The EUMETSAT Satellite Application Facility on Land Surface Analysis

Validation Report

MSG/SEVIRI

Vegetation Parameters (VEGA)

PRODUCTS: LSA-421 (MDFVC), LSA-422 (MTFVC), LSA-450 (MTFVC-R), LSA-423 (MDLAI), LSA-424 (MTLAI), LSA-451 (MTLAI-R), LSA-425 (MDFAPAR), LSA-426 (MTFAPAR), LSA-452 (MTFAPAR-R)

EUMETSAT
LSA SAF
LAND SURFACE ANALYSIS

LSA SAF
The EUMETSAT Network of Satellite Application Facilities
Land Surface Analysis

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Version 3.0	10/07/2017	First version prepared for the DRR.
Version 3.1	06/02/2018	Updated version considering reviewer's comments.

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List of Acronyms

ATBD   Algorithm Theoretical Basis Document

B   Mean bias

BELMANIP BEnchmark Land Multisite ANalysis and Intercomparison of Products

BRDF   Bidirectional Reflectance Distribution Function

C5   Collection 5

CAL/VAL   Calibration and Validation group of CEOS

CDR   Climate Data Record

CDOP   Operation Phase

CEOS   Committee on Earth Observation Satellite

CYCLOPES Cyclically Ordered Phase Sequence

DBF   Deciduous Broadleaf Forest

DHP   Digital Hemispherical Photos

EBF   Evergreen Broadleaf Forest

MDAL   MSG Daily Albedo

EOLAB   Earth Observation LABoratory

ESA   European Space Agency

ESU   Elementary Sampling Unit

MTAL   **MSG** 10-Days Albedo

EUMETSAT European Organisation for the Exploitation of Meteorological Satellites

EUVAL   European VALidation

FAPAR   Fraction of Absorbed Photosynthetically Active Radiation

FVC   Fraction of Vegetation Cover

FP7   Seventh Framework Programme

GCOS   Global Climate Observing System

GEOV1   Collection 1km Version 1 LAI, FAPAR, FCover products

GLC   Global Land Cover

ImagineS	Implementation of Multi-scale Agricultural Indicators Exploiting Sentinels
IPMA	Instituto Portugues do Mar e da Atmosfera
JRC	Joint Research Centre
LAI	Leaf Area Index
LIFD	Leaf Inclination Foliar Distribution
LPV	Land Product Validation Subgroup
LUT	Look Up Table
LSA SAF	Land Surface Analysis Satellite Applications Facility
MAR	Major Axis Regression
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
MSGVAL	MSG Validation sites
NARMA	Natural Resources Monitoring for Africa
NASA	National Aeronautics and Space Administration
NIR	Near-infrared
NLF	Needle Leaf Forest
NPV	Non-Photosynthetic Vegetation
NRT	Near Real Time
OLIVE	On Line Validation Exercise
PDFs	Probability Density Function
PR	LSA SAF Product Requirement
QA	Quality Assessment
RDVI	Ratio Difference Vegetation Index
RMSE	Root Mean Square Error
SAIL	Scattering by Arbitrarily Inclined Leaves
SBA	Sparse vegetated and Bare Areas
SEVIRI	Spinning Enhanced Visible and InfraRed Imager

SPOT /VGT   Satellite Pour l'Observation de la Terre / VEGETATION

UV   University of Valencia

V1   Version 1

VALERI   VAlidation of Land European Remote sensing Instruments

VEGA   Vegetation Products – FVC, LAI and FAPAR

WGCV   Working Group on Calibration and Validation (CEOS)

WMO   World Meteorological Organization

EXECUTIVE SUMMARY

The EUMETSAT LSA SAF service generates and disseminates a suite of vegetation products (i.e., Fraction of Vegetation Cover (FVC), the Leaf Area Index (LAI), and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)) derived from SEVIRI/MSG observations for the whole Meteosat disk (over land surfaces ideally free of snow and ice cover) at two different time resolutions: (i) Daily products based on the cloud-free BRDF parameters computed using a daily rolling compositing approach with a characteristic 5-day compositing period (MDFVC, MDLAI, MDFAPAR), and (ii) 10-day products derived from BRDF composited data (MTFVC, MTLAI, MTFAPAR). The SEVIRI products include the Fraction of Vegetation Cover (FVC), the Leaf Area Index (LAI), and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR).

The current algorithm for VEGAv3.0 is operational since June 2016 for the near-real-time (NRT) generation of daily products. A key feature of the v3.0 algorithm has been improving the description of soil and vegetation components in the FVC and LAI algorithms. This has contributed to reduce the observed bias and enhance the consistency with similar products derived in the Copernicus Global Land Service. The v3.0 improves also the filtering of traces of snow for masking unreliable observations. An identical version of VEGA algorithms (namely v2.0) is used for the generation of 10-day products in NRT. Hence, the VEGA daily differs from VEGA 10-day products only in the BRDF input (daily and 10-day, respectively). The details of the Version 3.0 algorithm (v2.0 for 10-day products) are given in the ATBD [SAF/LAND/UV/ATBD_VEGA/2.0]

The LSA SAF service has recently reprocessed the entire SEVIRI/MSG archive (2004-2012), with the latest version of the several retrieval algorithms in the processing chain (VEGAv3.0 for daily LAI, FAPAR and FVC and v2.0 for the equivalent 10-day products) in order to obtain a continuous and homogeneous dataset of Climate Data Records (CDR) of Land-SAF vegetation parameters suitable for many environmental and climate applications.

This report shows the validation of the SEVIRI/MSG VEGA CDR 10-day prosducts (MTFVC-R, MTLAI-R, MTFAPAR-R), but it also assesses the daily NRT products to extend the analysis to a longer period (2004-2016) improving thus the representativeness of the accuracy assessment. The QA is performed in agreement with guidelines of the CEOS LPV for validation of global LAI products, and includes several additional criteria and metrics for spatial and temporal consistency. The 2004-2012 period has been considered for the temporal analysis and stability of the time series. Inter-comparison exercises are performed using as reference the Copernicus Global Land GEOV1 product based on SPOT/VGT observations, and NASA MODIS C5 LAI, FAPAR products, using a two year period (2008-2009). Accuracy assessment

is achieved against matchups with ground-based reference maps coming from the OLIVE tool hosted at CEOS cal/val portal, and the ImagineS ground database. For this test, 2004-2012 period was used to validate the 10-day products, and the whole period was used (2004-2016) to assess the daily products.

Our results showed in overall a good quality of the MSG VEGA CDR. The products shows better spatio-temporal completeness than similar polar-orbiting satellite-based products, and missing values mostly due to snow cover. The spatial distributions of retrievals are smooth and present good quality (2008-2009). The comparison with reference satellite products shows good overall consistency with more than 70% of samples within target level consistency for LAI and FVC as compared to Copernicus GEOV1, and about 50% for FAPAR. For LAI and FVC, discrepancies are located mainly over Equatorial areas and Northern latitudes, which are problematic areas due to the persistent cloudiness and the extreme view zenith angle of SEVIRI instrument. Some discrepancies were also observed over semi-arid regions for FVC, which seems to indicate a small bias of MSG FVC products for low values. The FAPAR shows systematic differences with reference products, which is partly explained due to the different definition of the FAPAR (daily versus instantaneous), and to the optical properties of the leaves considered in the methods, but MSG showed better agreement with ground references mainly over crops. The temporal profiles show reliable inter-annual variations, with an intra-annual precision (smoothness) similar to GEOV1 and better than MODIS products. The inter-annual precision quantified as median absolute anomaly of the 5th and 95th percentile values, shows very good results matching the GCOS requirements for stability, similar to GEOV1 and better than for MODIS. The stability of the VEGA CDR has been investigated using Hovmöller, with two satellites as reference, without finding trend in the bias along the period under study. The accuracy assessment has shown different results:

1) For LAI, with a RMSE of 0.32 (N=13) and no mean bias with 85% of the samples within the LSA SAF target requirement for MTLAI-R products (2004-2012); and a performance (RMSE) of 0.74 (N=52, mainly croplands), slight positive mean bias (0.22) and 61% of the samples within the target requirement for MDLAI (2004-2016).

2) For MDFAPAR, a overall performance (RMSE) of 0.17 (due to some outliers), mean bias of (-0.06) and 55% of samples within the LSA SAF target requirements level, and remarkably good accuracy for most croplands (MTFAPAR was not assessed due to very limited ground dataset available, but similar performances than daily products is expected);

3) For FVC, a RMSE of 0.09 (N=15) and no mean bias, with 60% of the samples in the target accuracy level for MTFVC-R (2004-2012); However, a RMSE of 0.17 (N=37, mainly croplands) with systematic positive bias of 0.10 (mainly over croplands), and only

30% within target accuracy level for MDFVC (2004-2016). It should be noted that MSG FVC provides better accuracy results than GEOV1, and that the uncertainties attached to the ground datasets, in particular to the FVC, are not negligible.

With the current QA report, MSG VEGA CDR products reach Validation Stage 1 according to the 4 Stage CEOS LPV hierarchy for satellite product validation, and will reach Stage 2 once these results will be published in a peer-reviewed journal.

1 BACKGROUND OF THE DOCUMENT

1.1 OBJECTIVE

The objective of this document is to update the quality assessment results of the VEGA products derived from MSG/SEVIRI observations corresponding to the latest version of the algorithm (V3.0). This assessment is applicable to the following products:

(i) The suite of daily and 10-day MSG vegetation products operationally generated and disseminated in Near Real Time (NRT) products by the LSA-SAF system:

> LSA-421 (MDFVC), LSA-422 (MTFVC)
>
> LSA-423 (MDLAI), LSA-424 (MTLAI)
>
> LSA-425 (MDFAPAR), LSA-426 (MTFAPAR)

(ii) The homogeneous Climate Data Record (CDR) based on 10-day vegetation products reprocessed data corresponding to the period 2004-2012:

> LSA-450 (MTFVC-R)
>
> LSA-451 (MTLAI-R)
>
> LSA-452 (MTFAPAR-R)

The CDR dataset includes only 10-day VEGA products, and corresponds to the latest version of the whole processing chain algorithms (i.e.., v2.0 for the VEGA 10-day NRT products). However, a similar dataset of reprocessed daily products has been produced as "internal products". Although the daily products are not foreseen to be distributed as CDR, they may be made available upon request, or via the website.

It is worth mentioning that the VEGA algorithms of the daily products and the 10-day products are identical, differing only in the BRDF input (i.e. MDAL for daily products and MTAL for 10-day).

1.2 RELATED DOCUMENTS

The following documents are baseline references which provide complementary information, evaluation evidences and few conclusions on the performances of the algorithms:

- SAF/LAND/IM/VR/1.5 (January 2006), evaluates MSG Daily FVC and LAI products (version v1.2)
- Validation Report of LSA SAF Vegetation products (SAF/LAND/UV/VEGA_VR/2.0),

January 2007, 66 pp, evaluates MSG Daily FVC, LAI and FAPAR products (version v2.0)

- SAF/LAND/UV/VEGA_VR/2.1 (January 2008), evaluates MSG Daily FVC, LAI and FAPAR products (version v2.1)
- SAF/LAND/UV/VEGA_VR/2.1-4 (November 2013), evaluates MSG Daily FVC, LAI and FAPAR products and MSG 10-day FVC, LAI and FAPAR products including inter-comparisons with Copernicus Global Land products.
- Algorithm Theoretical Basis Document for Vegetation parameters (VEGA), (SAF/LAND/UV/ATBD_VEGA/2.0), February 2016, 40 pp, describes the current (v3.0) algorithm.
- Validation Report of LSA SAF Vegetation products (SAF/LAND/UV/VR_VEGA/2.1/5), February 2016, 122 pp, updated validation which evaluates the daily FVC and LAI products (version 3.0), primarily based on the intercomparison with Copernicus Global Land products.
- Product User Manual (PUM) of Land SAF Vegetation Parameters (VEGA) (SAF/LAND/UV/PUM_VEGA/3.0), July 2017, 52 pp, describes the characteristics of the current (v3.0) products and applied also to the reprocessed (CDR) products.

2   LSA SAF products

The algorithm for retrieving FVC and LAI relies on optimised Spectral Mixture Analysis (SMA) methods in which endmember signatures are no longer treated as constants, but they are represented by multi-modal probability density functions. Spectral endmembers are the "pure" spectra corresponding to each of the land cover components (i.e., vegetation and bare soils). The use of standardized SMA improves understanding of the impact of endmember variability on the derivation of subpixel vegetation fractions at a global scale. The LAI is estimated from a FVC using a semiempirical approach as in Roujean and Lacaze (2002). This method relies on a tractable physical model for interception of solar irradiance by vegetative canopies. A statistical approach is proposed for retrieving daily FAPAR from BRDF data, corrected of surface's reflectance anisotropy and minimising the effect of soil reflectance (Roujean and Bréon, 1995). FVC is defined as the fraction of green vegetation at nadir, LAI is defined as an actual green LAI, whereas FAPAR is defined as a daily-integrated green value for blue-sky conditions (i.e., considering direct and diffuse solar irradiance). The LSA SAF methodology has been applied to different remotely sensed data, including SPOT/VEGETATION, MODIS and Sentinel-2 like data, showing good performances (García-Haro et al. 2005; 2006; Verger et al. 2009a; 2009b, Camacho et al. 2013a). More details on the algorithm can be found in the ATBD (SAF/LAND/UV/VR_VEGA/2.0).

- **Known issues and limitations**

The PUM (SAF/LAND/UV/PUM_VEGA/3.0) describes the main know issues and limitations of the MSG products. Here we summarize the main issues:

SEVIRI products are mainly limited by large input BRDF errors at high view zenith angles and residual snow over Europe during winter time. The accuracy of the BRDF is dependent on intrinsic limitation of the BRDF model. Thus lower accuracy is expected over regions with large view zenith angles.

