily products at the sensors' native spatial and temporal resolution is essential for comparisons purposes on validation sites (prior applying time-composite or remapping technique).
- Significant efforts should be made to ensure the consistency of the various radiant energy fluxes (e.g. surface albedo, transmittance and FAPAR) derived from remote sensing observations, and their compatibility with the specific requirements of the models, especially in the context of data assimilation systems.
- *In situ* FAPAR datasets should be provided with detailed information on the spectral and architectural properties of the targets of interest, to help properly interpret the ground-based measurements.

5. Contributing networks and agencies

- Global Environmental Monitoring (GEM) of Institute for Environment and Sustainability (IES) of European Commission - Joint Research Centre (EC-JRC) delivers the longest dataset of FAPAR at global scale with the SeaWiFS and MERIS instruments. The latter has been achieved in collaboration with the European Space Agency (ESA).
- The European Space Agency Earth Observation G-POD (Grid Processing on Demand) also provides a computing environment for generating demonstration products at global scale which can be used by biosphere modellers.
- The GLOBCARBON project is funded by ESA and includes external partners such as Flemish Institute for Technological Research (VITO) and the SPOT VEGETATION program of CNES.
- NASA funds the MODIS and MISR instruments, FAPAR products are available through the Land Processes Distributed Active Archive Center (LP DAAC) and Atmospheric Science Data Center (ASDC), respectively.
- CYCLOPES was a European Union FP-5 project, which also benefited from additional funding from CNES, Région Midi-Pyrénées, and Réseau Terre et Espace. Coordinated by INRA Avignon, CYCLOPES operated in the framework of the POSTEL Thematic Centre.
- LANDSAF: The scope of Land Surface Analysis Satellite Applications Facility (LSA SAF) is to generate and distribute land surface products derived from the Meteosat families of satellites (MSG and EPS) of EUMETSAT.

6. Available data

6.1 *In Situ*

PAR measurements are typically acquired at ecological and carbon cycling research sites operating a flux tower (www.fluxnet.ornl.gov/fluxnet/index.cfm; www.carboeurope.org/). Observations are often acquired only above and below the canopy. They therefore correspond to intercepted radiations in the PAR region and account for both leaves and woody elements. These intercepted values can be used as a proxy of FAPAR, at the cost of making some assumptions and applying a correction factor to discount the contribution by vegetation elements other than leaves. In any case, field measurements are essentially point observations that remain difficult to compare with remote sensing measurements from low to medium resolution sensors. Turner *et al.* (2005) and others used higher resolution instrument (like LANDSAT) to up-scale ground-based measurements (mainly LAI) at ~ 1 km resolution.

Field estimates of FAPAR are often derived from LAI measurements, assuming a Beer-Bouger Law (BBL) for the extinction of radiation in the canopy. This is equivalent to using a 1-D radiative transfer model, and a correction factor may be required to account for the 3-D structure of the canopy in some cases.

6.2 Satellite

Table 3 summarizes the characteristics of FAPAR products generated by the main data providers on the basis of medium resolution optical spectral observations. The oldest datasets comes from SeaWiFS for which the continuous data series has been interrupted in December 2007. The MISR instrument on NASA’s Terra platform has already exceeded its design lifetime, though it may be operated for a few more years. In the case of MODIS, two sensors have been deployed, on the Terra and Aqua platforms. Both will also be phased out at some future point. The MERIS instrument on board ESA's ENVISAT platform is expected to be operated beyond 2010. FAPAR products can thus in principle be offered for the period from the end of 1997 until at least 2010. Some of these products differ from the others in part due to differences in retrieval algorithms or sensors characteristics.

Field Experiments	Summary of the approach for domain-averaged FAPAR estimations	References
Dahra and Tessekre (Senegal) 2000-2001	based on BBL's law with measurements of the LAD function; FAPAR(μo) derived from the balance between the vertical fluxes; <LAI> derived from PCA-LICOR	Fensholt *et al.* [2004].
BigFoot (Sevilleta, Bondville etc ...) 2000-2002	based on BBL's law with an extinction coefficient equal to 0.5 or 0.58 (Harvard); <LAI> derived from specific leaf area data and harvested above ground biomass; advanced procedure to account for spatiotemporal changes of local LAI	Turner *et al.* [2005]
Safari (Mongu) 2000-2002	based on FIPAR estimated from TRAC data; slight contamination by the woody canopy elements	Huemmrich *et al.* [2005]

Table 2: Examples of available FAPAR ground-based datasets for validation purposes and approach of assessments.

Sensor	Spatial/Temporal Resolution	Dates range	Products access	Product
SeaWiFS	1.5 km to 0.5° Daily, 10-day and monthly	Sept 97 to June 2006	http://fapar.jrc.ec.europa.eu/	Green Instantaneous FAPAR under direct illumination
MODIS Terra (Aqua)	1 km to 0.25° Daily; 8-day and monthly	Jan. 2000 (June 2002) to end of mission	http://edcdaac.usgs.gov/	FAPAR (direct and diffuse sources)
MISR	1.1 km to 0.5° Daily, monthly, seasonal and yearly products	Jan. 2000 to end of mission	http://eosweb.larc.nasa.gov/	FAPAR (direct and diffuse sources)
MERIS	1.2 km to 0.5° Daily; 10-day; and monthly.	June 2002 to end on mission	http://earth.esa.int/dataproducts/ http://envisat.esa.int/level3/meris/	Green Instantaneous FAPAR under direct illumination
ATSR/VGT	1km; 10km; 0.25°, 0.5° Daily	1998-2006	http://geofront.vgt.vito.be	Instantaneous 'black' FAPAR under direct illumination

Table 3: Actual Products availability and access links of main products providers

