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# LAI and fAPAR CYCLOPES global products derived from VEGETATION. Part 2: validation and comparison with MODIS collection 4 products

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**Abstract**

The main objective of this paper is the validation of CYCLOPES version 3.1 LAI and fAPAR products. It is achieved by the comparison with MODIS collection 4 and 4.1 products and ECOCLIMAP LAI climatology over the BELMANIP representative set of sites, and with ground measurements over a limited set of sites. Great attention is paid to the consistency of the comparison: for the spatial dimension, product PSF appears to be the main aspect governing the spatial resolution at which the comparison has to be achieved. For CYCLOPES, a minimal size of the sites should be 3 km × 3 km$^2$, while the optimal one is 10 km × 10 km$^2$; regarding the temporal sampling interval and resolution, the problem is much easier to solve when assuming a relatively smooth time course of vegetation characteristics (8–16 days). Great care was also paid to the departure of products from the nominal definition, particularly for LAI where different scales of clumping have to be considered.

Results showed that CYCLOPES and MODIS products have generally consistent seasonality, CYCLOPES being however characterized by a smoother temporal evolution as expected. Differences are mainly concentrated on the magnitude of products values, CYCLOPES achieving better performances both for LAI (RMSE = 0.73) and fAPAR (RMSE = 0.10) over the limited number of sites where ground measurements were available. This study also sets a framework to the validation exercise that could be used to evaluate other products or future versions of the same products and contribute to associate quantitative uncertainties as required by the user community.


*Keywords:* LAI; fAPAR; Validation; CYCLOPES; MODIS; Medium resolution sensors

## 1. Introduction

In the past ten years, various medium resolution sensors have been launched. Several land products derived from these sensors are, or will be soon available to the user community at both regional and global scales. As an example, Table 1 shows that, for year 2002, at least 6 different leaf area index (LAI) and 9 fraction of Absorbed Photosynthetically Active Radiation (fAPAR) products were developed. The user must therefore face the dilemma of choosing the most appropriate product to suit his application. All these products require therefore qualitative and quantitative accuracy assessment, which is, in addition, mandatory for many applications including those based on data assimilation into process models.

Evaluation of product accuracy is a very difficult task, particularly regarding the global extent of most of the products, their kilometric spatial resolution, as well as the dynamics of the vegetation. The Land Product Validation Subgroup (LPV) of the Committee Earth Observing Satellite (CEOS) was mandated to coordinate and standardize international validation activities (Justice et al., 2000; Morisette et al., 2006). Validation is generally achieved through direct validation, *i.e.* comparing satellite products to ground measurements of the corresponding biophysical variables. In the case of medium resolution sensors, the main difficulty relies in scaling local ground measurements to the extent corresponding to medium spatial resolution pixel

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Table 1
List of the most recent LAI and fAPAR products available to the community

| Reference | Project | Sensor | LAI | FAPAR | URL |
|---|---|---|---|---|---|
| Knyazikhin et al. (1998a) | NASA/MODIS | MODIS | 2000–now | 2000–now | http://cliveg.bu.edu/modismisr/laifpar/laifpar.html |
| Gobron et al. (1999) | ESA/MGVI | MERIS | | 2002–now | http://eoli.esa.int/servlets/template/welcome/entryPage2.vm |
| Roujean and Lacaze (2002) | CNES/POLDER | POLDER | 1996–1997 2003 | 1996–1997 2003 | http://polder.cnes.fr/ |
| Chen et al. (2002) | | AVHRR | 1993–2002 | | |
| Bacour et al. (2006) | ESA/MERIS | MERIS | 2002–now | 2002–now | http://www.brockmann-consult.de/beam/plugins.html |
| Baret et al. (2007-this issue) | FP5/CYCLOPES | VGT | 1998–2003 | 1998–2003 | http://postel.mediasfrance.org/ |
| Plummer et al. (2006) | ESA/GLOBCARBON | VGT and ATSR | 1998–2003 | | http://geofront.vgt.vito.be/geosuccess/ |
| | | MERIS | 1998–2003 | | |
| | | ATSR | 1998–2003 | 1998–2003 | http://geofront.vgt.vito.be/geosuccess/ |
| | | MERIS | 1998–2003 | 1998–2003 | |
| | | VGT | 1998–2003 | 1998–2003 | |

VGT stands for the VEGETATION sensor.

size. A realistic sampling strategy has to be designed, considering the available manpower and measurement methods.

Multiple initiatives have been conducted among the community to provide ground leaf area index maps at medium resolution (BigFoot (Cohen & Justice, 1999), CCRS (Fernandes et al., 2003), MODLAND (Morisette et al., 2002), VALERI http://www.avignon.inra.fr/valeri). They are all based on the use of high spatial resolution imagery to extend ground sampling measurements. CEOS LPV subgroup proposed a framework to share the ground LAI maps among the entire community to support this international LAI validation activity (Morisette et al., 2006). These maps have been used within many studies for product validation. However, the validation process is generally restricted to few sites (Cohen et al., 2003; Gobron et al., 2006; Huemmrich et al., 2005; Morisette et al., 2002; Privette et al., 2000; Tan et al., 2005; Tian et al., 2002a,b; Wang et al., 2004; Yang et al., 2006b) or limited to an area (Chen et al., 2002; Cohen et al., 2006b; Hill et al., 2006). Moreover, most of these LAI maps are a one shot effort: very few studies show repeated measurements along the year or between years. Up to now about 40 LAI maps are available. Fewer fAPAR and fCover validation maps are available mainly coming from the VALERI project.

To complement direct validation results which are limited by the small number of sites, indirect validation based on a larger ensemble of sites for which no ground measurements is required, provides a far better sampling both in space and time. Indirect validation includes inter-comparison between products as well as evaluation of their temporal and spatial consistency. Baret et al. (2006) propose the BELMANIP network of sites, designed to represent the variability of surface conditions over the Earth. This ensemble of sites is considered by CEOS/LPV as a benchmark for indirect validation.

Regardless direct or indirect validation and the considered product, particular attention must be paid to:

- *Product definition*: Although users generally agree on the definition of the product, departure from this definition could be observed both for ground measurement collection depending on the devices used, and for satellite products depending on assumptions embedded in the biophysical algorithm and the measurement configuration.
- *Product geometry*: to perform direct or indirect validation, particularly at the site level, the target must obviously match the same area, *i.e* corresponds to the same geographic location and size. Geolocation uncertainties, differences in projection systems and point spread functions have to be accurately accounted for.
- *Temporal sampling*: temporal compositing of the product differs from one algorithm to another. Again, when considering LAI products, this may vary from one single day (ground measurements), to daily (MERIS MGVI), via monthly (GLOBCARBON), weekly (MODIS) or every decade (CYCLOPES, CCRS). However, nominal temporal sampling interval could be hampered by missing data mainly due to cloud occurrence.

This paper focuses on the validation of CYCLOPES (version 3.1) LAI and fAPAR products derived from VEGETATION sensors (Baret et al., 2007-this issue) at 10 days temporal sampling (composited over 30 days windows) over a 1/112° plate–carrée spatial grid. Performances are compared to MODIS collection 4 LAI and fAPAR (Myneni et al., 2002) 8 days temporal sampling interval products (composited over 16 days windows) over a 1 km sinusoidal grid. However, for fAPAR, MODIS collection 4.1 fAPAR, delivered by the Boston University at monthly temporal sampling interval is used in place of fAPAR collection 4.0, since a bug was detected in the code generating the collection 4.0 product (FPAR under diffuse radiation produced instead of FPAR under direct solar radiation). In addition, ECOCLIMAP climatology values for LAI (Masson et al., 2003) are used as an independent reference. The validation is achieved from years 2000 to 2003. CYCLOPES products, developed in the setting up of the Land Surface Thematic Centre POSTEL, can be downloaded at http://postel.mediasfrance.org/en/DOWNLOAD/Biogeophysical-Products/, MODIS collection 4.0 products are available at ftp://e0dps01u.

ecs.nasa.gov/MOLT/MOD15A2.004/ and ECOCLIMAP LAI is provided at http://www.cnrm.meteo.fr/gmme/PROJETS/ECOCLIMAP/page_ecoclimap.htm.