Algorithms to retrieve vegetation parameters suffer from some loss of sensitivity since reflectance approaches saturation asymptotically under conditions of moderate-to-high green aboveground biomass. In these conditions, the small variations in the spectral reflectance levels cannot be related accurately to the actual LAI of the canopy. In closed forest canopies the multi-layer structure is responsible of a high amount of shadow, thereby reducing reflected radiant flux from the surface decreases and decreasing the signal-to-noise decreases. Consequently, higher

estimating errors of FVC are usually found over dark surfaces such as needle-leaf forests in Europe (e.g. Landes forest, France) and the tropical evergreen forests in Central Africa and South America. Definitions of satellite products such as LAI are based on simplifying assumptions. Woody fraction is never accounted and leaf clumping is usually only partly accounted. One limitation of SEVIRI LAI products is that clumping effects are incorporated using a biome map (i.e. the GLC2000 global land cover) to select the vegetation types present in the SEVIRI pixel and clumping values extracted from the literature.

The algorithm to retrieve VEGA products over land surfaces requires ideally free of snow and ice cover observations. Thus FVC, LAI and FAPAR products are derived from observations declared as snow-free over land. Since snow events in previous days, though influencing the signal, may be unidentified by the AL2 product, a traces of snow condition was thus necessary for masking unreliable inputs. However, spurious areas with unidentified residual snow may still be present.

● **Description of the data set evaluated**

The LSA SAF service centralized at IPMA has recently reprocessed the entire SEVIRI/MSG archive, with the latest version of the several retrieval algorithms in the processing chain (VEGAv3.0 for 1-day LAI, FAPAR and FVC and v2.0 for the equivalent 10-day products) in order to obtain a continuous and homogeneous dataset of Climate Data Records (CDR) of vegetation products (MTFVC-R; MTLAI-R; MTFAPAR-R).

Up to now, the CDR covers 9 years (2004-2012) for 10-day products and will be expanded in the near future to reprocess the whole period (2013 onwards). In order to extend the period of the analysis (mainly for the accuracy assessment), a similar dataset of reprocessed daily products (v3.0) was extended until 2016. Vegetation parameters from the VEGA v3.0 algorithm are operationally generated since June 2016. The gap between the CDR generated by IPMA and the operational near real time products (January 2013-June 2016) was generated by the UV with the same version to get a consistent time series of the whole SEVIRI data (2004-2016). The daily SEVIRI/MSG archive covering the 2004-2016 period can be regarded as "internal product" and is not distributed as CDR.

3   PRODUCT REQUIREMENTS

The LSA SAF requirements for SEVIRI vegetation products on accuracy (either 10 days or daily) are shown in Table 1 and Figure 1. The optimal levels have been established to match GCOS requirements on accuracy (see Table 2). The GCOS optimal level for LAI is expressed only as a relative value, and then for very low values it would be difficult to meet optimal levels. No requirements for stability have been defined.

Table 1: LSA SAF Product Requirements(*) for FVC, LAI and FAPAR MSG/SEVIRI products

	Optimal (GCOS)	Target	Threshold
LAI	15%	Max [0.5,20%]	Max [0.75,25%]
FAPAR / FVC	Max [0.05,10%]	Max [0.075,15%]	Max [0.1,20%]

(*) The accuracy requirements may not be met under low illumination angles or when only a very low number of clear sky and/or snow free observations are available during the retrieval period (30-day period processed every 10 days).
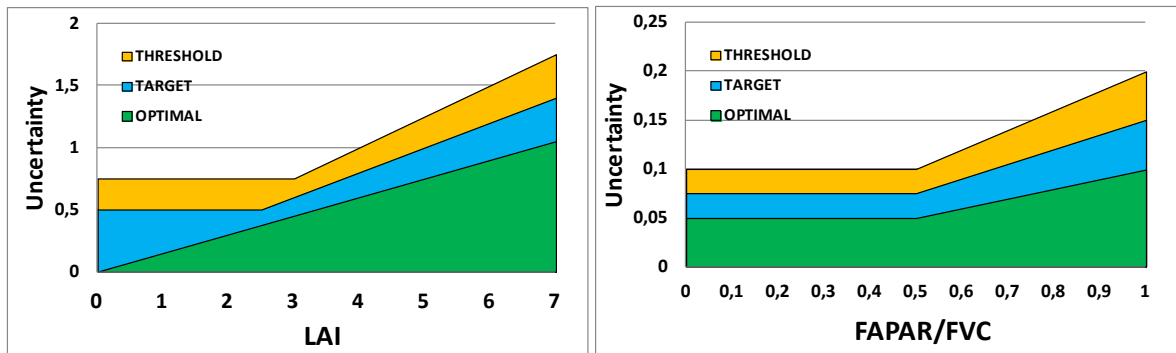
Figure 1: Defined uncertainty levels as a function of LAI (left) and FAPAR or FVC (right) values.

It should be noted that the uncertainty associated to LAI reference maps is expected to be around 1 LAI units for dense forest (Fernandes et al., 2003) or around 0.5 for croplands (Martínez et al., 2009), which is around 20%. Therefore, with the available ground truth reference data is difficult to achieve the optimal (GCOS) requirement on accuracy for LAI satellite-based products. Further research on FAPAR and FCOVER should be conducted to evaluate the uncertainty attached to ground reference maps, which could be also slightly higher than the

optimal requirement for satellite-based products.

- **GCOS requirements:**

The World Meteorological Organization (WMO) provides a set of requirements and recommendations for a functional and robust Global Climate Observing System (GCOS). The GCOS requirements for Essential Climate Variable derived from satellite observations are compiled in its Implementation Plan (GCOS-200, 2016). For LAI and FAPAR, the GCOS requirements are summarized in Table 2. The Accuracy corresponds to the optimal level of the LSA SAF Product Requirement, whereas the GCOS stability requirements will be used as a target to evaluate the precision and stability of MSG derived products.

Table 2: GCOS Requirements for LAI and FAPAR as Essential Climate Variables.

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
LAI	250 m	N/A	2- weekly averages	15%	Max (10%; 0.25)
FAPAR	250 m	N/A	2- weekly averages	Max (10%; 0.05)	Max (3%; 0.02)

4 VALIDATION METHODS AND REFERENCE DATASETS

4.1 VALIDATION PROTOCOL

The protocols and metrics used for this validation exercise were defined to be consistent with best practices proposed by Land Product Validation (LPV) sub-group of the Committee on Earth Observation Satellite (CEOS) Working Group on Calibration and Validation (WGCV). Several criteria of performance were assessed in agreement with previous global LAI validation exercises (Camacho et al., 2013b; Garrigues et al., 2008; Weiss et al., 2007), the OLIVE (On Line Validation Exercise) tool hosted by CEOS cal/val portal (Weiss et al., 2014), the recent CEOS LPV Global LAI product validation protocol (Fernandes et al., 2014) and metrics proposed to validate similar products in the Copernicus Global Land Service (Camacho et al., 2016; 2017).

The following criteria of performance and metrics were assessed:

Product Completeness

Completeness corresponds to the absence of spatial and temporal gaps in the data. Missing data are mainly due to cloud or snow contamination, poor atmospheric conditions or technical problems during the acquisition of the images and is generally considered by users as a severe limitation of a given product. It is therefore mandatory to document the completeness of the product (i.e. the distribution in space and time of missing data). Maps of missing values, distribution of gaps as a function of the season and the length of the gaps are analysed.

Spatial Consistency

Spatial consistency refers to the realism and repeatability of the spatial distribution of retrievals over the globe. A first qualitative check of the realism and repeatability of spatial distribution of retrievals and the absence of strange pattern of artefacts (e.g., missing values, stripes, unrealistic low values, etc.) can be achieved through systematic visual analysis of all global maps based on the expert knowledge of the scientist. The methodology for visual analysis includes the visualization of animations of global maps at a reduced (1/2 pixels) resolution.

The spatial consistency can be quantitatively assessed by comparing the spatial distribution of a reference validated product with the product biophysical maps under study. Difference maps at a monthly basis and annual mean differences between the products are analysed (mean bias, B) in order to identify regions showing differences for further analysis (e.g. temporal profiles). This analysis is complemented by the analysis of Probability Density Function (PDFs) and distribution of residuals per biomes and continents.

Two products are considered spatially consistent when the mean differences lie within predefined levels of discrepancies. Three levels of discrepancies (optimal, target and threshold) were used, in agreement with the LSA SAF PR (as described in Table 1). The percentage of land values within these uncertainty levels is quantified.

Temporal Consistency

Temporal consistency refers to the realism and stability of the inter-annual and intra-annual temporal variations. The temporal consistency of the products is assessed over the MSGVAL network of sites (see Section 4.4) of the vegetation variables are qualitatively analysed as compared to reference validated products.

Two quantitative metrics are used to analyse the temporal consistency of the products: the cross-correlation and the auto-correlation of the temporal series.

Cross-correlation is a standard method of estimating the degree to which two series are correlated. Consider two series $x(i)$ and $y(i)$ where $i=0,1,2...N-1$. The cross correlation ρ at delay d is defined as:

$$\rho = \frac{\sum_i[(x(i) - mx) \cdot (y(i - d) - my)]}{\sqrt{\sum_i(x(i) - mx)^2}\sqrt{\sum_i(y(i - d) - my)^2}}$$

where mx and my are the means of the corresponding series.

The auto-correlation is a particular case of the Cross-correlation where $x=y$.

The cross-correlation is computed with a delay $d=0$ in order to estimate the consistency between temporal profiles of different products with the same temporal support. The auto-correlation is computed with a delay of 1 year ($d=36$ dekad) for the product under study.

Precision

Inter-annual precision (i.e., dispersion of LAI values from year to year) can be assessed providing a box-plot of the median absolute deviation of anomalies versus product per bins until the maximum product value (Fernandes et al., 2014).

Intra-annual precision (smoothness) corresponds to temporal noise assumed to have no serial correlation within a season. In this case, the anomaly of a variable from the linear estimate based on its neighbours can be used as an indication of intra-annual precision. It can be characterized as suggested by Weiss et al., (2007): for each triplet of consecutive observations, the absolute value of the difference between the center$P(d_{n+1})$ and the corresponding linear interpolation between the two extremes $P(d_n)$ and $P(d_{n+2})$ is computed:

$$\delta = \left| P(d_{n+1}) - P(d_n) - \frac{P(d_n) - P(d_{n+2})}{d_n - d_{n+2}}(d_n - d_{n+1}) \right|$$

The distribution of the intra-annual precision is analysed, and the exponential decay constant is used as quantitative indicator of the typical smoothness value.

Stability of the time series

The stability of the time series is investigated displaying Hovmöller plots (Hovmoller, 1949) of the bias between two products for the period of the CDR. These provide the temporal evolution of bias and their latitudinal variation. The plots are generated using two reference products (SPOT/VGT and MODISC5) to better identify if there are trends in the time series of LSA SAF product.

The slope of the inter-annual precision (defined above) computed for each year of the period using as reference the first year of the time series was also investigated.

Overall statistical consistency

The inter-comparison of products offers a means of assessing the relative discrepancies (systematic or random) between products. The global statistical analysis is performed over a representative set of validation sites (MSG validation sites, see section 4.4) considering all the dates available or specific periods. To allow comparison between the products, the same temporal (10-days) and spatial (MSG pixel) supports are used. The distribution of products values is then generated in the form of PDFs (Probability Density Function) and distribution of the residuals (bias). The consistency between the product under study and the reference products is further quantified based on uncertainties metrics associated to the scatter plots between pairs of products. These analyses are achieved per continents and per aggregated land cover class based on the following generic classes derived from the GLC-2000 classification (Bartholome and Belward, 2005): Broadleaf Evergreen Forest, Broadleaf Deciduous Forest, Needle-leaf Forest, Shrublands, Herbaceous, Cultivated, Sparse and Bare areas. We have grouped Shrublands with Sparse vegetation and Bare areas in a single class representative of the low vegetation values and low seasonality.

Accuracy Assessment

Accuracy is quantified by several metrics reporting the goodness of fit between the products and the corresponding ground measurements (Table 3). Total measurement uncertainty (i.e., root mean square error, RMSE) includes systematic measurement error (i.e. Bias) and random measurement error (i.e., standard deviation of bias). RMSE corresponds to the Accuracy as there is only one product estimate for each mapping unit (Fernandes et al., 2014). RMSE is recommended as the overall performance statistic. Linear model fits are used to quantify the

goodness of fit. For this purpose, Major Axis Regression (MAR) was computed instead ordinary linear square because is specifically formulated to handle error in both of the x and y variables (Harper, 2014). Finally, the number of pixels within the LSA SAF MSG VEGA product requirements for accuracy is quantified. The accuracy assessment is computed against ground data set up-scaled according with the CEOS LPV recommendations (Morissete et al., 2006) described in Section 4.3. The confidence in the reference ground based map derived from empirical transfer functions depends on performances of the transfer functions that should be quantified with appropriate uncertainty metrics. For the accuracy assessment the closest product date to the field campaign was used.

Table 3: Uncertainty metrics for product validation

Gaussian Statistics	Comment
Scatter plot	Qualitative assessment of agreement.
N: Number of samples	Indicative of the power of the validation
RMSE: Root Mean Square Error	RMSE computed between ground and product values. Indicates the Accuracy (Total Error). (Relative values (%) are also provided using as mean value the average of x and y).
B: Mean Bias	Difference between average values of ground and product. Indicative of accuracy and possible offset. (Relative values (%) are also provided using as mean value the average of x and y).
S: Standard deviation	Standard deviation of the pair differences. Indicates precision.
R^2: Coefficient of determination	Indicates descriptive power of the linear accuracy test. Pearson coefficient was used.
Major Axis Regression (slope, offset)	Indicates some possible bias.
p-value (p<0.05)	Test on whether the slope is significantly different from 1.
% MSG requirements	Percentage of pixels matching the product requirements

Summary of Quality Assessment Procedure

Table 4 summarizes the number of validation metrics used for the validation of MSG VEGA vegetation products.

Table 4: Summary of the QA procedure (*).

