EVALUATION OF AN OPERATIONAL LEAF AREA INDEX RETRIEVAL APPROACH USING VEGETATION AND MODIS DATA

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ABSTRACT

An operational method has been proposed to estimate the leaf area index (*LAI*) from satellite imagery in the framework of EUMETSAT Satellite Application Facility on Land Surface Analysis (LSA SAF). This study evaluates the performance of the LSA SAF *LAI* retrieval algorithm when prototyped to VEGETATION/CYCLOPES and MODIS reflectances over Europe for the 2000-2003 period. The results indicate that LSA SAF algorithm retrieves consistent *LAI* estimates from multiple remotely sensed imagery even when input reflectances present systematic differences. High spatial and temporal consistencies between LSA SAF prototyped *LAI* and CYCLOPES and MODIS products are found. Differences in *LAI* between CYCLOPES products and LSA SAF estimates are lower than 0.4 *LAI* units in terms of RMSE. Larger discrepancies are found when comparing LSA SAF prototyped estimates against MODIS products due, in part, to differences in products assumptions (RMSE ranging from 0.2 up to 0.8 with higher (lower) LSA SAF *LAI* values compared to MODIS for herbaceous (woody) biomes). Direct validation indicates that LSA SAF prototype estimates achieve similar performances (0.8 and 0.6, respectively) as CYCLOPES and MODIS *LAI* products. This study constitutes a step forward for the validation and consolidation of the LSA SAF *LAI* algorithm.

INTRODUCTION

Leaf area index (*LAI*), typically defined as the one-sided area of green foliage projected onto a unit area of ground, is a key biophysical parameter of vegetation canopies controlling the exchanges of fluxes of energy, mass (e.g., water and CO_2) and momentum between the land surface and the atmosphere. *LAI* is required for a wide range of environmental applications related to vegetation monitoring, weather prediction and climate change.

Satellite remote sensing constitutes the single effective means of deriving continuous and global *LAI* estimates. Estimation of *LAI* from remotely sensed optical imagery can be achieved by several operational algorithms which span from simple empirical ones based on calibrated relationships with vegetation indices, up to complex physical algorithms based on the inversion of canopy reflectance models.

In Satellite Application Facility on Land Surface Analysis (LSA SAF), a computationally efficient method based on spectral mixing has been developed to estimate the *LAI* from the EUMETSAT satellites SEVIRI/Meteosat and AVHRR/MetOp. Since 2005, *LAI* from SEVIRI/Meteosat is routinely estimated by the LSA SAF system (1). But estimating *LAI* from merged data of MetOp and MSG satellites is foreseen until 2012. Prototyping the LSA SAF algorithm to other sensor data appears to be useful for algorithm validation and improvement.

In this study, a prototype of the LSA SAF retrieval algorithm (2) is applied to VEGETATION/SPOT and MODIS/TERRA reflectance data. The prototype estimates are compared to similar *LAI* products derived from the same sensors. In particular, version 3 of CYCLOPES *LAI* products (3) and collection 5 of MODIS *LAI* products (4) are considered. The assessment is achieved over Europe for the period of overlap between CYCLOPES and MODIS products (2000-2003). The main aim of this study is to assess the performance of the LSA SAF prototype estimates compared to

- the consolidated and validated MODIS and CYCLOPES *LAI* products, and

- ground-based maps.

Emphasis is also given to the evaluation of the impact of the algorithm and input data on *LAI* retrieval discrepancies.

METHODS

LAI algorithm

In the LSA SAF system, *LAI* is estimated from the fractional vegetation cover (*FVC*) based on the combined use of a novel mixture modelling method (2) and the *FVC*-*LAI* relationship proposed by (5):

$$LAI = \frac{-1}{b \cdot G(\theta_s = 0) \cdot \Omega} \cdot \frac{\ln(a_o - FVC)}{a_o} \tag{1}$$

where b is the backscattered fraction; $G(\theta_s)$ is the leaf projection factor; Ω is the clumping index. b characterises the spectral dependence of radiation interception including the leaf albedo and the asymmetry factor. After measurements in the visible, it is assumed that b=0.945 for all vegetation canopies (5). G is set to be equal to 0.5 assuming a spherical orientation of the foliage distribution. Although in the LSA SAF processing chain, an empirical clumping index (Ω) specific per biome class is introduced, here Ω is fixed to be equal to 1 assuming a random distribution of vegetation. This assumption leads to effective rather than true *LAI* calculation. An empirical coefficient a_o, equal to 1.05, is introduced in order to avoid maximum *LAI* values exceeding a value about 6-7 in fully vegetated areas (i.e. when *FVC*$\rightarrow$1). *FVC* in Eq. (1) is computed using an optimised mixture modelling approach in which soil and vegetation components are represented by multi-modal probability density functions (2). Standardised signatures of soil and vegetation components are used to reduce the influence of external factors (e.g. shading, brightness variations). The inputs of the SAF algorithm are reflectances in the red, near infrared and middle infrared spectral bands at nadir sun-view acquisition geometry.