A brief description of the considered products is first given along with geometrical considerations (effect of Point Spread Function (PSF) and projection). Then, the temporal continuity of products is investigated to evaluate the fraction of valid pixels. Indirect validation exercise is described, including temporal consistency and statistical distributions. Direct validation is then considered. Conclusions are finally drawn on both the methodology applicable to any land product, and the performances of LAI/fAPAR products.

## 2. Product definition and geometrical considerations

### 2.1. Product definition

The commonly accepted definition of LAI corresponds to half the developed green foliage area per unit horizontal ground area (Chen & Black, 1992; Stenberg, 2006). This definition corresponds to LAI measured using a planimeter and all possible allometric relationships (Frazer et al., 1997). It agrees generally with user community requirements (NPP estimation, carbon modeling, and global change). Production of ground LAI validation maps is most of the time achieved using indirect methods (Weiss et al., 2004) and this may correspond to several alterations of the main definition (Huemmrich et al., 2005) depending on the devices and processing methods used. These techniques generally provide an effective plant area index (PAI) that does not take into account foliage clumping effect although alternatives exist that may partly account for clumping (Chen & Cihlar, 1995; Lang & Yueqin, 1986). Satellite products themselves are based on assumptions on leaf clumping that correspond also to alterations of the nominal LAI definition: ECOCLIMAP LAI products are derived from LAI values extracted from the literature and scaled over the growth cycle according to AVHRR NDVI dynamics. It is therefore not obvious to evaluate precisely how leaf clumping is accounted for. CYCLOPES v3.1 products consider clumping at the landscape level through heterogeneous pixels (Baret et al., 2007-this issue). MODIS collection 4 LAI products consider the clumping at canopy level mostly for forest biomes (Knyazikhin et al., 1998a,b). Note also that the woody fraction is never accounted for in satellite products definition, and rarely corrected for in ground measurements (Bréda, 2003). Finally, understory green vegetation in forested surfaces is not always accounted for when making ground measurements, although satellite signal is potentially sensitive to this contribution, particularly in open forests. These different product definitions make the comparison more difficult, and may also confound the user for its application.

For fAPAR, the fraction of absorbed photosynthetically active radiation (400–700 nm) absorbed by green vegetation has to be defined under specific illumination conditions. fAPAR is used in dynamic vegetation models that run either at a time step smaller than the day, requiring instantaneous fAPAR values all along the day, or run on daily time step requiring thus daily integrated fAPAR estimates. Similarly to albedo (Martonchik, 1994), fAPAR could be defined by the black-sky fAPAR (directional fAPAR that depends on sun position) and the white sky fAPAR (diffuse fAPAR depending on sky irradiance directional distribution, often assumed isotropic). Then, the instantaneous or daily integrated value can be derived from the knowledge of black and white sky fAPAR values in addition to the variation of the diffuse fraction along the day, the sun course and the corresponding incoming radiance. Ground measurements of fAPAR used for direct validation are either derived from radiation balance monitoring (Fensholt et al., 2004; Steinberg et al., 2006) or directional gap fraction measurements achieved with one shot hemispherical photos (Baret et al., 1993; Weiss et al., 2004). In the later case, fAPAR is approximated by the light interception efficiency. Several studies report that the maximum difference between both quantities is observed for the medium to higher vegetation amount, but never exceeds few percents (Bégué et al., 1996). Note that absorption by woody elements is not accounted for, which amounts to consider these non green elements as photosynthetically active! MODIS fAPAR product is defined as the instantaneous fAPAR at the time of satellite overpass. For CYCLOPES, fAPAR is the instantaneous value at 10h00 local solar time which corresponds to a good approximation of the daily integrated value during clear sky days (Baret et al., 2004). Here again, slight differences are observed between satellite products, ground measurements and user requirements. However, the consequences on fAPAR values are far less important as in the case of LAI.

### 2.2. Geometrical considerations

Comparison between products must be achieved over the same support area. Product geometrical characteristics have thus to be considered, including geo-location uncertainties, point spread function, and projection system.

- *Geo-location uncertainties.* VEGETATION sensor is characterized by a multi-temporal registration uncertainty around 150 m (1σ) which was measured by Sylvander et al. (2003) and Fillol et al. (2006). For MODIS, Wolfe et al. (2002) measured a 50 m (1σ) geolocation accuracy although Roy (2000) found from simulations that mis-registration error for 16 days MODIS compositing products is closer to 0.5 pixel in the nadir configuration.
- *Point spread function (PSF).* Due to the point spread function, a substantial portion of the signal of each pixel comes from its surrounding area. When comparing products, the PSF should correspond to that of the product, which adds complementary terms to the proper sensor PSF: geo-location uncertainties, spatial resampling, and atmospheric scattering. CYCLOPES fCover product PSF was evaluated by adjustment of a gaussian PSF model over fCover high spatial resolution images derived from SPOT/HRV images (Fillol et al., 2006; Matthieu & Blanc, 2006). Results observed over an agricultural site located in South West of France show that 90% of the pixel information comes from a surrounding area of about 3.2 km diameter. These PSF characteristics obtained

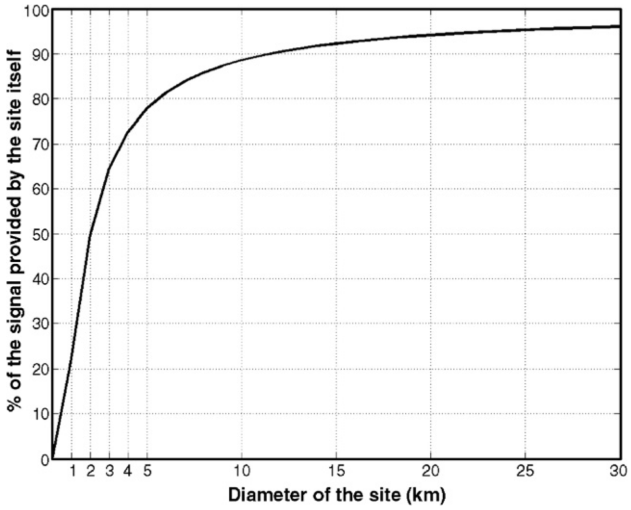


Fig. 1. Effect of the PSF: percent of the information coming from the site itself when considering increasing site size.

for fCover CYCLOPES product should also apply both to LAI and fAPAR that are derived from the same type of algorithm (Baret & Buis, 2007) with the same input VEGETATION radiometric data. To investigate the influence of the size of the support area on the fraction of information that comes from it, a simple simulation was made based on the Gaussian model proposed by Fillol et al. (2006) and Barker and Burelhach (1992). Fig. 1 shows that for a 1 km diameter pixel, only 20% of the information comes from the pixel itself which is similar to Tan et al. (2006) results who found a 30% value for MODIS. This percentage exponentially increases to reach approximately 90% for a 10 km diameter aggregated pixel, which appears to be the ideal resolution. With 3 km diameter, only 65% of the information comes from this area.