Quality Criteria	Product evaluated	Reference Product	Coverage (period)
Completeness	MSG VEGA 10D	SPOT/VGT GEOV1	MSG disk MSGVAL sites [2008-2009]

	Gap size distribution (average maps & temporal variations). Length of gaps.		
Spatial Consistency	MSG VEGA 10D	SPOT/VGT GEOV1 MODIS C5	Global MSGVAL sites [2008-2009]
	Visual inspection of global maps. Maps and histograms of residuals (global). Percentage of pixels within the uncertainty levels: optimal (GCOS), target and threshold. PDFs of retrievals & histograms of differences per biome and region.		
Temporal Consistency	MSG VEGA 10D MSG VEGA daily	SPOT/VGT GEOV1 MODIS C5	MSGVAL sites [2004-2012]
	Qualitative inspection of temporal variations.Cross-correlation. Histograms of Auto-correlation of MSG VEGA 10D, GEOV1 and MODIS C5. Histograms of Cross-correlation between MSG VEGA 10D, GEOV1 and MODIS C5.		
Intra-annual Precision (smoothness)	MSG VEGA 10D MSG VEGA daily	SPOT/VGT GEOV1 MODIS C5	MSGVAL sites [2008-2009]
	Histograms of the smoothness		
Inter-annual Precision	MSG VEGA 10D	SPOT/VGT GEOV1 MODIS C5	MSGVAL sites [2004-2012]
	Box-plot per bin and median absolute anomaly of 95th percentile and 5th percentile. Inter-annual slope of median absolute anomaly.		
Spatio-Temporal Consistency of the Time Series	MSG VEGA 10D	SPOT/VGT GEOV1 MODIS C5	MSGVAL sites [2004-2012]
	Hovmöller plots of Bias		
Statistical Consistency (Discrepancies)	MSG VEGA 10D	SPOT/VGT GEOV1 MODIS C5	MSGVAL sites [2008-2009]
	Scatter-plots & Uncertainty Metrics (R^2, RMSE, Bias, Scattering, Major Axis Regression, p-value) Box-plots of uncertainties per bin Box-plots of Bias per biome type and continental region.		
Accuracy Assessment (Error)	MSG VEGA Daily SPOT/VGT & PROBA-V GEOV1[(*)] MODIS C5	Ground-based maps	IN-SITU Reference products (see 4.3) [2004-2016]
	Scatter-plots, coefficient of determination. Root Mean Square Error (RMSE), bias (B), major-axis regression (offset, slope), p-value test, percentage of pixels within the accuracy levels.		

(*) MSG VEGA 10D for MTLAI-R, MTFAPAR-R, MTFVC-R and MSG VEGA Daily for MDLAI, MDFAPAR, MDFVC.

Satellite products must be compared over a similar spatial support area and temporal support period. For this purpose, reference products (GEOV1, MODIS C5) at 1-km were re-sampled to the MSG projection. The statistical analysis was conducted at MSG/SEVIRI spatial resolution and the temporal support period for the statistical assessment is 10-days. As different temporal compositing schemes are considered in the satellite product (Table 5) the following approach for comparison was followed: In the case of MSG VEGA 10D versus GEOV1 (both 30-days composite), the product with the most similar temporal window was inter-compared. In the case of MSG VEGA 10D (30 days window) versus MODIS products (8 days temporal window), a weighted average of best quality MODIS retrievals was used, considering the closest date (weight of 0.5) to the VEGA 10D product date, and the two neighbours dates (before and after,

with weight of 0.25).

The analysis was mainly focused on the two-year period of 2008-2009, and the comparison of MSG VEGA 10D (MTLAI-R, MTFAPAR-R, MTFVC-R) versus reference products (GEOV1 and MODIS C5). However, for the analysis of the time series (Temporal Consistency, Inter-Annual Precision, Spatio-Temporal consistency of Time series) and for the Accuracy Assessment, the period was extended until the whole available period (2004-2012 in case of MSG VEGA 10D, and 2004-2016 in case of MSG VEGA Daily).

Table 5: Temporal information where j is the product date

Product	Temporal window	Temporal window interval	Temporal frequency
VEGA 10D	30	[j-15, j+15]	10
VEGA Daily	5	[j-5, j]	1
GEOV1	30	[j-17, j+13]	10
MODIS	8	[j, j+8]	8

The following Quality Flag information of GEOV1 and MODIS was used to filter pixels flagged as out of range, saturated or invalid (Table 6) for the statistical analysis. For MSG we have filtered unreliable data using the error field (LAI error >1.5 and FAPAR/FVC > 0.15). This error fields were propagated through the algorithm using the input BRDF errors, and thus using these threshold values, the unreliable MSG estimates are discarded.

Table 6: Quality Flag information used to filter low quality or invalid pixels

Product	Quality Flag
GEOV1	Sea (bit 1), Snow (bit 2), Input status out of range or invalid (bit 6), LAI/FAPAR/FVC out of range or invalid (bits 7, 8, 9), B2 saturated (bit 10), B3 saturated (bit 11).
MODIS	Cloud state not clear (bit 4, 5 - Fpar, Lai), Main method failed or could not retrieve pixel (bit 6, 7 8, FparLai). Shore, freshwater, ocean (bit 1, 2, FparExtra), Cirrus detected (bit 5, FparExtra)

4.2 SATELLITE REFERENCE PRODUCTS

● **SPOT/VGT and PROBA-V Collection 1km Version 1 (GEOV1)**

The algorithm of SPOT VEGETATION (SPOT VGT) GEOV1 exploits the proven capacity of neural networks to estimate biophysical variables. The retrieval methodology is described in Baret et al., (2013). It relies on neural networks trained to generate the "best estimates" of LAI, FAPAR, and FVC obtained by fusing and scaling of MODIS and CYCLOPES products. The methodology is made of 3 steps: 1) the generation of the training dataset; 2) the neural network calibration; 3) the application of the network. The definition of LAI corresponds to an actual LAI, whereas FAPAR corresponds to instantaneous black-sky (direct) values at 10:30h. However, the optical properties of the leaves considered in the model simulations of CYCLOPES products also consider the absorption of brown pigments (Baret et al., 2007), thus some contribution from brown pigments to the absorbed PAR is expected. The FVC is defined as the green vegetation fraction at nadir.

GEOV1 products were based on SPOT VGT observations until the end of the mission in May 2014 and covered more than 15 years of data. To provide continuity to the service at 1 km, the GEOV1 processing chain was adapted to the Project for On-Board Autonomy-Vegetation (PROBA-V) mission, launched in May 2013 by ESA. One of the main objectives of PROBA-V was to ensure the succession of the VEGETATION instruments acting as "gap filler" between SPOT and Sentinel-3. Thus, since May 2014, the GEOV1 products are based on PROBA-V observations, with spectral characteristics nearly identical to VEGETATION. Both SPOT/VGT and PROBA-V GEOV1 product are freely available at https://land.copernicus.eu.In previous exercises (Camacho et al., 2013b), the accuracy of SPOT/VGT GEOV1 products was computed using a ground reference data set representative of an area of approximately 3x3 pixels that allows limiting the effects of point spread function and geometric accuracy. The in-situ data set was processed according to the guidelines defined by the CEOS/WGCV LPV subgroup (Morisette et al., 2006). The accuracy (RMSE) of SPOT/VGT GEOV1 products against the reference data set is 0.7/0.08/0.09 for LAI/FAPAR/FVC variables (Camacho et al., 2013b). Recent studies (Mu et al., 2015) reported an overestimation of the SPOT/VGT GEOV1 FVC by up to 0.2 over cropland sites in China, in line with recent studies (Doña et al., 2017).

The overall consistency achieved between SPOT VGT and PROBA-V GEOV1 evaluated over the BELMANIP2.1 network of sites (Sánchez et al., 2015) in terms of RMSE was 0.3/0.03/0.04 for LAI/FAPAR/FVC, better than the GCOS requirements on accuracy, with almost no mean bias (~2%) and coefficient of determination (R^2) higher than 0.96. The preliminary accuracy assessment showed an RMSE of 0.52 for LAI, 0.11 for FAPAR and 0.14 for FVC, showing a slight bias for FVC for higher values over cropland sites (Sánchez et al., 2015). Recent studies (Nestola et al., 2017) showed slight negative bias for FAPAR as compared to ground data of

canopy FAPAR over a Deciduous Beech Forest site in Italy, with up to 98% of cases within the GCOS requirements.

- **NASA MODIS (MODC5)**

Terra MODIS LAI/FAPAR (MOD15A2) collection 5, available since 2000 from https://lpdaac.usgs.gov/products/ is produced based on TERRA at 1 km spatial resolution and 8 days step over a sinusoidal grid (Yang et al., 2006). The main algorithm is based on Look Up Tables (LUTs) simulated from a three-dimensional radiative transfer model (Knyazikhin et al., 1998). The MODIS red and NIR atmospherically corrected reflectances (Vermote et al., 1994) and the corresponding illumination-view geometry are used as input for the LUTs. The output is the mean LAI/FAPAR computed over the set of acceptable LUT elements for which simulated and measured MODIS surface reflectances are within specified uncertainties. LAI is defined as an actual LAI whereas FAPAR is defined as black-sky at satellite overpass (around 10:30h).

The MODIS LAI/FAPAR product has been used in many validation and inter-comparison studies (Morisette et al., 2006; Steinberg et al., 2006; Pisek and Chen, 2007; Weiss et al., 2007; Garrigues et al., 2008; McCallum et al., 2010). However, the recent collection 5 has not been widely validated yet. A few studies suggest that MODIS LAI C5 shows improved temporal LAI dynamic over forest sites (De Kauwe et al., 2011; Fang et al., 2012), however the FAPAR C5 displays large differences with similar products (Seixas et al., 2006; Martínez et al., 2013; D'Odorico et al., 2014; Pickett-Heaps et al., 2014). The main drawbacks observed in MODIS LAI/FAPAR C5 are its low temporal stability and the systematic overestimation of FAPAR retrievals over sparsely vegetated areas (Camacho et al., 2013b). The estimated accuracy using the same ground reference data set than for evaluating SPOT/VGT GEOV1 products is RMSE of 0.92 and 0.1 for LAI and FAPAR respectively (Camacho et al., 2013b).

4.3 IN-SITU REFERENCE PRODUCTS

For the Accuracy Assessment, MSG VEGA daily products instead of MSG VEGA 10D were used. They are more suitable to compare with ground values in terms of temporal frequency (daily instead of 10-day) and temporal composites (5-day instead of 30-days composite). The accuracy assessment of MSG VEGA daily satellite products was performed against ground truth data processed according to CEOS LPV guidelines for validation of LAI products, by using a ground reference data set representative of an area of approximately 3x3 pixels that allows limiting the effects of point spread function and geometric accuracy. For this purpose, the in-situ data set was processed according to the guidelines defined by the CEOS/WGCV LPV subgroup

(Morisette et al., 2006). An empirical "transfer function" between high spatial resolution radiometric signal and the biophysical measurements is established using a representative number of elementary sampling units (ESUs) (e.g., Cohen and Justice, 1999; Martínez et al., 2009). It is then applied to all the high spatial resolution pixels of the whole site. The resulting high spatial resolution map of the considered biophysical variable is finally averaged over the 3×3 medium resolution pixels (Garrigues et al., 2008).

The ground data from 2004 to 2013 comes from the analysis of ground uncertainties of the OLIVE DIRECT database (Camacho et al., 2013b), available at CEOS OLIVE Cal/Val portal (http://calvalportal.ceos.org). Those forest DIRECT sites were understory was not characterized were discarded (Camacho et al., 2013b). Finally, for the MSG coverage and the period under study, 22 LAI ground references over 16 sites were available (see Table 7).

Table 7: Characteristics of the DIRECT validation sites and associated ground biophysical values used for validation of MSG VEGA products. #Sample is the number to identify the validation site in the Accuracy Assessment results.   (*) LAIeff

Site	Country	Lat (deg)	Lon (deg)	Land Cover	Dates (mm/yyyy)	LAI	FAPAR	FVC	#Sample
Barrax2	Spain	39.028	-2.074	Crop	07/2005	0.26*	NaN	NaN	1
Barrax	Spain	39.073	-2.104	Crop	07/2004	0.55*	NaN	0.27	2
					07/2005	0.27*	NaN	0.25	3
					06/2009	0.55*	0.20	0.15	4
					06/2010	1.35*	NaN	0.39	5
Demmin	Germany	53.893	13.207	Crop	06/2004	4.50	0.78	NaN	6
Hirsikangas	Findland	62.644	27.012	NLF	07/2004	1.47*	NaN	0.53	7
Jarvselja	Estonia	58.299	27.262	Mix.Forest	06/2005	4.02*	NaN	0.84	8
Plan_De_Dieu	France	44.199	4.948	Crop	07/2004	0.46*	0.22	0.17	9
Rovaniemi	Findland	66.457	25.351	NLF	06/2004	1.37*	NaN	0.42	10
					06/2005	1.46*	NaN	0.49	11
Sonian	Belgium	50.768	4.411	Mix.Forest	06/2004	5.66	0.91	0.90	12
Wankama	Niger	13.645	2.635	Grass	06/2005	NaN	0.07	0.03	13

Chimbolton	UK	51.164	-1.431	Crop	06/2006	NaN	NaN	0.65	14
Donga	Benin	9.77	1.778	Grass	06/2005	1.85	0.47	0.42	15
Hyytiälä	Finland	61.851	24.308	NLF	07/2008	NaN	NaN	0.61	16
Guyaflux	French Guiana	5.2817	-52.912	EBF	11/2005	7[*]	NaN	NaN	17
Utiel	Spain	39.5807	-1.2646	Crop	07/2006	0.49[*]	NaN	0.26	18
		39.5807	-1.2646		09/2008	NaN	0.26	0.24	19
Harth Forest	France	47.806	7.45	Mix.Forest	06/2013	4.57	0.85	NaN	20
					09/2013	3.79	0.84	NaN	21
Marmande	France	44.461	0.206	Crop	09/2007	NaN	NaN	0.47	22

From 2013 to 2016 over the MSG disk, 44 LAI ground references over 18 new sites (see Table 8) were used coming from the FP7 ImagineS project. The ground data was collected by different institutions using mainly digital hemispherical photos (DHP) and LAI-2200 instruments. Ground data was up-scaled by EOLAB using either SPOT-5 or Landsat imagery. Field data collection and up-scaling procedures for all the sites were done according to well-established guidelines (Camacho et al., 2014) in agreement with the VALERI protocols and the CEOS LPV recommendations (Morissete et al., 2006). The ground data, up-scaled maps and data processing reports for all sites are available in the ImagineS website (http://fp7-imagines.eu). Note that the Albufera 2015 data is not part of ImagineS. The data was collected by the University of Valencia in the framework of FP7 ERMES project and the upscaling was made by EOLAB following the same ImagineS protocol.

Table 8: Characteristics of the validation sites and associated ground biophysical values (ground data provided by ImagineS). #Sample is the number to identify the site in the Accuracy Assessment results.