Data used and preprocessing

VEGETATION/CYCLOPES and MODIS constitute suitable data bases for testing the LSA SAF algorithm. First, numerous validation experiments support the reliability of VEGETATION/CYCLOPES and MODIS *LAI* products (e.g. 4,6,7,8). Second, input data similar to the one considered here, i.e. reflectances in the red, near infrared and middle infrared bands adjusted at a common acquisition geometry, are accessible from the multispectral and multiangular EUMETSAT satellites. But the LSA SAF preprocessing algorithms to provide atmospherically corrected cloud-cleared data of the bidirectional reflectance distribution function (*BRDF*) for AVHRR/MetOp are still underdeveloped and data were not available to be included in this study. Furthermore, the 1 km spatial resolution of VEGETATION and MODIS allows for a better comparison with ground acquisitions than using SEVIRI with a spatial resolution which is variable from 3 km at nadir up to 12 km in northern latitudes. Europe has been considered as the study area because even if previous studies demonstrate the potential of the LSA SAF products (1), large uncertainties are found over areas in Europe where the reliability of SEVIRI BRDF at large zenith angles is poor.

Version 3 of CYCLOPES products derived from VEGETATION/SPOT is available from http://postel.mediasfrance.org. Reflectances standardised at nadir viewing and zenithal illumination geometry, and *LAI* products are used here. The radiometric calibration process of VEGETATION data, cloud screening, atmospheric correction, directional standardisation and biophysical vegetation parameters retrieval are described in (3).

MODIS/TERRA reflectances at nadir sun-view geometry (MOD43B1) (9) and *LAI* collection 5 (MOD15A2) (4,10) were downloaded from http://edcdaac.usgs.gov. The MODIS *LAI* products have been filtered with respect to their quality flag and only products generated by the main algorithm have been included in our data base.

To ensure the consistency of the comparison of *LAI* products, particular attention must be paid to:

- *Input data*. Comparing *LAI* products derived from the same sensors and processing chains makes it possible to reduce the differences in the characteristics of data that usually hamper the comparability between remote sensing products. Note, however, that although the *SAF* algorithm is prototyped over the same satellite sensors data as the MODIS and CYLOPES *LAI* products, the input reflectances differ. Both *SAF* and CYCLOPES use anisotropy corrected reflectances but standardised in a different acquisition geometry: nadir-view at the median solar zenith angle for CYCLOPES, and nadir sun-view geometry for SAF. MODIS algorithm ingests a daily bidirectional reflectance factor (*BRF*) in red and near-infrared bands while *SAF* algorithm uses temporal composited nadir *BRDF*-adjusted reflectance data in an additional middle infrared band. Differences also exist between the CYCLOPES and MODIS reflectances at the *LSA SAF* retrieval conditions with root mean square errors, *RMSE* (relative *RMSE*), about 0.02 (20%) in red, 0.07 (25%) in near infrared and 0.04 (15%) in middle infrared with systematic higher values for MODIS reflectances. These systematic differences can be due to inaccuracies of radiometric calibration and atmospheric correction (11) but further investigations are required to better identify and quantify the sources of these differences.

- *Product assumptions*. The MODIS algorithm accounts for clumping at the canopy, leaf (shoot) and landscape scales through three-dimensional radiative transfer formulations (10). The CYCLOPES and LSA SAF prototype estimates correspond to some effective *LAI* where only clumping at the landscape scale is considered (2,3). These inconsistencies in the definition of products constitute a clear limitation in our study and partially explain the observed differences in *LAI*.
- *Spatial attributes of products*. To achieve a proper comparison, MODIS products are reprojected to the plate-carrée projection system of VEGETATION. And the comparison between *LAI* products is achieved over 7 km × 7 km in order minimise the differences in the spatial domain (e.g. effects of point spread function and coregistration errors).
- *Temporal characteristics of products*. MODIS *LAI* products are 8-day composited and MODIS reflectances are 16-day composited. CYCLOPES present a compositing period of 30 days displaced by 10- day shifts. The lowest temporal frequency (i.e. 16 days) is considered and products are interpolated at the same date.