- *Projection system.* Products may be available in distinct projection systems: MODIS products are in a sinusoidal projection, CYCLOPES ones are in plate–carrée, while most ground validation maps are produced in UTM, WGS84. To compare these products, the same projection system has to be used that should ideally keep the size of the sites independently from latitude. Reprojecting a product from one system to another requires resampling. Bi-cubic resampling as recommended by Reichenbach and Geng (2003) was used here in the case of continuous fields such as LAI and fAPAR products. However, data resampling may pose specific problems as observed by Seong (2005). A study performed on the BELMANIP sites, using MODIS LAI product and the MODIS reprojection tool (DAAC, 2006), showed that the root mean square error between the average LAI value over $3\times3$ km$^2$ sites computed in the two projections is 0.64 (LAI varying between 0 and 7). A detailed analysis of the results (not shown here) show that consistency is ensured mainly in cases where no pixel with LAI background fill value corresponding, for example, to the presence of a water body, is in the vicinity of the sites. Most differences are also observed for the higher latitudes where deformations from one system to another are the largest. Among the three geometrical factors considered above, product PSF is certainly the most important one that should drive the selection of the support area to effectively inter-compare products. It should take into account the product having the largest PSF. The PSF of MODIS products is not precisely known. However, red and near infrared bands used in the MODIS algorithm result from aggregating 16 pixels of 250 m spatial sampling interval. Huang et al. (2002) provided some indications on MODIS PSF at 250 m. The resulting PSF at 1 km should be therefore relatively close to the ideal PSF. Considering that VEGETATION has a larger PSF than MODIS, our results suggest that $10\times10$ km$^2$ sites would be ideal since most of the signal would come from the interior of this area. However, such large sites would probably reduce the number of available data because of cloud contamination. Further, this size is much larger than the usual $3\times3$ km$^2$ size of ground validation sites. We thus propose to use a $3\times3$ km$^2$ sites with quite homogeneous surrounding (up to $10\times10$ km$^2$), particularly with regards to surface classes that produce background LAI fill values such as water bodies or urban areas. In a previous study (Baret & Pavageau, 2006), fAPAR CYCLOPES products over a sub set of BELMANIP sites have been compared with $3\times3$ km$^2$ and $7\times7$ km$^2$ site extent. Results were showing a very good agreement between both sizes, justifying the use of $3\times3$ km$^2$ over carefully selected sites. Note that an inter-comparison exercise at $10\times10$ km$^2$ resolution is also achieved by Garrigues (2007). All the comparisons were based on MODIS sinusoidal projection system that ensured consistency of the size of the sites independently on latitude. CYCLOPES products (plate–carrée) were thus reprojected into the MODIS sinusoidal system.

## 3. Indirect validation

Indirect validation consists in evaluating the performances of the different products, without comparing them to actual ground measurements. The temporal continuity and consistency of CYCLOPES and MODIS are first investigated. Then, statistical distributions for the main surface classes are compared.

### *3.1. Evaluation of product temporal continuity*

For most applications including investigations on global biogeochemical cycles and climate, users need products available all the time, ideally with no gaps. However, due to cloud occurrence, sensor problems or retrieval algorithm failures, products may not be available all the time. For CYCLOPES, products are not available when there is less than 2 clear observations in the compositing temporal window (30 days) or when the product value derived from neural nets is out of range (LAI less than 0 higher than 8). For MODIS, when the main algorithm based on look-up-tables (LUT) fails, a Back-Up Algorithm (BUA) based on NDVI is triggered. When the main algorithm is used, the quality flag indicates whether saturation occurs or not (Myneni

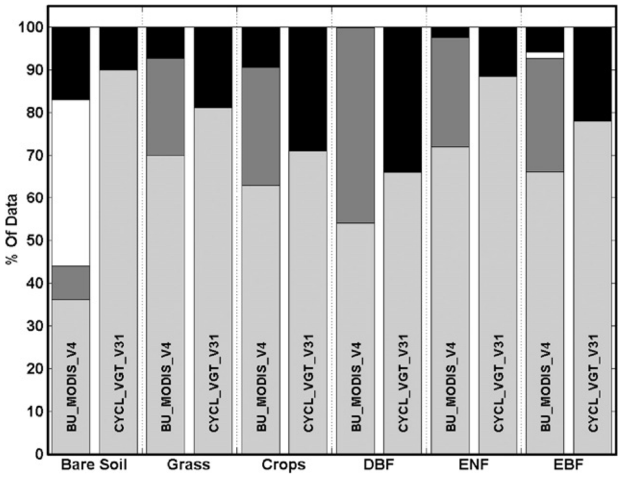


Fig. 2. Fraction of valid pixels observed over the 397 BELMANIP sites during year 2002 and 2003 for MODIS collection 4.0 and CYCLOPES version 3.1 LAI products. Results are presented according to the 6 main surface classes: Bare Soil, Grass, Crops, Deciduous Broadleaf Forest (DBF), Evergreen Needle-leaf Forest (ENF), and Evergreen Broadleaf Forest (EBF). Invalid pixels are shown in black, valid pixels are shown in grey. For MODIS, main (grey) and back-up algorithm (dark grey) pathways are separated. For MODIS, pixels flagged as ‘Bare surfaces’ are also separated (white).

et al., 2002). In the following study, main MODIS algorithm includes cases flagged ‘saturation’. The fraction of valid pixels was evaluated in the product original projection system over 3×3 pixels sites extracted from the BELMANIP data base (Baret et al., 2006) for 2002 and 2003. For MODIS, a distinction was made between main and backup algorithm pathways for the valid pixels. For bare surfaces such as deserts, MODIS LAI and fAPAR products are not computed but flagged as ‘bare surfaces’ (Myneni et al., 2003). The fraction of valid pixels is computed for the 6 main ECOCLIMAP biome types defined by Baret et al. (2006).

For bare soils, results (Fig. 2) show that both for CYCLOPES and MODIS, the fraction of valid pixels reaches up to 80% (even 90% for CYCLOPES) if MODIS pixels flagged as ‘bare surfaces’ are considered as valid pixels for bare surfaces. The back-up algorithm for MODIS corresponds to a minimum fraction around 5% of the total number of ‘bare soil’ pixels. For the other surface classes, MODIS provides the highest fraction of valid pixels, with fractions always higher than 90% (Fig. 2). However, the back-up algorithm represents between 25% and 40% of the total number of pixels. Wang et al. (2001) demonstrated that MODIS main algorithm failure occurred mostly because of residual clouds or poor atmospheric correction. Therefore, the reliability of products derived from the backup algorithm is questionable which will be confirmed later in this paper. Restricting the analysis to the main algorithm pathway shows (Fig. 2) that performances are relatively similar, with however slightly higher performances for CYCLOPES across all surface types with fraction of valid pixels being 5% to 15% higher than that of MODIS main algorithm (that includes main with saturation). These relatively similar performances are connected to the fraction of minimum valid pixels in the compositing window which is 1/16 for MODIS and 2/30 for CYCLOPES. For both sensors, higher fractions of main algorithm pixels are observed over crops, deciduous broadleaf forest and grass. They correspond to locations where cloud occurrence is relatively low. Conversely, evergreen forests (EBF and ENF) achieved the poorest scores due to much higher cloud occurrence locations.

### 3.2. Temporal consistency

The temporal evolution of CYCLOPES and MODIS products was checked over the 397 BELMANIP sites during the 2000 to 2003 period. CYCLOPES products have been first projected in the sinusoidal MODIS projection system. Then, for each site, the mean value over the 3×3 km$^2$ area was computed. For MODIS data, the quality flag associated to each point corresponds to that getting the highest score within the 9 pixels. The ECOCLIMAP climatology LAI values are also plotted to provide an additional source of information. In the following, we present results over sites corresponding to the 5 main biomes: Gourma, in Mali (www.avignon.inra.fr/valeri), classified as bare soil by ECOCLIMAP but corresponding indeed to a sparse vegetation; Fundulea a crop site located in Romania (www.avignon.inra.fr/valeri); Harvard (Massachusetts, USA) is a mixed forest classified by ECOCLIMAP as a deciduous broadleaf forest (BigFoot data (Cohen et al., 2006a)); Järvselja, in Estonia, classified as an evergreen needleleaf forest by ECOCLIMAP but actually corresponding to a mixed forest (www.avignon.inra.fr/valeri), and TAPA (BigFoot data (Cohen et al., 2006a)). Those sites were chosen since they are representative of the overall behavior of the other BELMANIP sites, and correspond to ground validation sites. Moreover, for some of these sites, several measurements throughout the 2000–2003 period were available. Results for LAI are only present here, since the behavior of fAPAR products is quite similar. Moreover, the temporal frequency of the two products is closer for LAI (respectively 10 days and 8 days) than for fAPAR (respectively 10 days and one month).