Site	Country	Lat (deg)	Lon (deg)	Land Cover	Dates (mm/yyyy)	LAI	FAPAR	FVC	#Sample
Pshenichne	Ukraine	50.077	30.232	Crop	05/2013	0.57	0.26	0.21	23
					06/2013	2.08	0.58	0.44	24
					07/2013	3.53	0.81	0.63	25
					06/2014	2.14	0.64	0.55	26
					07/2014	2.76	0.70	0.68	27
					06/2015	2.36	0.58	0.46	28
					07/2015	2.61	0.69	0.62	29

					07/2015	2.12	0.56	0.53	30
Merguellil	Tunisia	35.566	9.912	Crop	03/2013	0.48*	NaN	NaN	31
					05/2013	0.19*	NaN	NaN	32
					01/2014	0.18*	NaN	NaN	33
					04/2014	0.93*	NaN	NaN	34
SouthWest_1	France	43.551	1.089	Crop	06/2013	1.39	0.61	0.53	35
					07/2013	1.01	0.32	0.30	36
					07/2013	1.19	0.39	0.32	37
					08/2013	1.70	0.39	0.30	38
					09/2013	1.15	0.34	0.27	39
SouthWest_2	France	43.447	1.145	Crop	06/2013	1.31	0.58	0.49	40
					07/2013	0.64	0.29	0.21	41
					07/2013	0.69	0.46	0.36	42
					08/2013	2.33	0.53	0.45	43
					09/2013	1.88	0.53	0.44	44
Rosasco	Italy	45.253	8.562	Crop	07/2014	4.2	0.85	NaN	45
LaReina_1	Spain	37.819	-4.862	Crop	05/2014	1.08	0.30	0.30	46
LaReina_2	Spain	37.793	-4.827	Crop	05/2014	1.59	0.42	0.41	47
Barrax-LasTiesas	Spain	39.0544	-2.101	Crop	05/2014	1.50*	0.36	0.37	48
					05/2015	0.74*	0.29	0.27	49
					07/2015	0.70*	0.23	0.22	50
Albufera	Spain	39.274	-0.316	Crop	06/2014	0.58	0.21	0.18	51
					06/2014	1.51	0.46	NaN	52
					07/2014	3.77	0.73	NaN	53
					08/2014	5.78	0.85	NaN	54
					07/2015	3.86	0.80	NaN	55
AHSPECT_MTO	France	43.573	1.375	Crop	06/2015	0.85	0.28	0.26	56
AHSPECT_PEY	France	43.666	0.219	Crop	06/2015	1.33	0.41	0.38	57
AHSPECT_URG	France	43.639	-0.434	Crop	06/2015	2.01	0.60	0.55	58
AHSPECT_CRE	France	43.993	-0.047	Crop	06/2015	2.17	0.63	0.59	59
AHSPECT_CON	France	43.974	0.336	Crop	06/2015	1.16	0.36	0.33	60
AHSPECT_SAV	France	43.824	1.175	Crop	06/2015	0.99	0.31	0.29	61
Collelongo	Italy	41.850	13.590	DBF	07/2015	4.58	0.87	0.84	62
					09/2015	3.86	0.87	0.86	63

Capitanata	Italy	41.464	15.487	Crop	03/2014	1.82	0.56	NaN	64
					05/2014	3.08	NaN	NaN	65
					04/2015	3.49	0.76	NaN	66
Muragua-Upper-Tana	Kenya	-0.772	36.974	Crop	03/2016	1.88	0.60	0.58	67

(*) LAI effective values.

Furthermore, 3 additional locations over desertic areas were included in order to increase the sampling over this specific biome type. For this purpose, 3 sites coming from BELMANIP2.1 network (Baret et al., 2006a) were selected over the Sahara Desert. Table 9 shows the characteristics of these sites, on which ground values were fixed to zero. Note that different years were selected (from 2010 to 2012), and the date was selected during the dry season in the Northern hemisphere.

Table 9: Characteristics of the additional validation sites over desertic areas. #Sample is the number to identify the site in the Accuracy Assessment results.

Site	Country	Lat (deg)	Lon (deg)	Land Cover	Dates (mm/yyyy)	LAI	FAPAR	FVC	#Sample
B2.1 #421	Algeria	32.6672	6.71096	Desert	12/2012	0	0	0	68
B2.1 #422	Algeria	25.3348	0.879467	Desert	12/2011	0	0	0	69
B2.1 #426	Mauritania	20.5313	-8.05804	Desert	12/2010	0	0	0	70

Due to the fact that MSG/SEVIRI pixel size is dependent of the location, and ground reference values are available at $3 \times 3 km^2$ of spatial resolution, an analysis was done in order to check if these ground values are representative at the MSG/SEVIRI spatial resolution. For this purpose, scatter plots of GEOV1 at $3 \times 3 km^2$ of spatial resolution versus GEOV1 reprojected to MSG/SEVIRI pixel are generated for the sites and dates with in-situ data (see Figure 2). For FVC and FAPAR, sites presenting differences beyond optimal GCOS FAPAR requirements (i.e. differences> Max [0.05, 10%]) were discarded for the accuracy assessment (see grey values in Figure 2). Similarly, in case of LAI, sites with differences larger than target accuracy (i.e. differences > Max [0.5, 20%]) were not considered in the accuracy assessment (grey values in Figure 2). The following values were discarded for the accuracy assessment exercise.

➢ For FVC, 16 values were not considered, 3 coming from forest sites (#7 Hiriskangas; #10 Rovaniemi; #62 Collelongo), and 13 from croplands (#1 Barrax2; #5 Barrax; #9 Plan_De_Dieu; #23, #24, #26 Pshenichne; #41 SouthWest_2; #46 LaReina_1; #47 LaReina_2; #48, #49, #50 Barrax-LasTiesas; #61 AHS_PECT_SAV).

➢ 10 LAI ground reference values were discarded, 4 corresponding to Forest sites (#7 Hiriskangas; #12 Sonian; #62, #63 Collelongo), and 6 corresponding to Cultivated sites

(#24, #27, #30 Pshenichne; #47 LaReina_1; #48 Barrax-LasTiesas; #64 Capitanata).

➢ Finally, for FAPAR 11 values were discarded, 2 from Forest sites (#7 Hiriskangas; #10 Rovaniemi) and 9 from Cultivated (#1 Barrax2; #5 Barrax; #19 Utiel; #23, #26 Pshenichne; #47 LaReina_2; #48, #49, #50 Barrax-LasTiesas). Note that all of them are common to the FVC discarded values except #19.

➢ The final number of ground data available for validation is 38, 53 and 43 FVC, LAI and FAPAR respectively from 2004 to 2016.
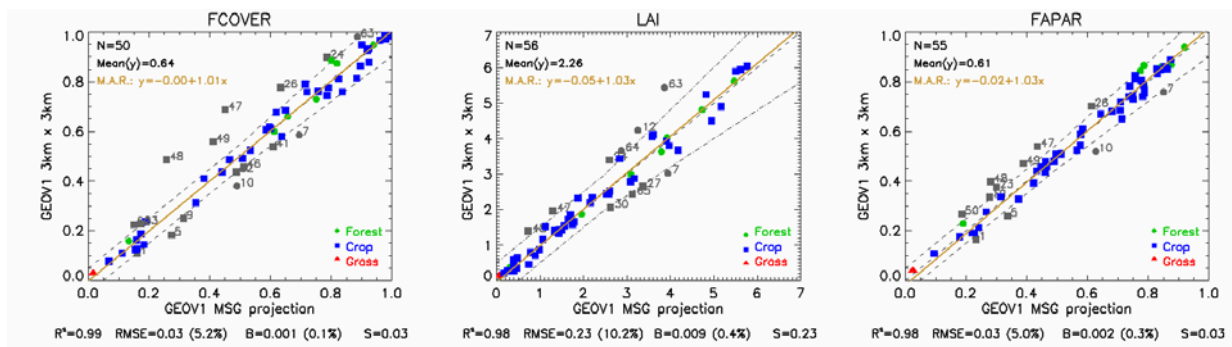
Figure 2: Comparison of GEOV1 FVC, LAI and FAPAR product at 3x3 km2 of spatial resolution versus GEOV1 reprojected to the MSG/SEVIRI grid over sites and dates with available ground values. Grey symbols correspond to pixels beyond uncertainty levels (target in in case of LAI and optimal (GCOS) in case of FVC and FAPAR). Numbers identify the ground data (Table 7 and 8). Dashed lines correspond to the 1:1 line and uncertainty levels, and continuous yellow line to the linear fit using Major Axis Regression (M.A.R.).

4.4 REGIONAL/BIOME ASSESSMENT

The 445 BELMANIP-2.1 network of sites designed to represent globally the variability of land surface types was used (Baret et al., 2006a) for the computation of several metrics. Due that it was initially designed to validate global products, and some of the sites are located out of the MSG coverage, it was complemented with additional sites coming from different networks. A total of 478 sites were used: 239 BELMANIP-2.1 sites covering the MSG disk (http://calvalportal.ceos.org), 120 EUVAL sites located over Europe and North of Africa (Camacho et al., 2016), 29 African validation sites used by JRC NARMA (Natural Resources Monitoring for Africa) user during geoland-2 project, 8 Enviro-Net sites (www.enviro-net.org/) across South of America, 63 sites coming from OLIVE DIRECT (http://calvalportal.ceos.org), and 19 coming from ImagineS.

The MSGVAL sites were classified according to the main biome type as described in section 4.1 as well as per continents to assess the product performance per regions and biomes (Figure 3).
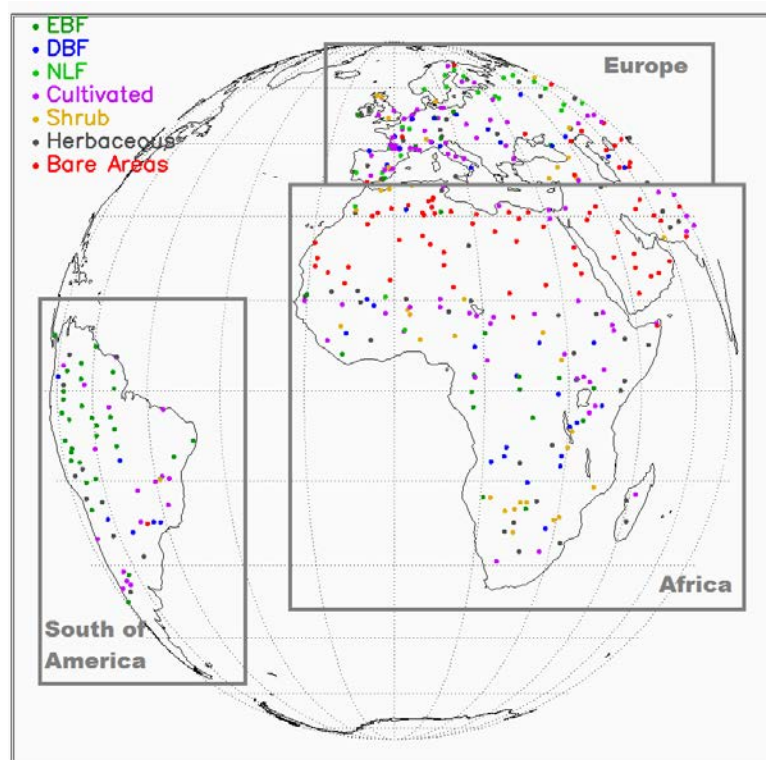
Figure 3: Location of the 478 MSGVAL sites. All the classes are aggregated in the following main biomes (up to down in the legend): Evergreen Broadleaf Forest (EBF), Deciduous Broadleaf Forest (DBF), Needle-leaf Forest (NLF), Cultivated, Shrublands, Herbaceous and Bare Areas.

5 VALIDATION RESULTS

5.1 PRODUCT COMPLETENESS

Figure 4 displays the maps of the percentage of missing values during the 2008-2009 period for VEGA 10D, and for the reference GEOV1 at the MSG disk projection. Furthermore, the temporal evolution of the fraction of missing values for the two products under study during the 2008-2009 period is showed in Figure 5.
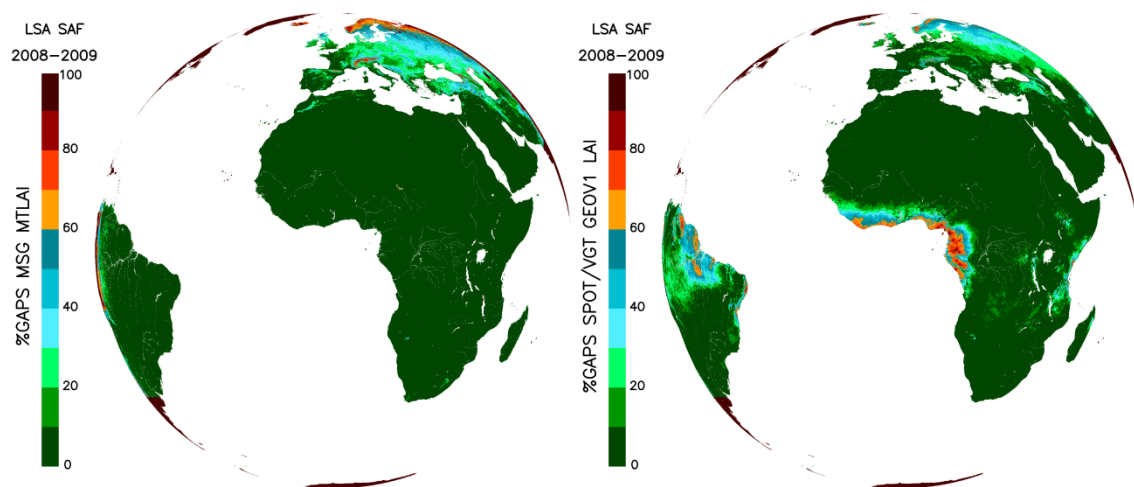
Figure 4: Percentage of missing values during the 2008-2009 year period for MSG MTLAI and SPOT/VGT GEOV1 products.

The results are displayed for LAI and very similar (almost the same) results were found for the other variables (FAPAR, FVC). Figure 4 shows the following findings:

➢ Very low fraction of missing values for VEGA products as compared to GEOV1, mainly over South of America and Africa, explained in the better sampling of SEVIRI instrument. GEOV1 products are derived from observations coming from sensors in polar orbiting platforms, with up to 100% of missing observations over equatorial areas due to the persistent cloud coverage (Camacho et al., 2013b). However, SEVIRI is on-board a geostationary platform and acquires a much frequent sampling that allows to accumulate enough cloud-free observations along a single day.