RESULTS

Comparison with CYCLOPES and MODIS products

To assess the consistency and discrepancies between *LSA SAF* prototype estimates from CYCLOPES (*SAF*/CYC) and MODIS (*SAF*/MOD) reflectances, CYCLOPES and MODIS *LAI* products, density scatter plots of *LAI* estimates are analysed over a number of 177 areas of 7 km × 7 km representing the prevalent surface types and conditions in Europe for the year 2003 (Figure 1). Selected areas are centred on the BELMANIP (http://lpvs.gsfc.nasa.gov/lai_intercomp.php) and MODIS (http://daac.ornl.gov/modis) land validation networks of sites (Figure 1d). Discrepancies between *LAI* estimates are quantified by the correlation coefficient (r^2), slope and offset of the linear regression, the mean value of differences (*B*), the standard deviation of the differences (*S*) and the *RMSE* ($RMSE^2=B^2+S^2$).

The scatter plot of *SAF*/CYC and *SAF*/MOD (Figure 1a) reveals high consistency with no bias between *LSA SAF* prototype estimates despite the systematic biases between CYCLOPES and MODIS reflectances. Most of the contribution to the total *RMSE* comes from the random fluctuations (*S*). Differences between *SAF*/CYC and *SAF*/MOD are lower than 0.5 *LAI* in terms of *RMSE*, fulfilling user consistency requirements for *LAI* estimates from multiple sensors (12).

The comparison of *SAF*/CYC and CYCLOPES estimates shows a good agreement with an overall *RMSE* lower than 0.4 and r^2 higher than 0.9. But *SAF*/CYC *LAI* values are systematically higher than CYCLOPES ones in dense canopies (Figure 1b). An early saturation of CYCLOPES *LAI* at about 4 was also detected in other validation studies (6,7).

The comparison of *SAF*/MOD and MODIS (Figure 1c) indicates a lower consistency with an overall performance around 0.6 in terms of *RMSE* and high scattering (most of the overall *RMSE* is due to *S* contribution). These discrepancies are partially due to differences in the vegetation structure representation between canopy models, and errors in auxiliary data (i.e. land cover map). An analysis per vegetation classes reveals that *SAF*/MOD provides systematically higher *LAI* values than MODIS over herbaceous canopies (i.e. shrubs, grasses and crops) and lower values over woody biomes (i.e. savannas and forests) with differences ranging from 0.2 (30%) up to 0.8 (40%) in terms of *RMSE* (relative *RMSE*). These systematic discrepancies can be explained in part due to the differences in clumping assumptions.