CYCLOPES LAI product displays strong seasonality over the Gourma site, with significant inter-annual variability (Fig. 3). MODIS main LAI algorithm agrees relatively well with CYCLOPES, although temporal variation is much more shaky. In addition, MODIS LAI seems to keep a too high value in between the vegetation peaks: during the long dry season, there is no green vegetation, apart from a few trees and shrubs (Mougin et al., 2000). MODIS backup algorithm provides here consistent LAI values as compared to the main algorithm, especially for years 2001 to 2003. Note that a relatively high frequency of backup algorithm estimates is observed over this site, despite quite small cloud occurrence. ECOCLIMAP shows well phased seasonality with those of CYCLOPES and MODIS, with however no inter-annual variability (by definition of the climatology) and differences in magnitude, particularly in between the vegetation peaks.

Seasonality of Fundulea site is also very well depicted by CYCLOPES, MODIS and ECOCLIMAP (Fig. 3). MODIS again shows a shakier time course. Relatively few points were derived from the backup algorithm, except in winter due to snow occurrence. The same comments apply to HARVARD site: snow induces the use of BUA for MODIS and missing data

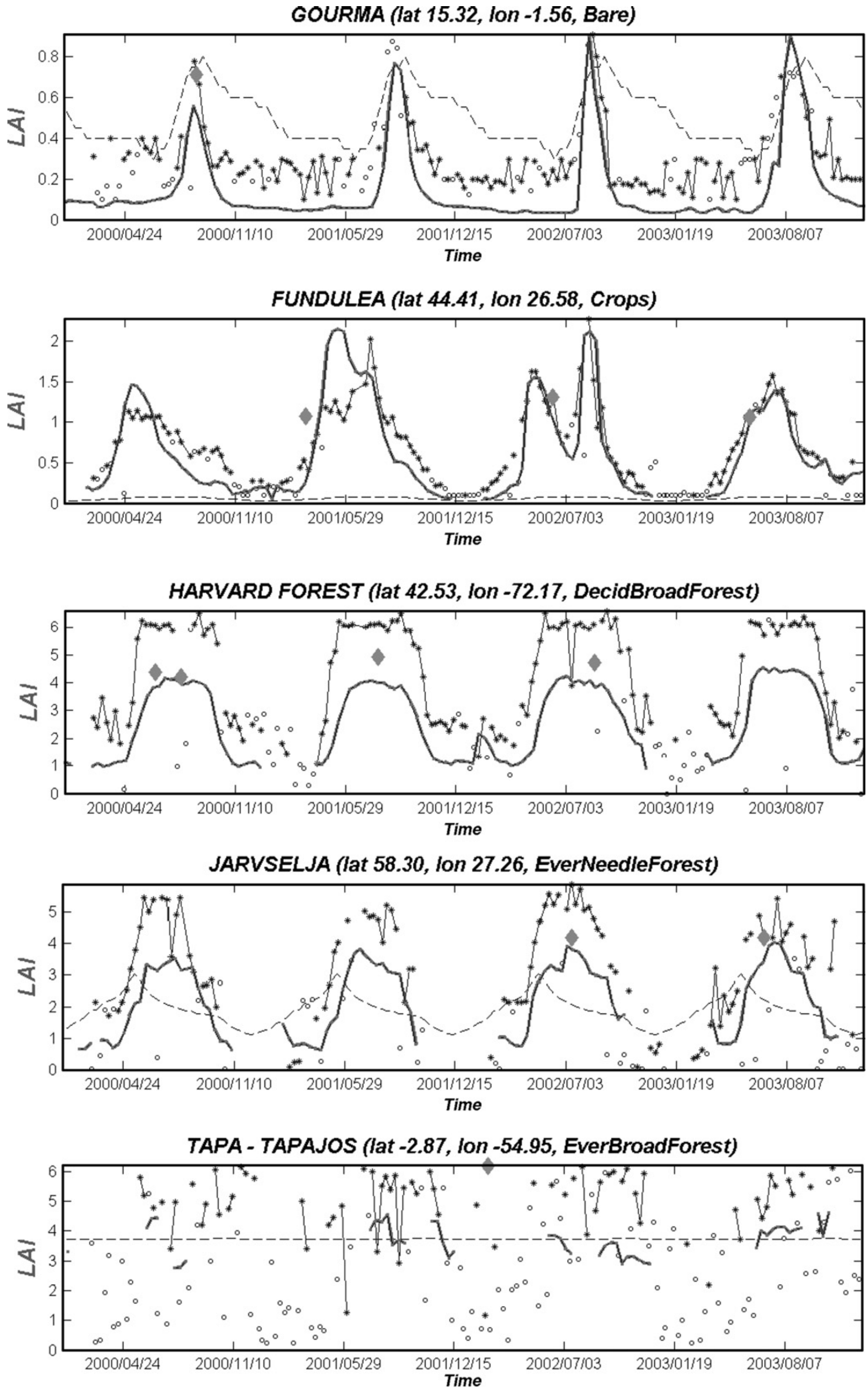


Fig. 3. Temporal evolution of CYCLOPES (bold solid line), MODIS main algorithm (thin solid line) and ECOCLIMAP (dashed line) LAI for period 2000–2003 over four $3\times3$ $km^2$ sites. The name, location and ECOCLIMAP main surface class of each site are indicated above each graph. Stars correspond to MODIS main algorithm, empty circles correspond to the MODIS Back-Up Algorithm. Full diamonds represent ground measurement values.

for CYCLOPES. However the seasonality is well depicted both by CYCLOPES and MODIS products: little LAI variability between years is observed, which agrees also with ground measurements, especially for years 2001 and 2002. Nevertheless, high discrepancies (up to 2) between CYCLOPES and MODIS are observed during the whole cycle: MODIS tends to

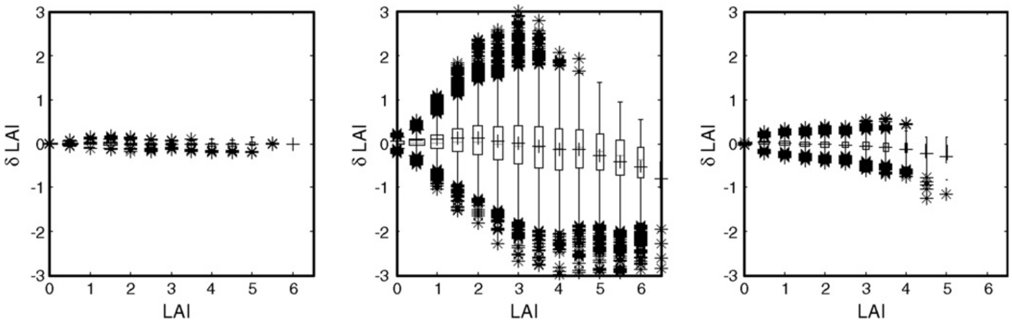


Fig. 4. Boxplot of the $\delta$ value as a function of LAI($t$) value for ECOCLIMAP (left), MODIS (centre) and CYCLOPES (right) LAI products. Crosses and horizontal line in the box indicate mean and median values. The box contains 50% of the data, black lines show the 95% confidence interval and stars represent outliers.

overestimate the LAI (which for this site, corresponds to an effective LAI) while CYCLOPES underestimates it. The same is observed for the Jarvselja site, for which CYCLOPES seems to provide better estimates as compared to ground measurements since they correspond to effective LAI. The seasonality observed for the Järvselja site may be due both to the presence of an understorey and to the fact that it is actually a mixed forest.

Large discrepancies between LAI estimates from the backup algorithm (underestimation) and the main algorithm are observed over the TAPA site with a very high frequency of backup pathways. This is related to the high cloud occurrence experienced over this site (Cohen et al., 2006b). This explains also the very few CYCLOPES data available (Fig. 3). Because of the lack of data and relatively low temporal consistency observed over this site, the seasonality does not show off although other authors have had more success (Xiao et al., 2006). Magnitude of LAI values is relatively different between products, with a stronger underestimation of the actual effective LAI value as measured from the ground, for CYCLOPES product.