➢ On the other hand, higher fraction of missing values was found for VEGA 10D as compared to GEOV1 over Europe (northern latitudes), partly explained in the fact that SEVIRI observes each surface target with large viewing angles and coarser spatial

resolutions (more difficult to have cloud or snow free pixels than in GEOV1).

➢ Similar temporal evolution of missing values was found for VEGA 10D and GEOV1, with VEGA 10D showing generally better slight fraction of valid observations (around 2%). The larger fraction of missing values for VEGA 10D (around 14%) was found for end of January whereas the lower fraction (around 5%) was found during the period from June to September.
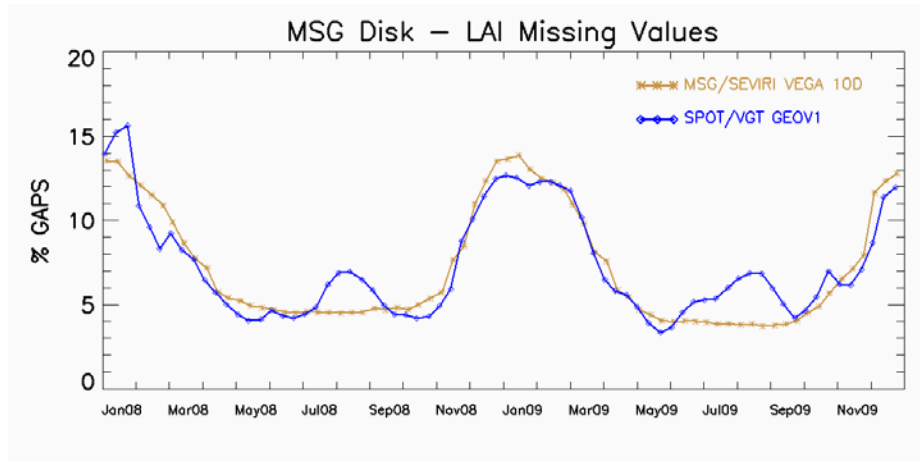
Figure 5: Percentage of missing values during the 2008-2009 period for MSG MTLAI and SPOT/VGT GEOV1 products.

The distribution of the temporal length of the missing values was also evaluated in order to better understand the impact of the gaps for monitoring the temporal variations. The length of gaps, evaluated over MSGVAL sites during the 2008-2009 period is shown in Figure 6:

➢ Around 50% of the VEGA 10D gaps are shorter than 30 days, showing the most typical case (~30%) corresponding to 30 days which means three consecutive missing observations.

➢ GEOV1 shows that around 60% of gaps are shorter than 30 days with around 35% of them corresponding to only one missing observation.

➢ The different distributions for MSG 10D and GEOV1 can be explained due to the differences in the temporal sampling of MSG (15 minutes temporal frequency) and SPOT/VGT (typically one observation per day). As a result, MSG presents lower overall amount of gaps than GEOV1 (Figure 5), but the temporal length of gaps is higher because VEGA 10D gaps corresponds mainly to persistent clouds due to the higher ability of MSG to get cloud-free observations.
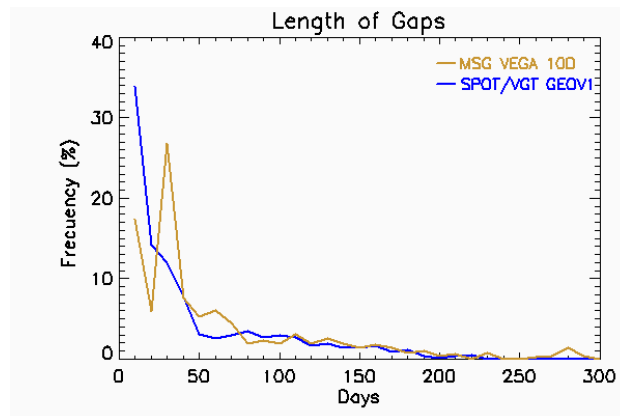
Figure 6: Percentage of missing values during the 2008-2009 period for VEGA10D and SPOT/VGT GEOV1 products.

5.2 SPATIAL CONSISTENCY

5.2.1 Visual inspection of global maps

Maps of the three VEGA variables derived from MSG/SEVIRI were displayed and compared to that of GEOV1 and MODIS C5 reprojected products over the MSG disk. Figures 7 to 9 show maps of VEGA 10D, GEOV1 and MODIS C5 products. Three different dates (one date for each variable) were selected to better illustrate the spatial distribution over the time. Similar spatial distributions were found for the three products over the MSG disk without detecting any anomalous patterns. It can be observed higher LAI and FAPAR values over equatorial areas in the MODIS C5 products than in MSG or GEOV1, which is explained by the biome-dependent MODIS algorithm and the particular parameterization for EBF which results in high values. Annex I displays the maps (one example per month) of the FVC, LAI and FAPAR VEGA 10D variables during one year of data.
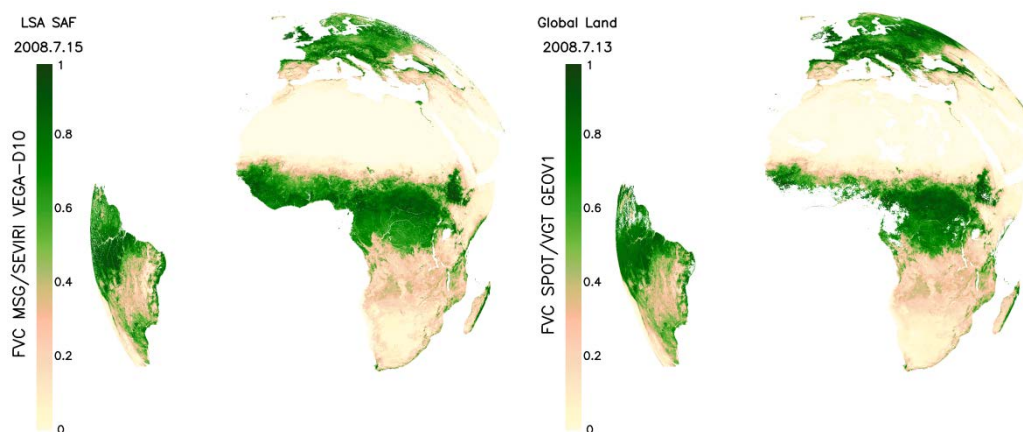
Figure 7: VEGA 10D and GEOV1 FVC maps at MSG projection for mid of July, 2008.
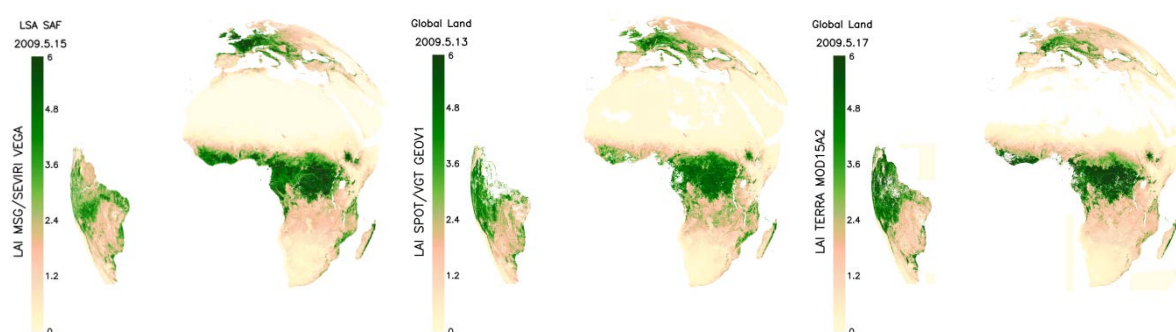
Figure 8: VEGA 10D, GEOV1 and MODIS C5 LAI maps at MSG projection for mid of May, 2009.
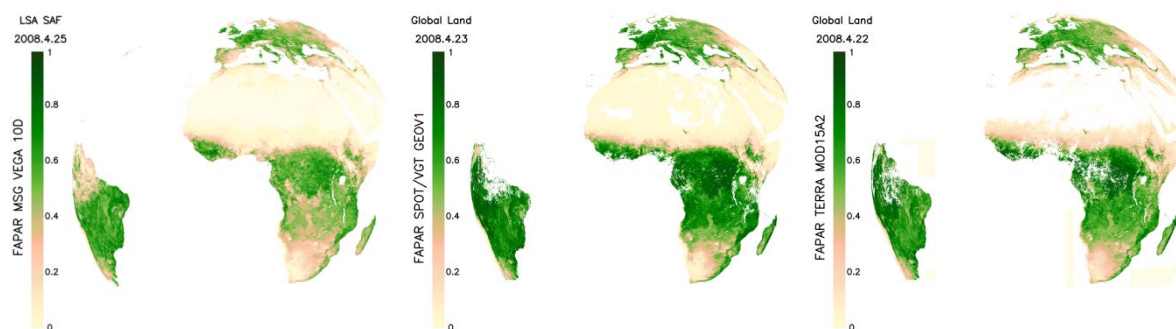
Figure 9: VEGA 10D, GEOV1 and MODIS C5 FAPAR maps at MSG projection for end of April, 2008.

Figure 10 shows some examples of FVC, LAI and FAPAR error estimates associated to the product. Note that large errors were observed over equatorial areas (typically higher values over Evergreen Forests) and northern latitudes.
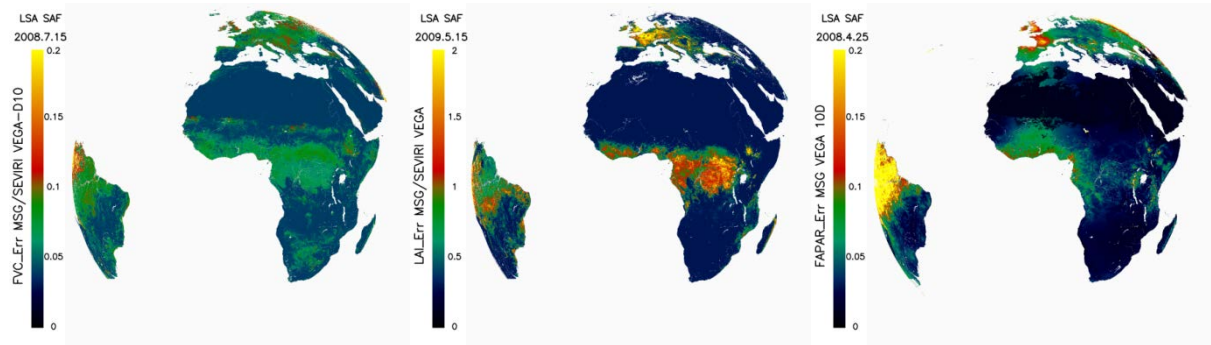
Figure 10: VEGA 10D FVC, LAI and FAPAR error estimates for several dates in 2008.