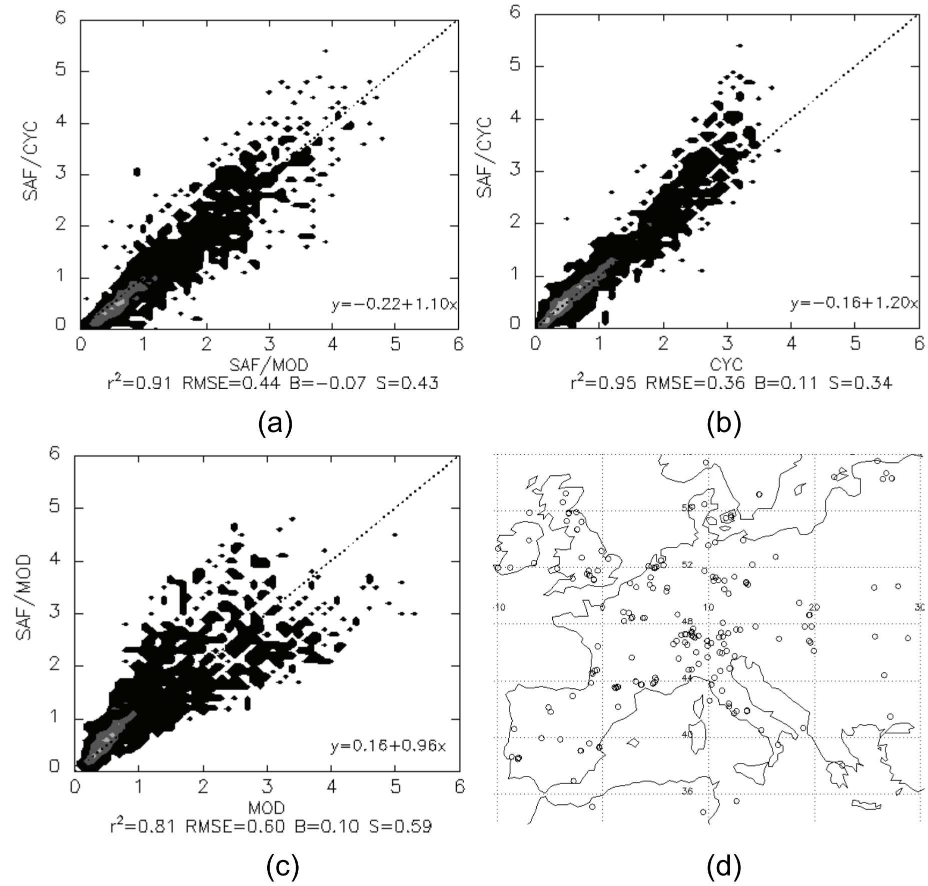

Figure 1: Comparison of LAI estimates from prototyping of LSA SAF algorithm using CYCLOPES reflectances (SAF/CYC) and MODIS reflectances (SAF/MOD) (a), CYCLOPES (CYC) LAI (b) and MODIS (MOD) LAI (c) over a network of sites in Europe (d) for 2003. Number of samples, n=1689.

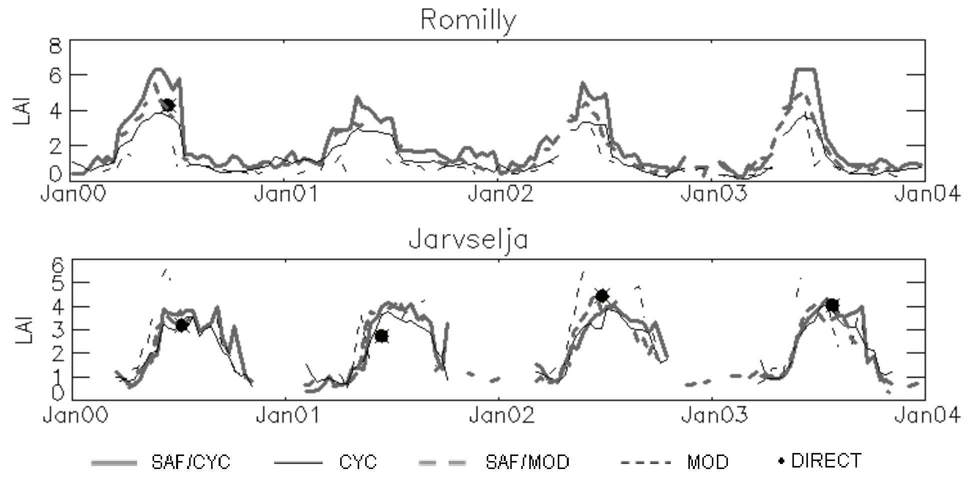

Figure 2: Temporal profiles of LAI estimates from prototyping of LSA SAF algorithm using CYCLOPES and MODIS reflectances, CYCLOPES LAI and MODIS LAI for the period 2000-2003 over Romilly and Jarvselja validation sites.

To illustrate the main features of the temporal behaviour of LAI products, temporal profiles over Romilly cropland area and Jarvselja boreal forest are shown in Figure 2. Temporal profiles indicate high temporal consistency between different LAI estimates that generally reproduce adequately the expected seasonality of vegetation and agree with ground measurements for the most part of the dates (Figure 2). At Romilly agricultural site different LAI estimates follow very similar seasonal trajectories which are mainly controlled by water irrigation management. The observed seasonality at Jarvselja can be explained in part due to the presence of understorey and deciduous species.