From these examples illustrating qualitatively the main features observed over the 397 BELMANIP sites, a relatively good agreement is observed between CYCLOPES and MODIS for the seasonality and its phasing. However, large differences exist for LAI magnitude. MODIS back-up algorithm appears relatively unreliable and generally inconsistent with the main algorithm, mainly because of undetected cloud contamination. MODIS main algorithm (with and without saturation) will be the only pathway considered in the following sections. MODIS main algorithm shows a relatively high level of noise as compared to CYCLOPES that appears much smoother. This feature can partly be explained by the width of the temporal window (1 month for CYCLOPES, 16 days for MODIS) that is used in the BRDF normalization process.

Apart from accidents such as fire, flooding, storms or brutal changes in land use due to human actions, vegetation structure variables vary continuously with time. Indeed, the incremental nature of biomass production and allocation processes from which leaf area index and subsequent fAPAR result, leads to slow variation of these canopy state variables. A smooth temporal course of these products is therefore expected. To quantify the 'smoothness' of products, the difference $\delta$ between the LAI ($t$) product value at date $t$ and the mean value between the two bracketing dates (1/2(LAI($t+\Delta t$)+LAI($t-\Delta t$))) was computed:

$$\delta = (1/2(\mathrm{LAI}(t+\Delta t) + \mathrm{LAI}(t-\Delta t))) - \mathrm{LAI}(t) \quad (1)$$

where $\Delta t$ is the temporal sampling interval. Difference $\delta$ is computed only if the two bracketing LAI values exist. The smoother the temporal evolution, the smaller the $\delta$ difference should be. This was achieved over the 397 BELMANIP sites during period 2000–2003.

Results (Fig. 4) show that ECOCLIMAP LAI has obviously the smoothest temporal profile since it is a climatology: the possible noise is smoothed out over several years and large areas. MODIS temporal profiles are shaky, even for low LAI (<1), with residue varying between −3 and 3. The dissymmetry observed for the higher LAI values is due to the low probability to get a higher LAI value at time $t+\Delta t$ or $t-\Delta t$ when LAI($t$) is high. Temporal profiles are very smooth for CYCLOPES LAI product, confirming the previous visual qualitative observations. Indeed, the root mean square error between LAI($t$) and the mean value between the two bracketing dates is low for ECOCLIMAP (0.04) and CYCLOPES (0.13) and increases for MODIS (0.58). Larger $\delta$ values are observed for high LAI values, in agreement with known algorithm performances that decrease for the larger LAI values due to the saturation of the LAI/reflectance relationship. The maximum LAI value estimated by CYCLOPES is around 5 whereas MODIS is able to estimate LAI higher than 6, which is more realistic.

Previous results were focusing on LAI products. However, similar smooth pattern was observed for fAPAR CYCLOPES product since it is derived from the same input top of canopy reflectance with similar algorithms. The smoothness of fAPAR MODIS product collection 4.1 was not checked since it represents a much longer temporal sampling interval (30 days) as compared to CYCLOPES 10 days.

### 3.3. Statistical distributions

Histograms of product values were investigated for each of the 6 main ECOCLIMAP surface dominant classes. Rather than sampling exhaustively the globe, the BELMANIP 397 sites sub-sampling that is designed to represent the surface types and conditions (Baret et al., 2006) was preferred for sake of

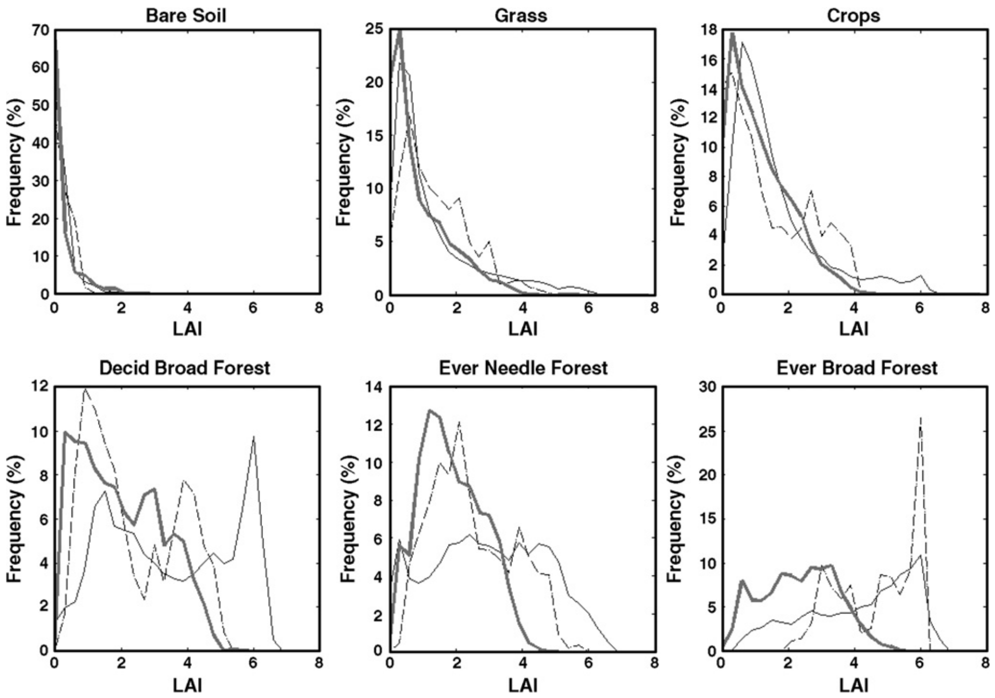


Fig. 5. Histogram of CYCLOPES (thick solid line), MODIS (thin solid line) and ECOCLIMAP (dashed line) LAI products for each main ECOCLIMAP surface class. Results computed over 397 BELMANIP sites, 3 × 3 km$^2$ size during 2000–2003 period. Only the main algorithm is considered here for MODIS.

simplicity. This was achieved using the mean product value over the 3 × 3 km$^2$ sites, in the MODIS sinusoidal projection system, during period 2000–2003. Note that only products issued from the main MODIS algorithm are considered here.

For LAI, results show consistent distributions for bare soils (Fig. 5). Values higher than 0.0 are explained by the fact that a 3 × 3 km$^2$ site classified as dominant bare soil may include some pixels belonging to another surface type, with significant amount of vegetation. In addition, some misclassification within ECOCLIMAP is also possible and was already observed on some direct ground validation site. For crops and grass, CYCLOPES and MODIS provide similar LAI distribution patterns although

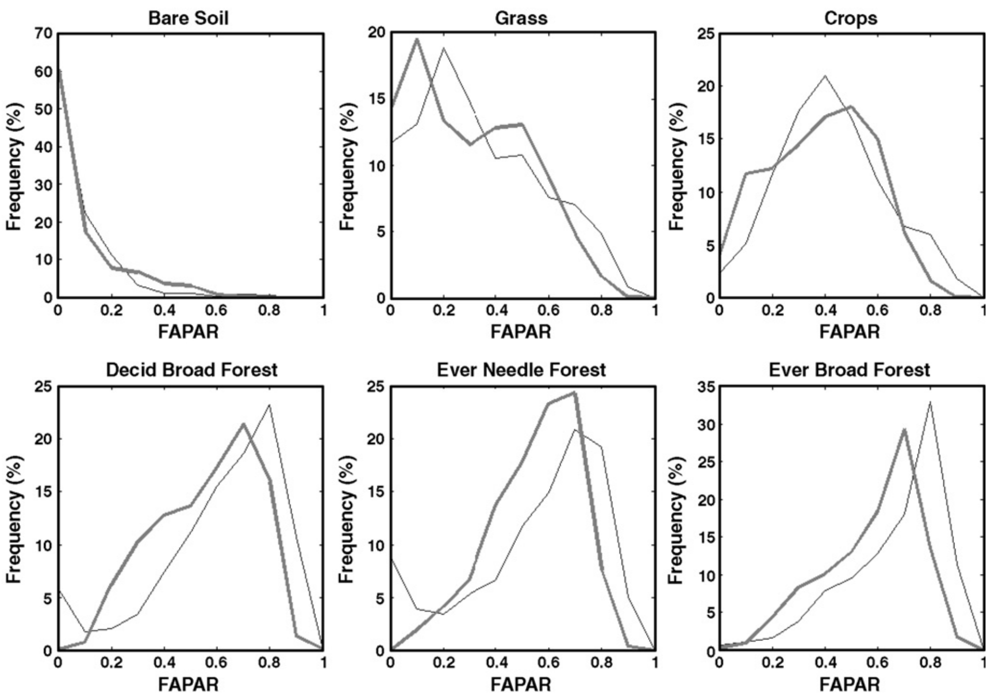


Fig. 6. Histogram of CYCLOPES (thick solid line), and MODIS (thin solid line) FAPAR products for each main ECOCLIMAP surface class. Results computed over 397 BELMANIP sites, 3 × 3 km$^2$ size during 2000–2003 period. Only the main algorithm is considered here for MODIS.