5.2.2   Difference maps and consistency levels among products

- **VEGA 10D versus SPOT/VGT GEOV1**

Figures 11, 13 and 15 show the maps of differences between VEGA 10D and SPOT/VGT GEOV1 FVC, LAI and FAPAR products for end of June 2009, and the histograms of differences during the whole 2009 year (one per month). Furthermore, the percentage of differences between the optimal, target and threshold uncertainty levels considered (see Table 1, Figure 1) have been quantified, and displayed in Figures 12, 14 and 16 during the 2009 year. Difference maps between VEGA 10D and SPOT/VGT GEOV1 products for the whole 2009 year are shown in Annex II (one example per month). Note that VEGA pixels with error estimate higher than 1.5 in case of LAI, and higher than 0.15 in case of FVC and FAPAR have been discarded from the analysis. In case of GEOV1, only good quality pixels according to Table 7 have been used.
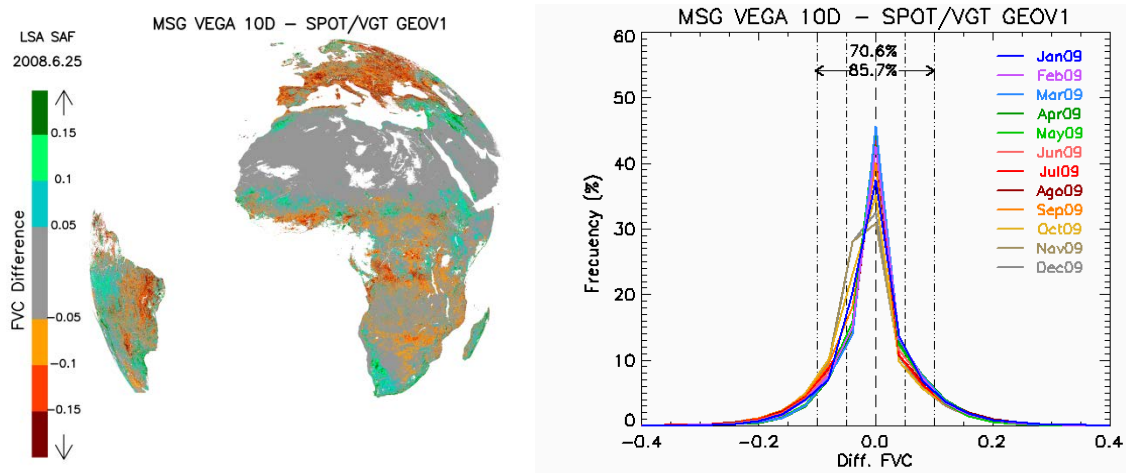
Figure 11: FVC difference map between VEGA 10D and SPOT/VGT GEOV1 products for end of June, 2009 (left side). Histogram of differences per month from January to December 2009 (right side).
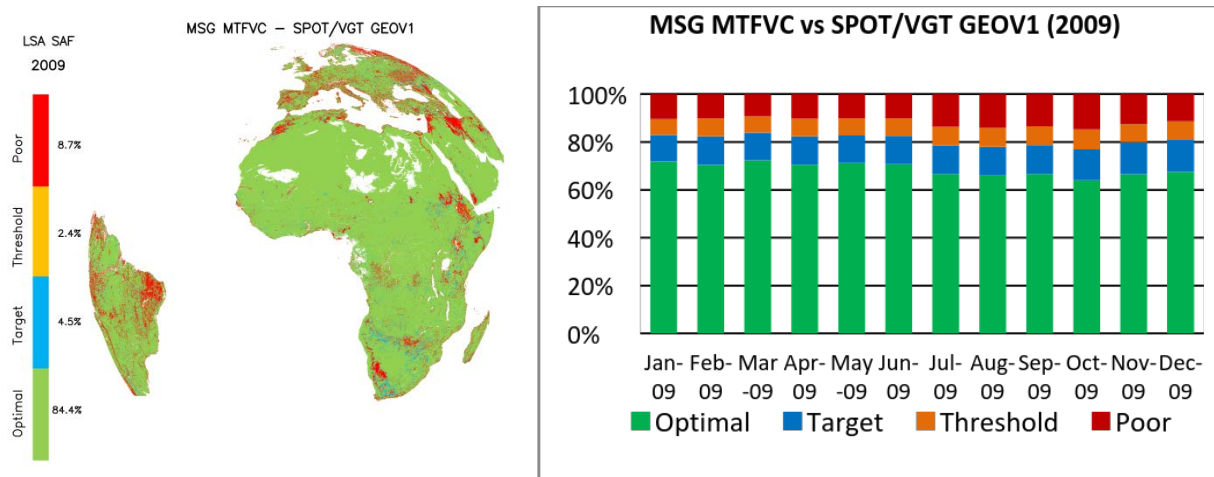
Figure 12: Map of the most frequent FVC consistency levels between VEGA 10D and SPOT/VGT GEOV1 products and percentage of differences lying the optimal (GCOS), target and threshold levels of consistency from January to December 2009 (right side).
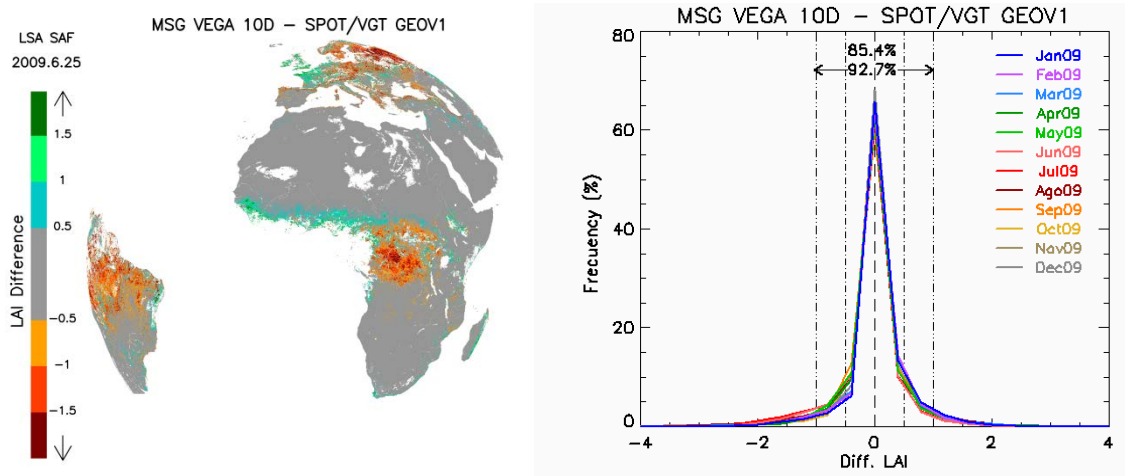
Figure 13: LAI difference map between VEGA 10D and SPOT/VGT GEOV1 products for end of June, 2009 (left side). Histogram of differences per month from January to December 2009 (right side).
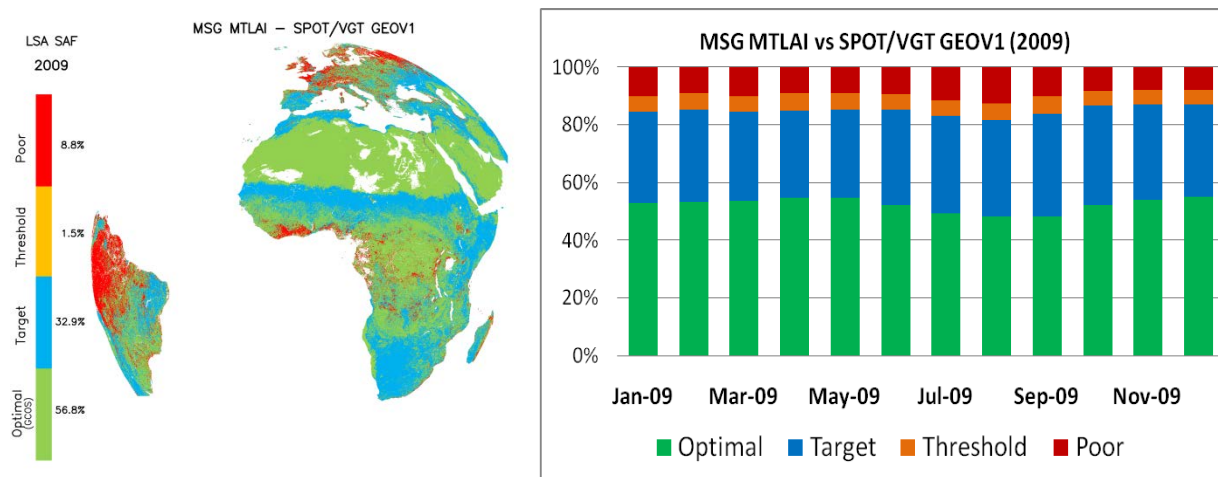
Figure 14: Map of the most frequent LAI consistency level between VEGA 10D and SPOT/VGT GEOV1 products and percentage of differences lying the optimal (GCOS), target and threshold levels of consistency from January to December 2009 (right side).

Figure 15: FAPAR difference map between VEGA 10D and SPOT/VGT GEOV1 products for end of June, 2009 (left side). Histogram of differences per month from January to December 2009 (right side).

Figure 16: Map of the most frequent FAPAR consistency level between VEGA 10D and SPOT/VGT GEOV1 products and percentage of differences lying the optimal (GCOS), target and threshold levels of consistency from January to December 2009 (right side).

These results show that:

For the FVC:

➢ Good spatial consistency was found over large areas except over northern regions in Europe and equatorial areas, explained in the extreme viewing angle in case of MSG

_____

(northern regions) and the higher cloud contamination over these regions. Noticeable is the lower bias observed between VEGA 10D and GEOV1 products over herbaceous and shrublands in Africa, achieving a good improvement of the consistency as compared to previous VEGA version (2.1) (SAF/LAND/UV/VEGA_VR/2.1-4; Camacho et al., 2010).

➢ Histograms of FVC differences are centered at zero, showing more 71% of land pixels with absolute differences lower than 0.05, and 86% of pixels with absolute differences lower than 0.1.

➢ In average, around 70% of pixels shows optimal level of consistency (differences < Max [0.05,10%]) along the 2009 year, and only around 10% showing poor consistency (differences >Max [0.1, 20%]). The optimal level was the most frequent case in up to 84% of MSG land pixels during 2009.

For LAI:

➢ Both products are spatially consistent, with differences lower than 0.5 almost for all continental regions. Spatial discrepancies were found mainly over equatorial areas and northern latitudes where VEGA provides lower values up to 1.5.

➢ The histogram of differences shows very similar distributions during the whole 2009, showing differences lower than 0.5 LAI units in around 85% of cases, and only 7% of pixels showing differences larger than ±1 LAI units.

➢ Around 55% of samples are matching the optimal (GCOS) level of consistency, and goes up to 85% of samples for the target level of consistency. Only around 10% of pixels showed poor consistency. The optimal level was the most frequent case in about 57% of MSG land pixel during the study period.

For FAPAR:

➢ Larger discrepancies were observed, with systematic negative differences up to -0.4 (VEGA 10D< GEOV1) over the whole MSG disk except for Sahara and Arabian deserts and for South of Africa. Poor consistency level was found over these large areas.

➢ The peaks of histograms of differences are centered at zero for all dates but a clear tendency to provide lower values in MSG VEGA was observed.

➢ The percentage of optimal FAPAR consistency level (GCOS) ranges from around 55% (May to June, 2009) to 60% (January 2009). Between 25% and 40% of pixels are showing poor consistency. The most frequent case was optimal consistency in 55% of MSG land pixels, but the second top frequent case was poor consistency in 39% of MSG pixels.

➢ The higher discrepancies found for FAPAR products are in line with previous studies

(Seixas et al., 2006; Martinez et al., 2013; Camacho et al., 2013b, Pickett-Heaps et al., 2014) and can be partly explained due to the different definitions of the FAPAR satellite products. The MSG FAPAR is daily-integrated FAPAR, whereas GEOV1 and MODIS are black-sky FAPAR at 10:30h solar local time. Even if all satellite products refer mainly to green FAPAR, the optical properties of leaves are not defined equally, and could also consider brown pigments in the model simulations as in the CYCLOPES products (used as input for GEOV1).

- **VEGA 10D versus TERRA/MODIS C5**

The spatial consistency of VEGA 10D products with MODIS C5 products was also examined, as shown in Figures 17 and 18 for LAI, and in Figures 19 and 20 for FAPAR. The maps of differences are shown in Annex III. Note that as in the case between VEGA 10D vs GEOV1, here VEGA pixels with error estimate higher than 1.5 in case of LAI, and higher than 0.15 in case of FAPAR have been discarded from this computation. In case of MODIS C5, only good quality pixels according to Table 6 were used.
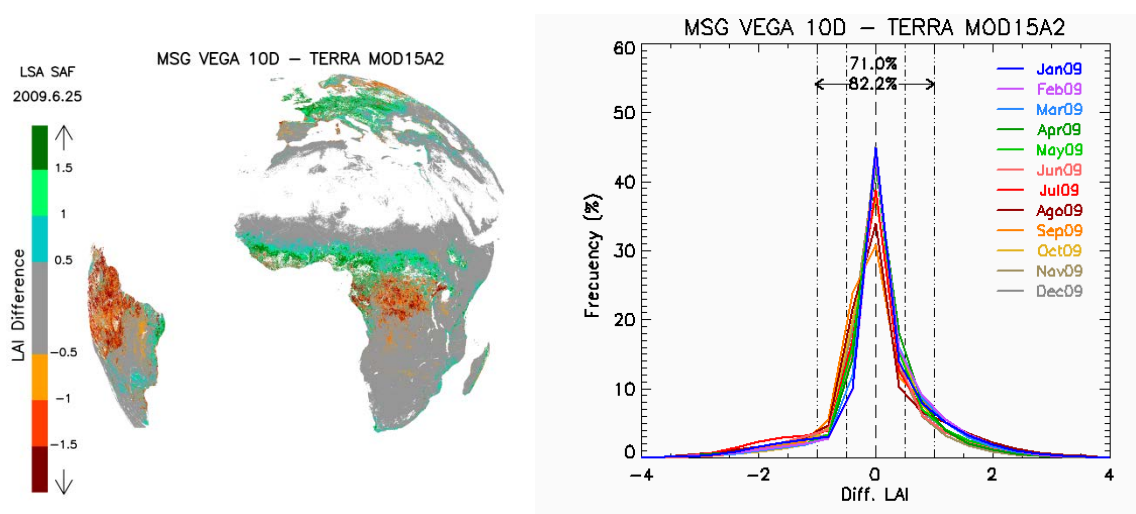
Figure 17: LAI difference map between VEGA 10D and TERRA/MODIS C5 products for end of June, 2009 (left side). Histogram of differences per month from January to December 2009 (right side).
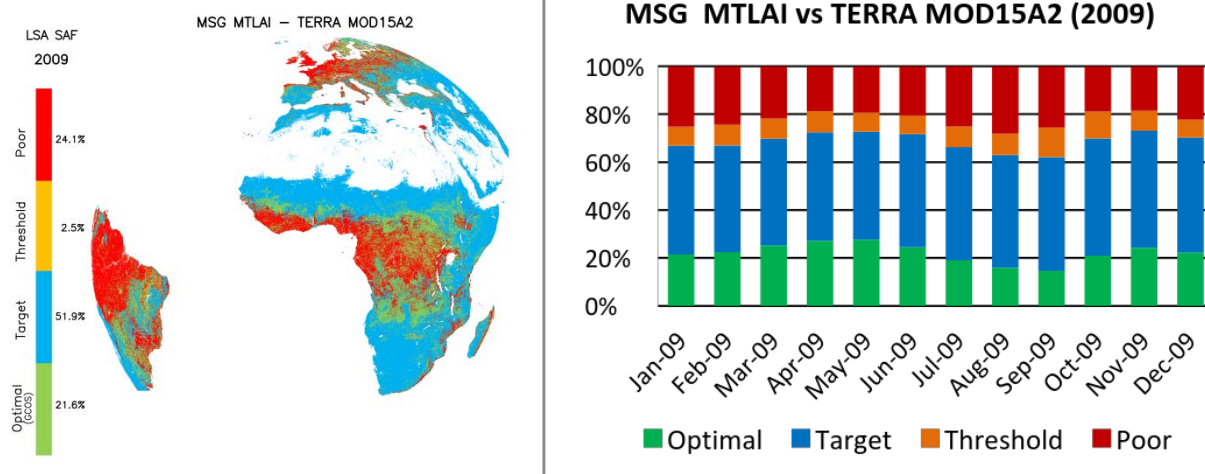
Figure 18: Map of LAI consistency levels between VEGA10D and TERRA/MODIS C5 products and percentage of differences lying the optimal (GCOS), target and threshold levels of consistency from January to December 2009 (right side).
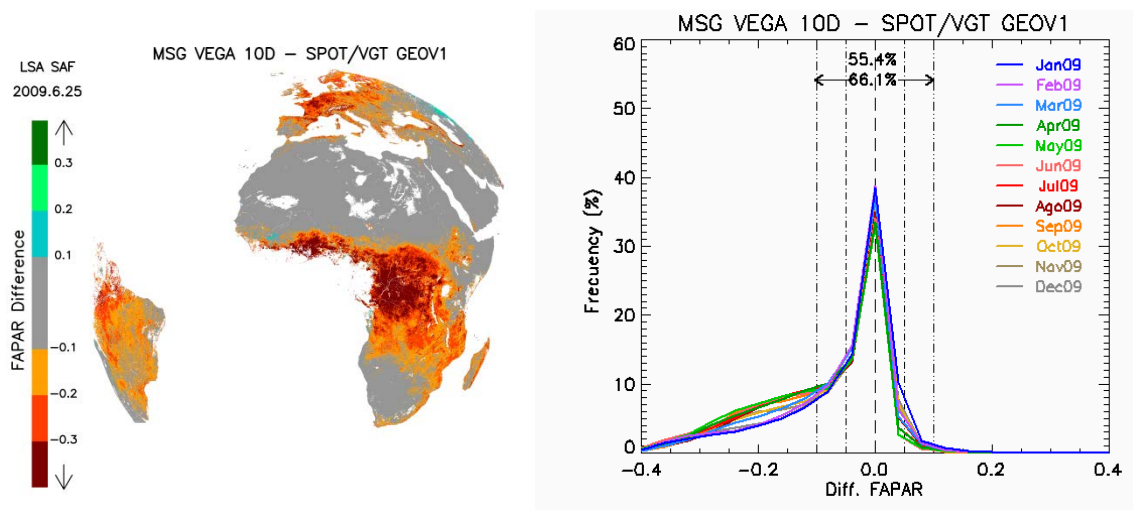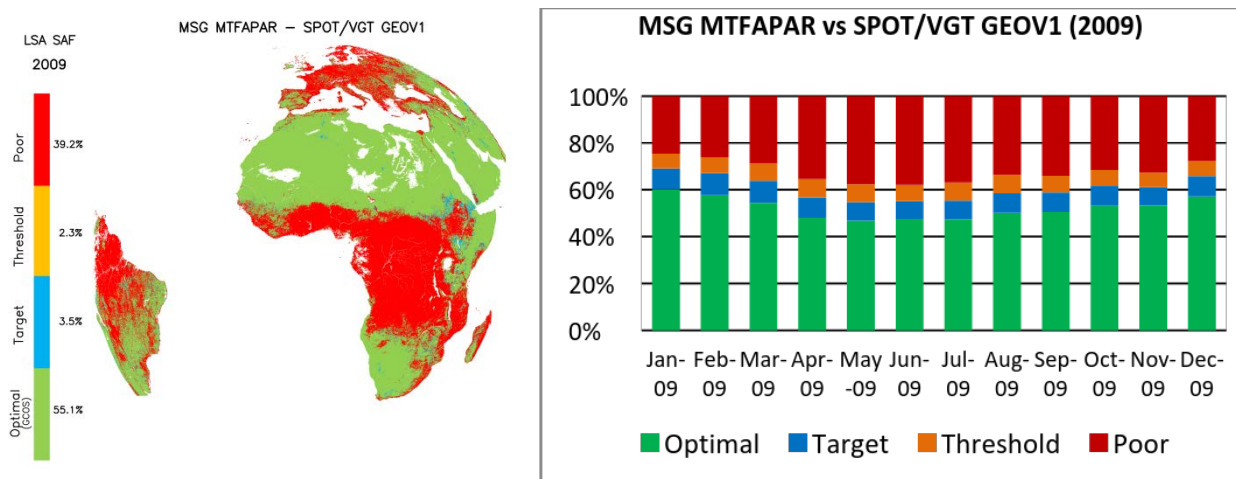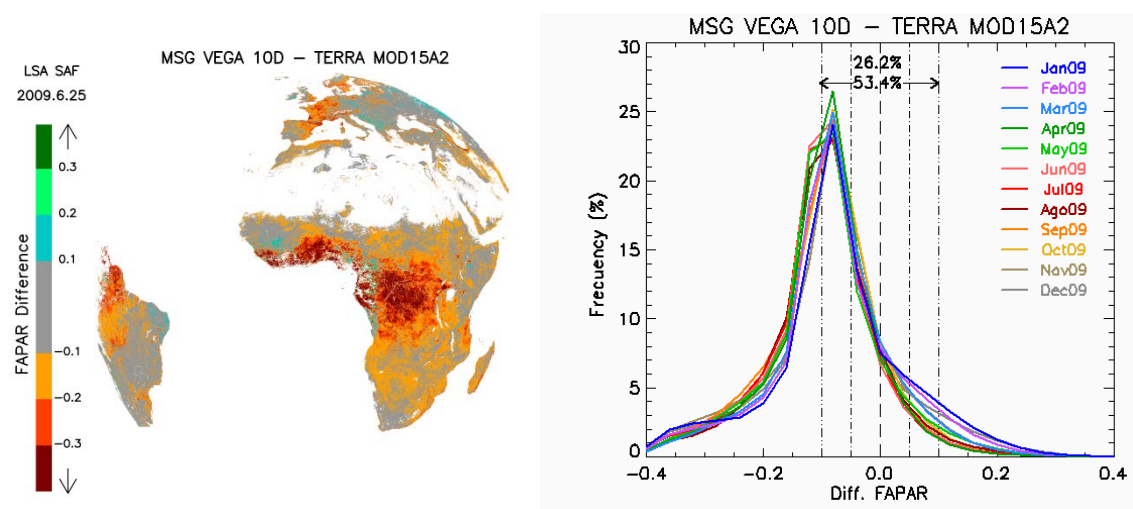