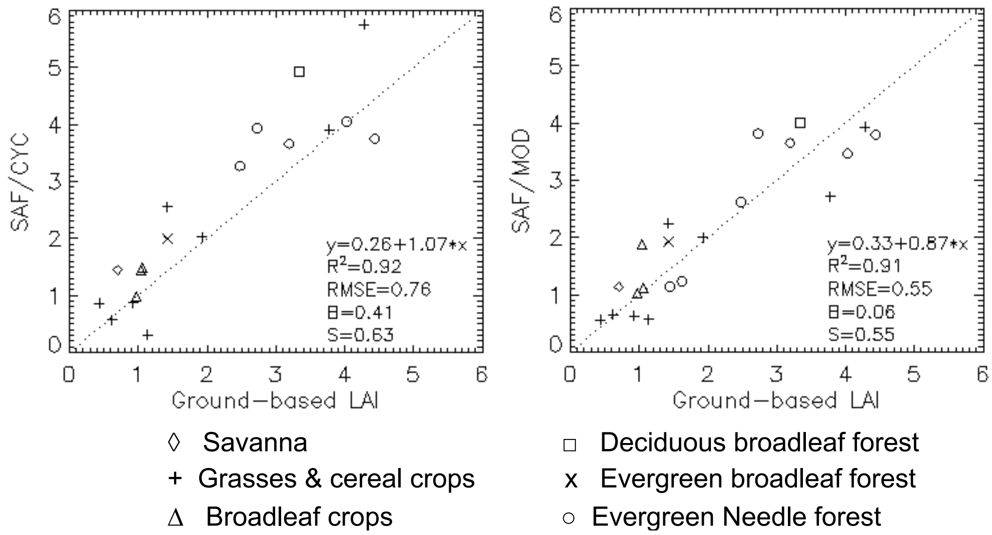

Figure 3: Comparison of LAI estimates from prototyping of LSA SAF algorithm using CYCLOPES and MODIS reflectances with direct ground measurements.

Direct Validation

The state of the art direct validation approach consists of using transfer functions and ancillary information such as high-spatial resolution imagery to scale the ground measurements up to moderate resolution of products (13). The Validation of Land European Remote sensing Instruments (VALERI) (http://www.avignon.inra.fr/valeri/) provides us with 21 reference ground-based maps over Europe for the 2000-2003 period. These high spatial resolution maps were degraded to 1 km spatial resolution of VEGETATION and MODIS. The validation was achieved by using mean values over 3 km x 3 km areas, which correspond to the typical size of validation sites. *LAI* estimates were interpolated to the acquisition date of ground measurements.

Results (Figure 3) reveal that *SAF*/CYC and *SAF*/MOD estimates achieve good performances scoring overall RMSE errors similar to CYCLOPES and MODIS *LAI* products: 0.76 and 0.55 for *SAF*/CYC and *SAF*/MOD, respectively, compared to 0.59 and 0.85 for CYCLOPES and MODIS. The differences in the uncertainties (*RMSE* regarding ground measurements) of *SAF*/CYC, *SAF*/MOD, CYCLOPES and MODIS *LAI* are smaller than the expected error for most reference maps, i.e. 0.5 *LAI* units.

CONCLUSIONS

This study is focused on evaluating the performance of the *LSA SAF* generic algorithm for the estimation of *LAI* by prototyping with CYCLOPES and MODIS reflectances. The intercomparison of *SAF*/CYC and *SAF*/MOD *LAI* estimates (*RMSE* (relative *RMSE*) lower than 0.5 *LAI* units (30%)) reveals the robustness of *LSA SAF* algorithm to be applied to multiple optical sensors even if systematic discrepancies in surface reflectance values exist (relative *RMSE* between CYCLOPES and MODIS nadir reflectances is 10% in red, 15% in middle infrared and 25% in near infrared). A noticeable good agreement (*RMSE* lower than 0.5) between *SAF*/CYC retrievals and CYCLOPES *LAI* products was also found. Differences in the vegetation structure representation (e.g. clumping, woody to total area) between algorithms and in the definition of *LAI* lead to larger discrepancies between *SAF*/MOD and MODIS (*RMSE* (relative *RMSE*) from 0.2 (30%) up to 0.8 (40%)).

Direct validation against ground-based maps shows that the *LSA SAF* prototype estimates achieve similar performances (*RMSE* of 0.8 and 0.6 for *SAF*/CYC and *SAF*/MOD, respectively) as CYCLOPES and MODIS products. The differences between *LSA SAF* prototype estimates and ground-based *LAI* lie within the overall uncertainty of ground measurements (about 0.5 *LAI* units) in more than 50% of the cases. *LSA SAF* prototype estimates fulfil thus the typical target accuracy for satellite *LAI* products (12).

This prototyping exercise constitutes a step forward for refinement, validation and consolidation of the *LSA SAF* algorithm for the estimation of *LAI* from EUMETSAT satellites (1).

ACKNOWLEDGEMENTS

This work has been supported by *LSA SAF* (EUMETSAT), DULCINEA (CGL2005-04202) and ARTEMIS (CGL2008-00381) projects. The CYCLOPES products are generated under EU/FP5 CYCLOPES project, using algorithms developed by CNES, CNRM, INRA, and Noveltis. They are produced and provided by the POSTEL Service Centre at MEDIAS-France. MODIS products are generated under NASA support, using algorithms developed by Boston University. They are provided by LPDAAC. Ground-based data result from VALERI project driven by INRA and funded by CNES.

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