MODIS shows more frequent high LAI values (Fig. 5). Good overall agreement is also observed with ECOCLIMAP LAI values, except for the apparent bimodal distribution for crops.

Discrepancies between the three products are observed for forest canopies. CYCLOPES histogram is always narrower than those of ECOCLIMAP and MODIS. As stated earlier, the CYCLOPES product appears to be more affected by LAI saturation as compared to MODIS. This is also due to the fact that MODIS LAI includes some clumping at the tree level for forests, which is not the case for CYCLOPES which is closer to an effective LAI value since clumping at the landscape level is less likely to happen as compared to agricultural landscapes. For deciduous broadleaf forest, the CYCLOPES distribution is slightly shifted towards low LAI values as compared to ECOLIMAP and MODIS. This appears realistic since in winter time, very low LAI can be observed. High LAI values are again near 5 for CYCLOPES whereas it can go up to 7 for MODIS. ECOCLIMAP and MODIS histograms have the same shape with a shift towards high values for MODIS, showing two peaks for low and high LAI values, the intermediate values being less represented. Considering evergreen needle leaf forest, ECOCLIMAP and CYCLOPES present similar distributions with a peak for intermediate LAI values (1.5 for CYCLOPES, 2 for ECOCLIMAP), although CYCLOPES is not able to estimate LAI higher than 4. MODIS distribution is much wider with a quasi equi-probability of LAI value. Note that both for MODIS and CYCLOPES, very low LAI values for evergreen needle leaf forest are not very realistic. This can be explained either by an error in ECOCLIMAP classification or by the presence of snow not always detected in the MODIS and/or CYCLOPES processing chains. This, indeed, was verified for some of the sites when looking at the temporal evolution during the 2000–2003 period.

For FAPAR, the shape of the MODIS and CYCLOPES product distribution are more consistent as compared to the LAI (Fig. 6). However, except for bare soil, the MODIS distribution is always shifted to high fAPAR values as compared to CYCLOPES. Note that for evergreen needleleaf and deciduous broadleaf forests, MODIS provides very low fAPAR values. This is mainly due to the use of the MODIS BUA while CYCLOPES provides no data when there is snow over the site. This is in agreement with what was found for LAI distributions and was verified when analyzing fAPAR product temporal evolution (results not shown here).

Scatter plots between CYCLOPES and MODIS products were generated to better describe their agreement and/or differences. To increase the consistency of the comparison process, products were interpolated at the lowest temporal frequency (*i.e.* CYCLOPES 10 days frequency for LAI and MODIS collection 4.1 1 month frequency for fAPAR). However, when no product was available within ±15 days around the date considered, the point was discarded. Again this comparison was applied to the 397 BELMANIP sites, using the average product value computed over the $3\times3$ km$^2$ extent, in the MODIS sinusoidal projection system, during period 2000–2003. Only values issued from the main MODIS algorithm were retained.

LAI scatter plots (Fig. 7) show that, except for bare soils, MODIS provides generally higher LAI estimates than CYCLOPES. This confirms the previous findings. The scatter is relatively important for deciduous broadleaf forests. For crops, many points are close to the 1:1 line, whilst a significant fraction follows the general biased trend. These scatter plots show also

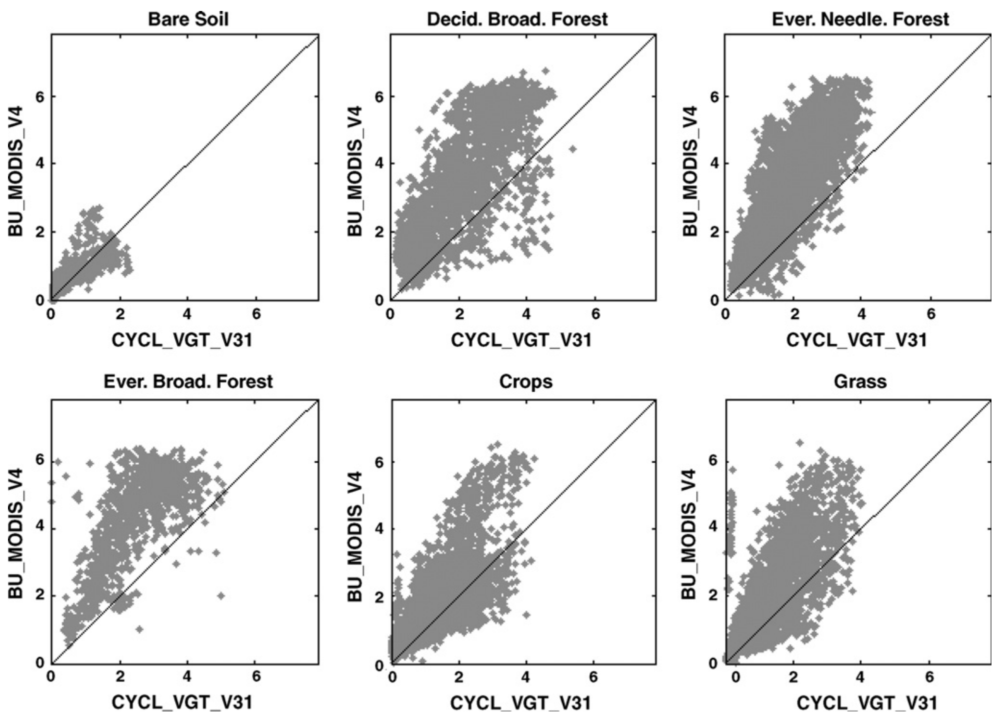


Fig. 7. MODIS collection 4.0 LAI versus CYCLOPES version 3.1 as a function of ECOCLIMAP main surface classes.

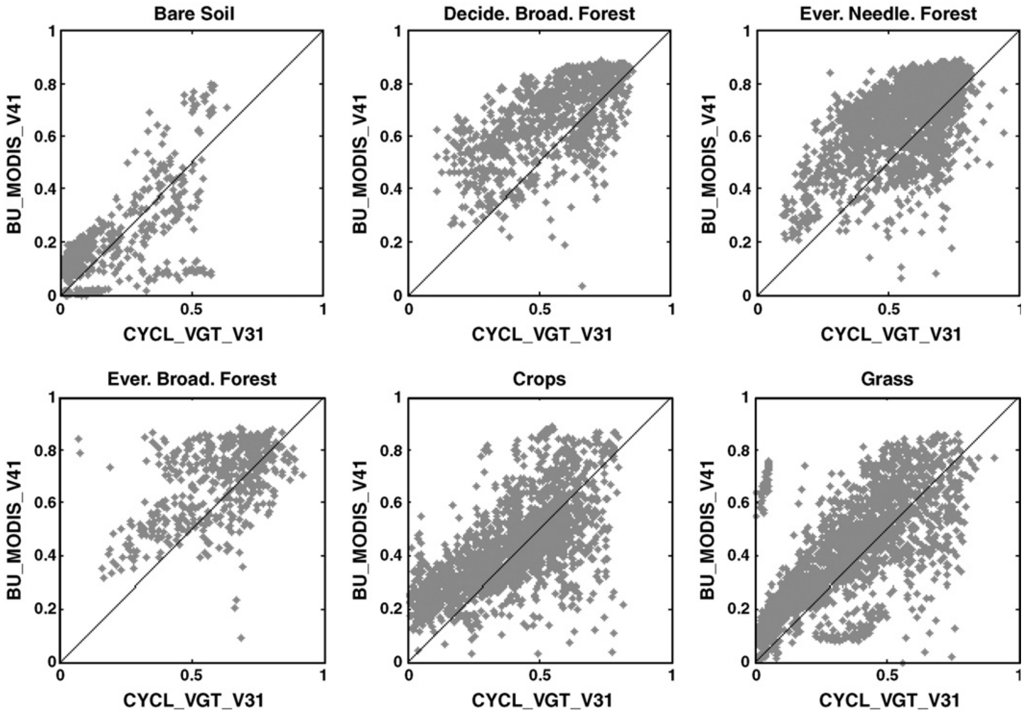


Fig. 8. MODIS collection 4.1 FAPAR versus CYCLOPES version 3.1 as a fonction of ECOCLIMAP classes.