7. Other issues

- While currently operating sensors on environmental platforms (MODIS, MISR, MERIS, etc) appear to be working adequately well beyond their design lifetime, there may be a gap in data acquisition if these fail before the next generation of instruments (e.g., NPOESS, SENTINEL-2 and 3) becomes operational.
- In the mean time, it would be useful to define and widely implement protocols on how to acquire field measurements so that the data sets acquired can be readily exploited for the validation of remote sensing products. Issues that need more attention include the spatial sampling (to address the difference between local point measurements with area averages of satellite products, or to address 3-D canopy structure issues, especially in the case of high spatial resolution sensors).
- The free access to the native products as well as information on their accuracies is essential to ensure their validation. The CEOS-CALVAL portal seems to be the appropriate entity for answering this.
- Validation programs have to be prepared and scheduled in advance for future sensors like EOS validation programme did with TERRA.

8. Conclusions

No standard method has been internationally agreed upon to estimate FAPAR from satellite remote sensing observations yet, though most product providers have moved to physically-based approaches. About 10 years of FAPAR products are now available, and the climate as well as carbon cycling communities have started to exploit these to constrain their simulations or to study changes of land properties (Potter *et al.*, 2003; Tian *et al.*, 2004; Gobron *et al.*, 2005, Wenze *et al.*, 2006; Knorr *et al.*, 2005, 2007; Galy-Lacaux *et al.*, 2008; Jung *et al.*, 2008; van der Werf *et al.*, 2008 etc.).

Although standardization of satellite-derived products is not essential, there is strong need to develop community-consensus procedures for the validation of FAPAR products from individual satellite optical sensors, and for the inter-comparisons of such products from different sensors or missions.

While experimental FAPAR products have been generated from satellite data sources, limited validation and inter-comparisons of products have been conducted to date using ad hoc experimental protocols; such activities could be usefully combined with those focused on the leaf area index.

Due to the spatial and temporal variability of FAPAR, the information required for climate change purposes can only be obtained through measurements by satellite optical sensors assuming the sensor includes at least a spectral band in the blue domain to ensure accurate atmospheric corrections.

Further R&D activities are on-going to adapt current methods to the specifications of future sensors, and to develop methodological frameworks capable of delivering not only suites of internally consistent and compatible products, but also precise characterizations of the uncertainties associated with these products. This is essential to foster the exploitation of remote sensing products using assimilation techniques.

Significant efforts should be made to ensure the consistency of the various radiant energy fluxes (e.g. surface albedo, transmittance and FAPAR) derived from remote sensing observations, and their compatibility with the specific requirements of the models, especially in the context of data assimilation systems.

9. Recommendations

Networks of ground-based measurements for the routine acquisition of relevant observations, in particular over sub-sampled geographical regions should be promoted. These networks must ensure that observations follow well-defined protocols that recognize the existence of different radiation transfer regimes (such as those prevailing in forested versus agricultural environments). The main difficulty here is to correctly sample of the ecosystems exhibiting very high spatial variability at scales that matter for medium resolution sensors.

Finally, research and developments efforts should focus on improving the reliability and accuracy of these products to facilitate their ingestion by data assimilation systems. This will, in turn, lead to a better understanding of the climate system an may improve weather forecasts as well. This leads, for example, to a major effort for assessing the consistency of various radiant energy fluxes (e.g. surface albedo, transmittance and FAPAR) between current observations together with the models.

9.1 Standards and methods

- For use in diagnostic or prognostic climate models, FAPAR products should ideally allow users to infer the values associated with various external conditions such as direct versus diffuse incoming radiation as well various Sun zenith angles.
- FAPAR datasets should be provided with detailed information on the spectral and architectural properties of the targets of interest, to help properly interpret the ground-based measurements.
- Protocols for validation should indicate the type of vegetation radiation transfer regime applicable, as well as the ambient conditions prevailing at the time of the in-situ measurements.

9.2 Other recommendations

- Space agencies and data providers should ensure that when a RT model is used in the operational retrieval of FAPAR that these models undergo exhaustive testing and benchmarking, for instance by participating in RAMI (Widlowski *et al.*, 2007).
- Free access to daily products at the sensors' native spatial and temporal resolution is essential for comparisons purposes on validation sites (prior applying time-composite or remapping technique).
- Time series of ground-based estimates is more informative than point measurements.
- Currently the CALVAL portal is only dedicated to calibration of Infrared and Visible Optical Sensors (IVOS). It should be extended to validation of ECVs.

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Web links

ESA MERIS FAPAR
http://earth.esa.int/dataproducts/
http://envisat.esa.int/level3/meris/
http://gpod.eo.esa.int/

JRC-FAPAR
http://fapar.jrc.ec.europa.eu/

GLOBCARBON
http://geofront.vgt.vito.be/

Landsaf
http://landsaf.meteo.pt/

NASA MODIS products
http://edcdaac.usgs.gov/modis/dataproducts.asp#mod15

NASA MISR products
http://eosweb.larc.nasa.gov/PRODOCS/misr/level3/overview.html

Bigfoot
www.fsl.orst.edu/larse/bigfoot/overview.html

SAFARI 2000
http://daac.ornl.gov/S2K/safari.html

CALVAL portal
www.brockmann-consult.de/CalValPortal/welcome.do
www.licor.com/env/Products/Sensors/rad.jsp
http://rami-benchmark.jrc.ec.europa.eu/HTML/Home.php
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c/o Land and Water Division (NRL)
Food and Agriculture Organization of the United Nations

Viale delle Terme di Caracalla 00153 Rome, Italy
E-mail: GTOS@fao.org   Tel: (+39) 06 57054206   Fax: (+39) 0657053369
www.fao.org/gtos