Figure 19: FAPAR difference map between VEGA 10D and TERRA/MODIS C5 products for end of June, 2009 (left side). Histogram of differences per month from January to December 2009 (right side).
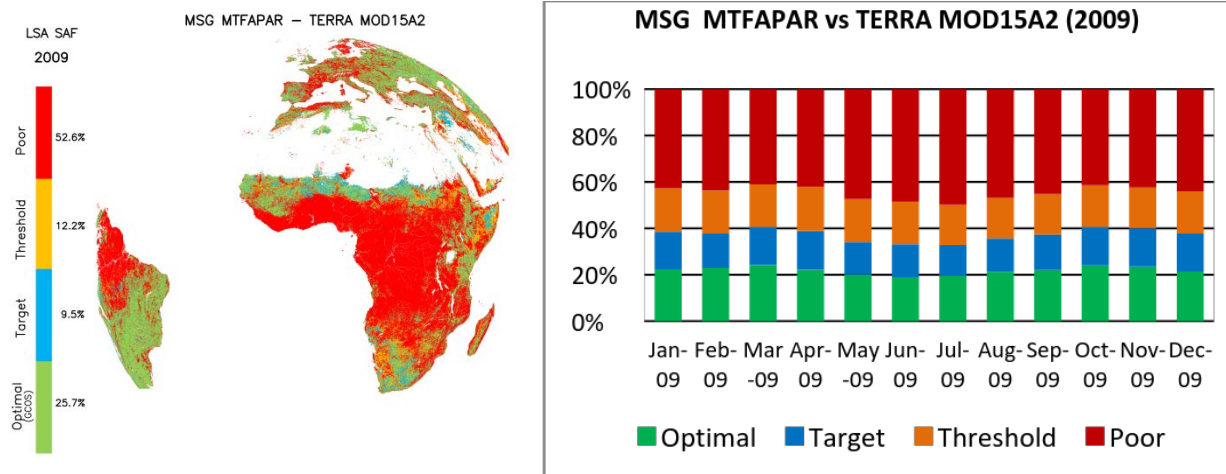
Figure 20: Map of FAPAR consistency levels between VEGA 10D and TERRA/MODIS C5 products for end of June, 2009 (left side). Percentage of differences lying the optimal (GCOS), target and threshold levels of consistency from January to December 2009 (right side).

These results show that:

For the LAI:

➢ Good spatial consistency (optimal or target levels) was found over large areas with discrepancies over densest vegetated regions. MODIS C5 provides larger values over equatorial forest whereas VEGA 10D provides large values over other regions (DBF and Crops). This is partly explained because both product algorithms are biome dependent. MODIS provides much larger values in EBF than MSG.

➢ Histograms of LAI differences show good results, with maximum values centred at zero and a slight tendency towards positive values (MSG > MODIS). Around 71% of differences for the year 2009 are ranging between ±0.5 LAI units.

➢ Around 20% of samples showed optimal level of consistency along the year and around 65% in the target level. The most frequent case was target level in 52% of MSG land pixels, whereas poor level of LAI consistency was found in around 24% of cases, typically located over equatorial areas and northern regions in Europe.

For the FAPAR:

➢ Larger discrepancies were found, VEGA 10D products provide systematically lower values than MODIS C5 over the whole MSG disk, with differences between -0.1 and -0.2 over large areas, and up to -0.4 over equatorial regions. Histograms of differences are centred around -0.08 for all the dates, showing the systematic negative bias between both

products, partly explained by the different definition of FAPAR. MSG is defined as daily-integrated FAPAR whereas GEOV1 and MODIS are black-sky FAPAR at 10 solar local time. In both cases FAPAR refers to green elements, but differences are also encountered in this definition.

➢ Optimal level of FAPAR consistency was achieved in around 20% of pixels, whereas poor level of consistency was found in more than 60% of cases along the year. The most frequent case along the year was poor consistency in 52% of MSG land pixels. This highlights the large differences in the FAPAR satellite-product. The accuracy assessment is shown in section 5.8, with better agreement with ground truth (40 samples) for MSG than other products (MODIS and GEOV1).

5.2.3 **Distribution of retrievals and differences per biome type**

The distribution of values and the histograms of differences for the three products under study (MSG VEGA 10D, GEOV1 and MODIS C5) were computed over the MSGVAL sites during the 2008-2009 period and analyzed per biome type. Results show that:

For FVC (Figure 21):

➢ Similar distributions were found for MSG VEGA 10D and GEOV1 for all biome types except for EBF and NLF, where slight discrepancies were found.

➢ Histograms of difference are centered at zero for all biome types except for DBF, NLF and Cultivated, with slight tendency towards negative values (GEOV1> MSG VEGA 10D).

For LAI (Figure 22):

➢ Some discrepancies were found between MSG VEGA 10D and the reference products, where the main discrepancies are observed for EBF biome type. Furthermore, LAI values derived from MODIS data show an overestimation for the lowest LAI values in non-forest areas, as is reported in Camacho et al. (2013b).

➢ Histograms of differences are generally centered at zero except for EBF with a clear tendency towards negative values (MSG VEGA 10D< GEOV1& MODIS C5).

For FAPAR (Figure 23):

➢ Larger discrepancies between MSG VEGA 10D and both references (GEOV1 and MODIS C5) were found, generally for forest sites, unlike the results obtained for non-forest areas, where MODIS show larger discrepancies in comparison with MSG VEGA

10D and GEOV1.

➢ Histograms of differences are consistent with the results mentioned before. It can be observed that MSG VEGA 10D shows higher negative differences for forest areas as compared to both references. Note that GEOV1 is based on MODIS products, so better agreement is expected between both. Comparisons with other satellite product (e.g. MERIS FAPAR) showed that MSG provided an intermediate solution between the existing satellite products (e.g., Martínez et al., 2013).

Figure 21: Distribution of FVC values (left panel) and differences (right panel) for the MSGVAL sites during the 2008-2009 period for each biome type.
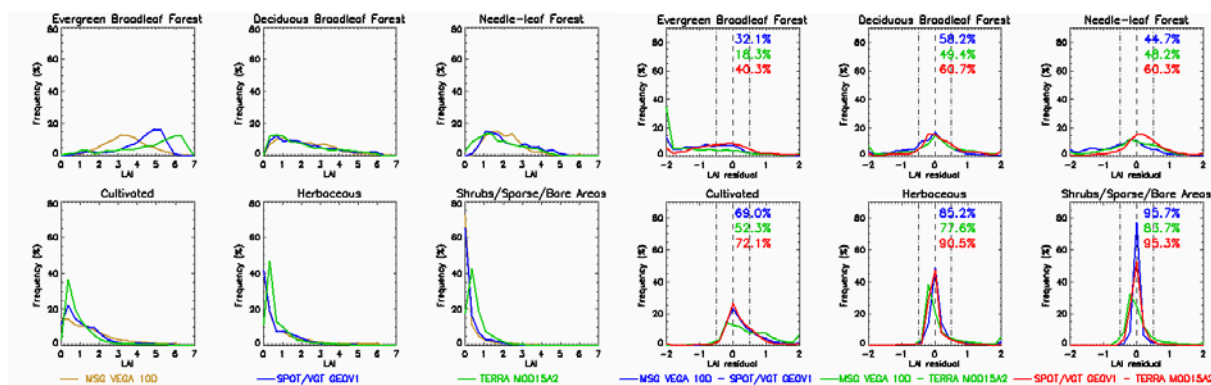
Figure 22: Distribution of LAI values (left panel) and differences (right panel) for the MSGVAL sites during the 2008-2009 period for each biome type.

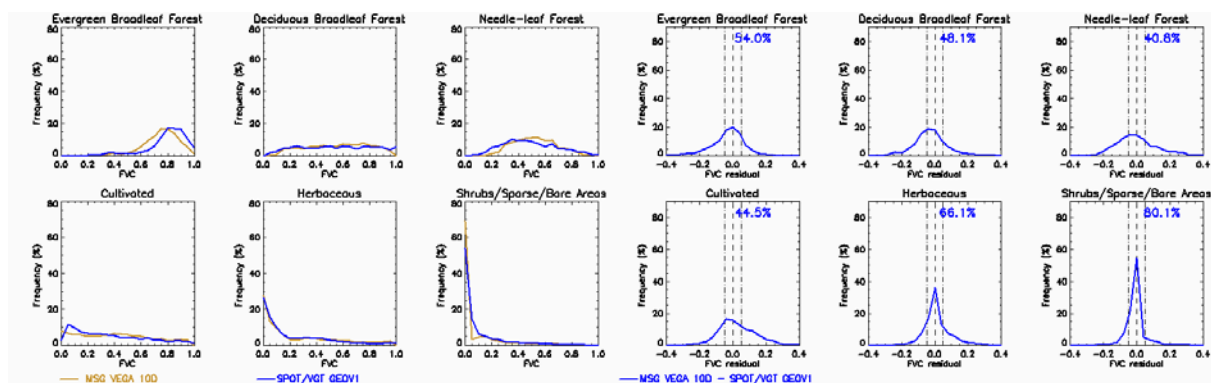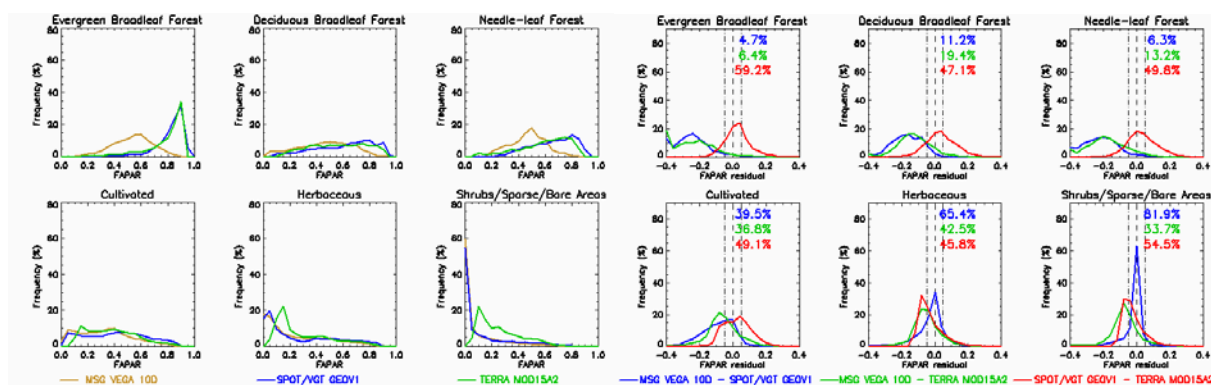
Figure 23: Distribution of FAPAR values (left panel) and differences (right panel) for the MSGVAL sites during the 2008-2009 period for each biome type.