that MODIS LAI products are generally much higher than the CYCLOPES ones for the lowest vegetation amounts. This was already pointed out earlier over sites and periods corresponding to very low amount of vegetation: MODIS LAI values seemed to overestimate the actual values. Few 'outliers' are also observed for Evergreen broadleaf forests, Crops and Grass: for very small CYCLOPES LAI estimates much higher LAI values are provided by MODIS.

For fAPAR, results (Fig. 8) does not show strong biases between fAPAR CYCLOPES and MODIS products conversely to what was observed for LAI (Fig. 7). However, the scattering is relatively large. For Crops and to a lesser extent Grass, MODIS seems to estimate higher fAPAR values than CYCLOPES. This was already noticed for LAI.

## 4. Direct validation

Thanks to the international effort lead by the CEOS LPV subgroup, Garrigues et al. (in preparation) gathered about 40 ground LAI measurement maps. Although the number of available sites is relatively low, Fig. 9 shows that their distribution both in location and surface type is quite large with however an over-representation of the Northern hemisphere. Note that about 10 sites were sampled several times

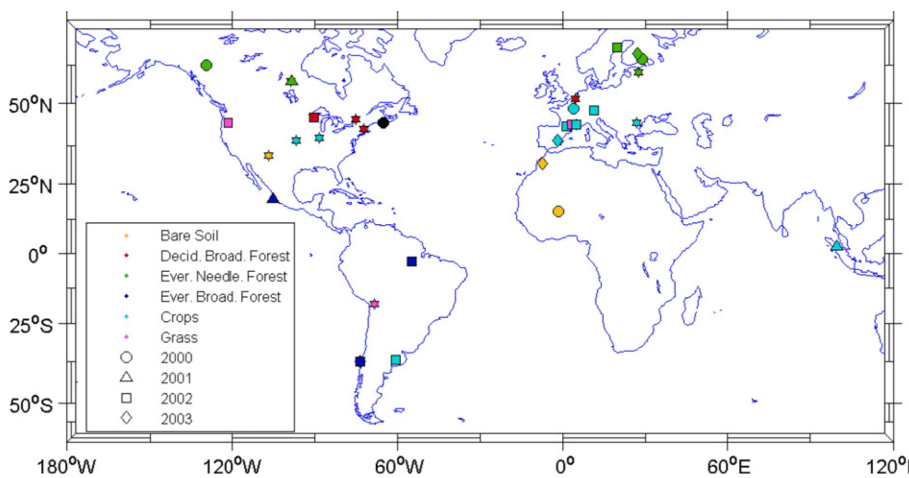


Fig. 9. Location and date of the available ground validation maps. The grouped ECOCLIMAP classes (Baret et al., 2006) are indicated for each site.

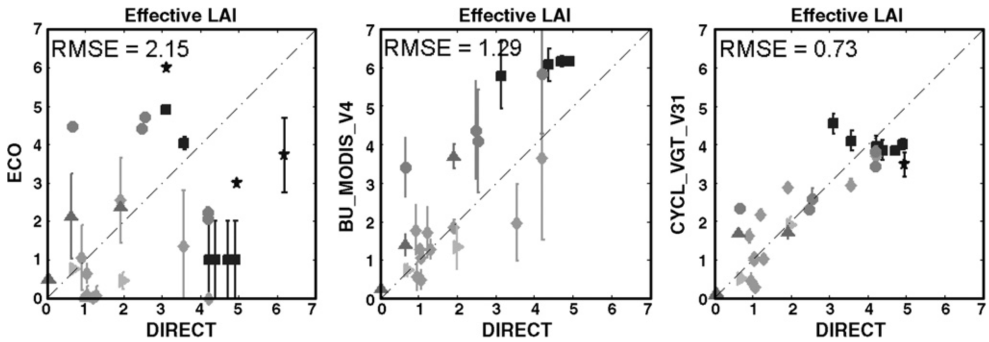


Fig. 10. Comparison between direct ground measurements of effective LAI (28 points) and ECOCLIMAP, MODIS collection 4.0 and CYCLOPES version 3.1 LAI products. Gray levels correspond to the main surface types.

from 2000 to 2003. LAI derived from ground measurements may correspond to different definitions, depending on the instrument used and processing methods. Two definitions of LAI derived from indirect measurements are considered here (Weiss et al., 2004):

- effective LAI that does not take into account any clumping assumption (LAI2000, Hemispherical photography depending on the processing) which is close to the definition of CYCLOPES and ECOCLIMAP products,
- true LAI (TRAC, Hemispherical photography depending on the processing, lai2000 with clumping correction), that do take into account some clumping effect.

In this direct validation exercise, for the MODIS product, data produced by the back-up algorithm were not used. The value of each product is interpolated at the date of the ground measurements if there are at least two valid product values between ±15 days around this date. Therefore, the ground measurements used for the comparison slightly differ due to the availability of each product. The root mean square errors indicated in the following graphs were computed using solely the validation sites that are common to all the products. The differences with the root mean square error computed using all the validation sites are nevertheless very low (0.04 maximum on LAI). For fAPAR, the validation sites were the same both for MODIS and CYCLOPES. The standard deviation (spatial variability of the product) over the 9 pixels that compose the site was also computed for each product. For ground measurements the PSF of each product should be taken into account to properly compute the corresponding site variability. Since the PSF of each product is not precisely known, no measure of the variability is presented. However, the ground measurement sites are generally chosen to be the most homogeneous (at 1 km resolution) as possible in order to minimize PSF and geolocation effects. Note also that the within site variability is not a measure of the uncertainties.

Results (Fig. 10) show that CYCLOPES products perform the best with a RMSE value of 0.73 for effective LAI. We note however, that the maximum LAI value estimated is slightly higher than 4, as already noticed earlier. As expected, MODIS LAI product shows a general overestimation of the effective LAI values, with a RMSE value of 1.29. ECOCLIMAP products achieve very poor performances with very high scatter of data and RMSE = 2.15. Note that the standard deviation is very low for CYCLOPES products whereas it can be significant for some of the site for MODIS and ECOCLIMAP:

- In the case of ECOCLIMAP, some of the 9 $km^2$ sites may correspond to different classes, and therefore have high discrepancies between the LAI of one pixel to its neighbors. As an example, the Harvard forest site is classified in ECOCLIMAP as a mixture of 44% deciduous broadleaf forest (actual biome type) and 56% conifers. Depending on the season, the LAI resulting from the ECOCLIMAP climatology may be quite different for the two classes, and

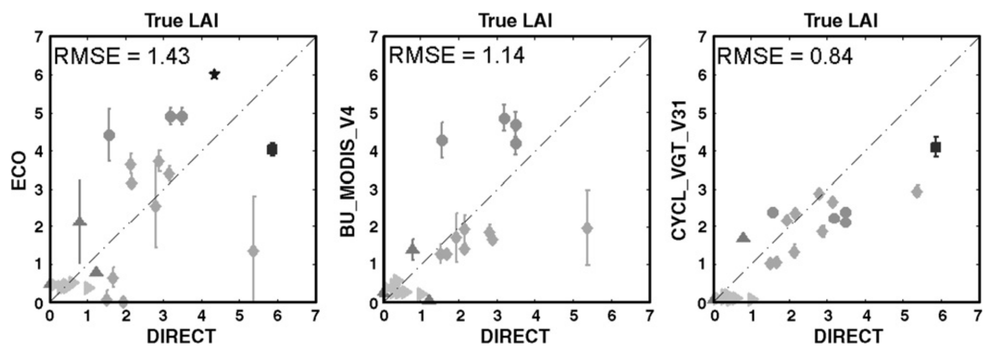


Fig. 11. Comparison between direct ground measurements of true LAI and ECOCLIMAP, MODIS collection 4.0 and CYCLOPES version 3.1 LAI products. Gray levels and symbols correspond to the main surface types.

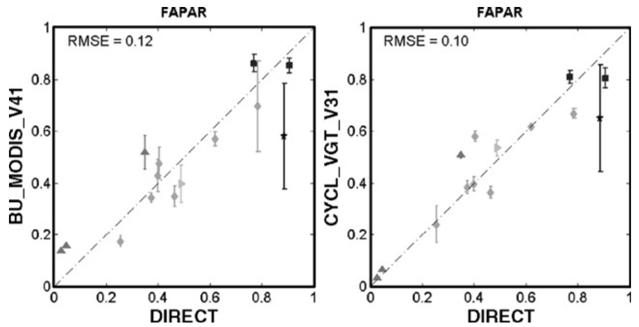


Fig. 12. Comparison between direct ground measurements of fAPAR and MODIS collection 4.1 and CYCLOPES version 3.1 fAPAR products. Gray levels and symbols correspond to the main surface types.

a standard deviation of about 1 is observed for this site (Fig. 10, 4 black squares corresponding to 4 acquisition dates in Harvard, with ground LAI between 4 and 5).

- In the case of MODIS, the standard deviation may be affected by the way the LAI is derived. Indeed, a combination of site and acquisition is declared valid when at least half of the pixels are flagged with the main algorithm. This was defined to allow a reasonable number of validation points. As shown previously, the back-up-algorithm may lead to high discrepancies with the main algorithm, and therefore induce high standard deviation inside the 9 $km^2$. In addition, similarly to what is observed for ECOCLIMAP, presence of different surface types may induce additional site variability.
- In the case of CYCLOPES, very small values of standard deviation are observed since the product is always derived with the same algorithm. Moreover, the CYCLOPES PSF may be larger than the MODIS one, since MODIS reflectances in red and near infrared are derived from the aggregation of 250 m resolution pixels.

When considering true LAI ground measurements (Fig. 11) CYCLOPES still performs the best with a RMSE = 0.84. However an under-estimation for the larger LAI values is observed, where clumping might play an important role. Performances for MODIS products marginally improved as compared to effective LAI, with a RMSE = 1.14. Note also that MODIS still tends to over-estimate high LAI values. This may be attributed to the way the clumping is taken into account both in the MODIS algorithm and true LAI derived from indirect ground measurements (TRAC, CAN-EYE). ECOCLIMAP performances are still the worst as expected for climatology when compared to information derived from actual measurements. Nevertheless, according to the product definition, ECOCLIMAP RMSE improved significantly when compared to effective LAI measurements. Note however, that these results must be taken with care since errors are associated to the ground measurements. They mainly come from the measurement itself (indirect estimates through gap fraction measurements) and the techniques used to spatialise local measurements (for example, around 20 to 50 points covering around 20 m × 20 m areas) to the whole site extent (3 km × 3 km).

Only few fAPAR ground validation data were available, since most of the effort was focusing on LAI. However, the 14 available sites describe well the whole range of variation of fAPAR values. Results show far better performances for fAPAR products both for CYCLOPES and MODIS (Fig. 12). Products follow quite well consistently the 1:1 line, with no apparent bias. MODIS shows however still a slight offset for the lower fAPAR values, as already observed in the scatter plots (Fig. 8).

## 5. Conclusion

The main objective of this paper was the validation of CYCLOPES version 3.1 LAI and fAPAR products, by comparison with MODIS and ECOCLIMAP products, as well as ground measurements.

Results of this study showed that CYCLOPES products have reached a reasonable level of maturity: as compared to MODIS similar products, CYCLOPES achieved the best performances both for LAI (RMSE = 0.73 for effective, 0.84 for true) and fAPAR (RMSE = 0.10). CYCLOPES products show also very good temporal consistency, providing a far clearer characterization of vegetation seasonality. However, problems have been identified, mainly regarding an early saturation of LAI products: CYCLOPES LAI values hardly go over LAI = 4. Although this situation may correspond to effective LAI in agreement with CYCLOPES product definition for the higher LAI levels, attention has to be paid on this feature in the next versions. MODIS LAI products show that the backup algorithm lacks reliability because its input data are likely to be contaminated by clouds or by residual atmospheric effects, confirming the results from Yang et al. (2006a). MODIS main algorithm is characterized by a poor temporal consistency, although the seasonality generally agrees with that of CYCLOPES. Large improvements have to be implemented in the compositing algorithm to reduce the multi-temporal noise. This lack of temporal stability of MODIS products explains part of the poorer performances observed for LAI products collection 4.1. For the monthly fAPAR, better performances are observed (RMSE = 0.12). However, MODIS shows some difficulty to describe very low LAI or fAPAR values. This might be either due to the soil background used in the look-up-tables, and to the stochastic nature of the solution that may incorporate higher LAI values in the retained possible solutions from which the average is computed. As compared to actual CYCLOPES and MODIS products, ECOCLIMAP climatology achieved poor performances. Seasonality is not always correct, sometimes completely shifted from the actual one since the climatology is based on AVHRR data provided in 1992. Magnitude of LAI values appears to be not very realistic, at least when compared to the relatively small number of ground validation sites used. Satellite products such as CYCLOPES and MODIS should be now used to build a climatology that could be used for many applications as well as to provide some background values in case of absence or uncertain satellite data. Note that from this point of view, CYCLOPES preprocessing steps are quite efficient, particularly regarding cloud screening and BRDF normalization (Baret et al., 2007-this issue) that preserve a large amount of good quality data (75% on the average, but with very large disparities between regions).

In this validation exercise, great attention was paid to the consistency of the comparison. For the spatial dimension, product PSF appears to be the main aspect governing the spatial resolution at which the comparison has to be achieved. For CYCLOPES product, the relatively broad PSF forces to select a minimal resolution of $3 \times 3$ km$^2$ in agreement with the typical size of direct ground validation sites. Similarly, products would be ideally set into a common projection system and grid to reduce reprojection artifacts. The MODIS projection system appears to be a good compromise, since it preserves the area independently from latitude, while avoiding pixel replications for the higher latitudes. Having a common reprojection system would also greatly facilitate possible fusion between several products. This is particularly true regarding the qualitative information attached to each pixel (flags) that are very difficult to interpolate or resample. Tools such as MODIS reprojection software should then allow users to extract a subset of data in its preferred projection system. Regarding the temporal sampling interval and resolution, the problem is much easier to solve, assuming a relatively smooth time course of vegetation characteristics. However, temporal resolution in between 8 to 16 days should be used. This validation methodology may be used as a framework for the evaluation future versions of these products or products coming from new sensors or algorithms.

This validation exercise reached stage 2 of the validation exercise (Morisette et al., 2006): "Product accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts". The relatively small number of ground validation sites was here complemented by intercomparison of several products based on the BELMANIP network of sites (Baret et al., 2006). Significant efforts have still to be accomplished to reach stage 3 of the validation: "Product accuracy has been assessed, and the uncertainties in the product well-established via independent measurements made in a systematic and statistically robust way that represents global conditions". Therefore, much more ground experiments should be conducted, while better exploiting past archived ones which are either not always fully processed or distributed. The new experiments to be conducted should focus more on the seasonality of the vegetation structure which is of great importance for a number of applications.

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