5.3 TEMPORAL CONSISTENCY ANALYSIS

In this section, the temporal consistency of MSG VEGA products is analysed as compared to SPOT/VGT GEOV1 and TERRA MODIS C5 products. Note that MSG VEGA, 10D and Daily products were displayed in order to check the consistency between the daily product and the 10D monthly composites. From Figure 24 to Figure 30, two examples for each biome type are displayed. Additional temporal profiles can be found in Annex IV. The quantitative assessment (i.e., histograms of auto-correlation and cross-correlation) per biome type is presented below.

➢ In general, similar temporal variations were observed for all biome types between MSG VEGA 10D and daily products, showing smooth trajectories in case of 10D due to the monthly composites as compared to daily products, which are NRT products with a temporal compositing window (semi-Gaussian) of 5 days.

➢ For Evergreen Broadleaved Forest (Figure 24), noisy temporal trajectories of MSG VEGA products were found, with lower noise than MODIS but slightly higher than GEOV1. Remarkably good is the low percentage of missing values as compared to reference products, both derived from polar-orbit satellite observations with typically cloud coverage over these areas. In general, the temporal trends showed by VEGA products match with the reference products (see B2.1#142), although a clear tendency to underestimate (as compared to reference products) LAI and FAPAR was observed over South America temporal profiles (see B2.1#42), and FAPAR over Africa (see B2.1#142).

➢ For Deciduous Broadleaved Forest (Figure 25), good temporal consistency of MSG VEGA products was generally found as compared with both references (GEOV1 and MODIS C5). In general, lower magnitude of the MSG VEG values was observed at the peak of the season, mainly for FAPAR but also for FVC and LAI. Note that over South of America (see B2.1#9 in Figure 25 and B2.1#20in Annex IV) MSG VEGA reaches values close to zero in winter time for some years at the end of the season, which might be an unrealistic drop as compared to other years or other products.

➢ For Needle-Leaf Forest (Figure 26), typically located over northern regions with extreme viewing angles in case of MSG products, good temporal consistency was found for FVC and LAI products as compared with both references. For LAI a slight tendency to provide lower values of magnitude was found at the peak of the season. For FAPAR, similar temporal course was found, but lower in magnitude.

➢ For Cultivated (Figure 27), the temporal trajectories of MSG VEGA products show a very good consistency with GEOV1 and MODIS C5, correctly reproducing the temporal cycle.

➢ For Shrublands (Figure 28) and Herbaceous (Figure 29), a good temporal agreement was found in most of the sites. However, for Herbaceous some inconsistent higher values

were found over some sites close to the border of the MSG disk (see B2.1#328 in Annex IV). For Shrublands discrepancies in magnitude were found in some cases, mainly for FAPAR but also for FVC.

Finally, for Bare Areas (Figure 30), stable trajectories close to zero were found. The unrealistic seasonal behaviour of FVC detected in GEOV1 is not shown in MSG VEGA (see B2.1#209 site in Figure 30). However, as observed for Herbaceous, inconsistent higher retrievals were found over locations close to the border of the MSG disk (see B2.1#377 in Annex IV).
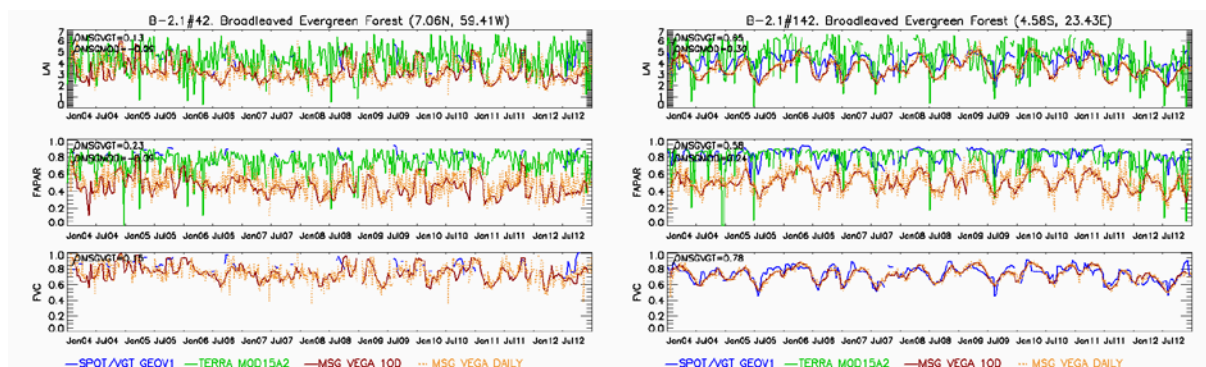
Figure 24: Temporal profiles of MSG VEGA (10D and Daily), SPOT/VGT GEOV1 and TERRA MODIS C5 over two selected Evergreen Broadleaved Forests during the 2004-2012 period. Cross-correlation estimates of MSG VEGA 10D and SPOT/VGT GEOV1 (ρ_{MSGVGT}), and MODIS C5 (P_{MSGMOD}) are shown in the figure.
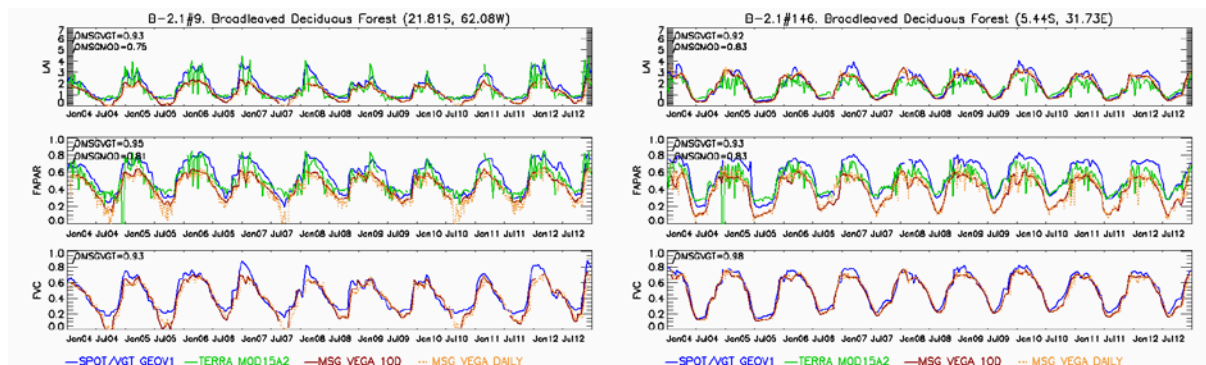
Figure 25: As in Figure 24 for Broadleaved Deciduous Forest.
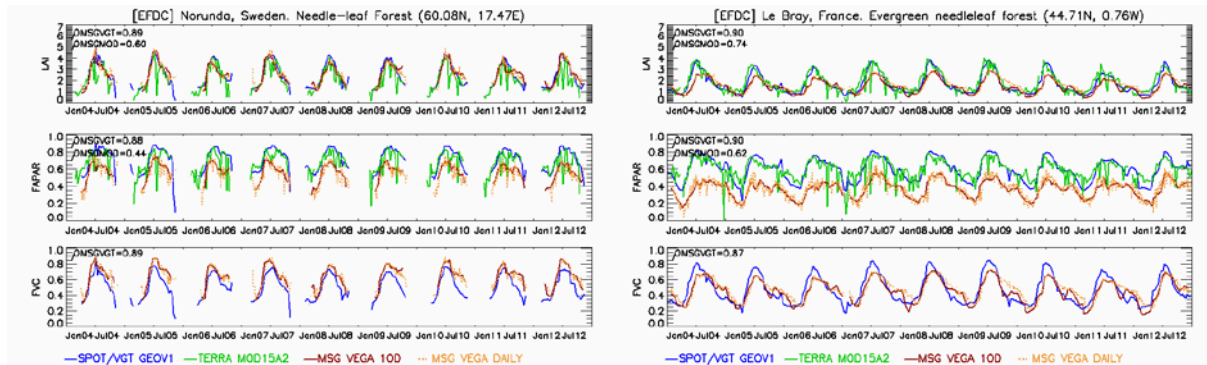
Figure 26: As in Figure 24 for Needle-Leaf Forest.
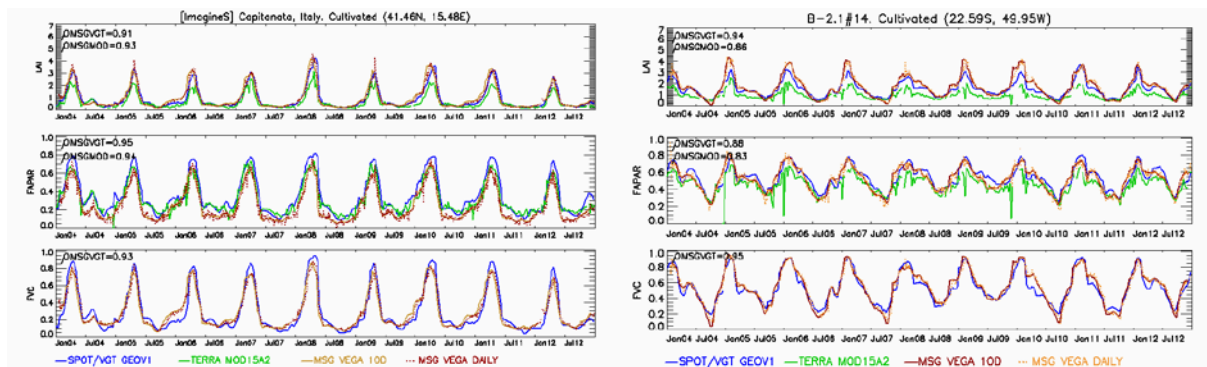
Figure 27: As in Figure 24 for Cultivated.
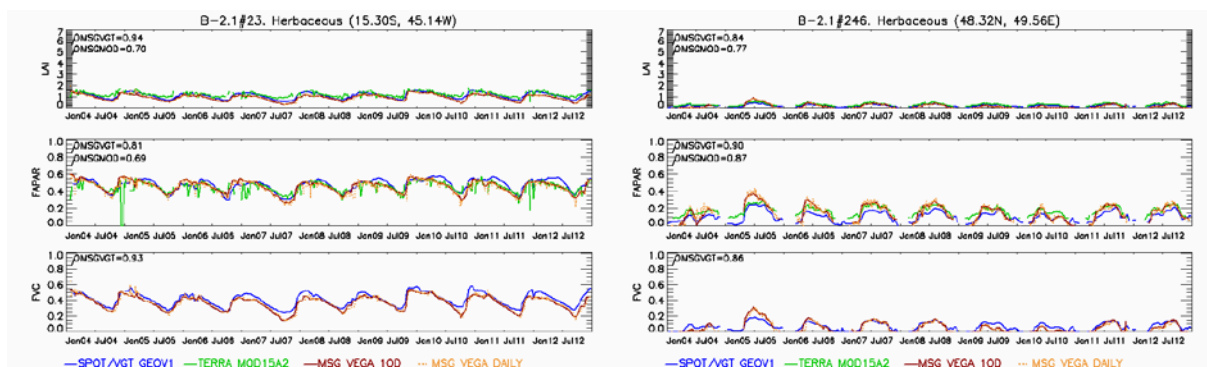
Figure 28: As in Figure 24 for Herbaceous.
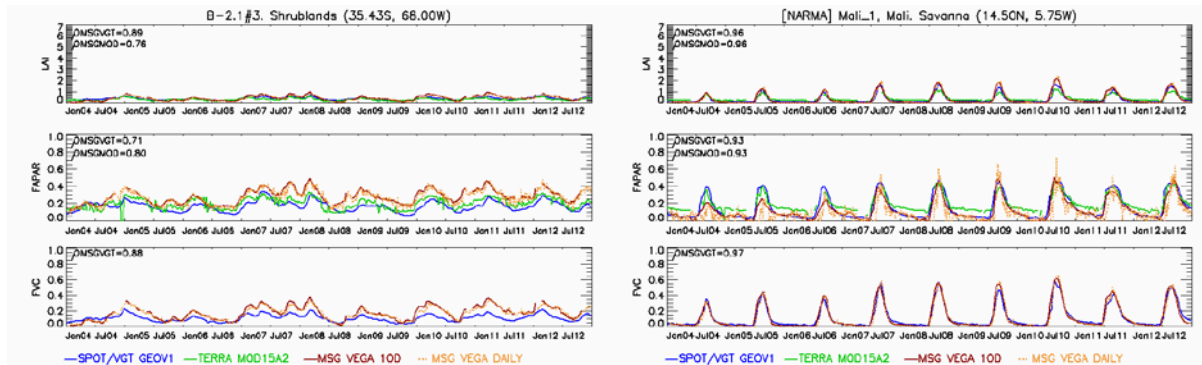
Figure 29: As in Figure 24 for Shrublands
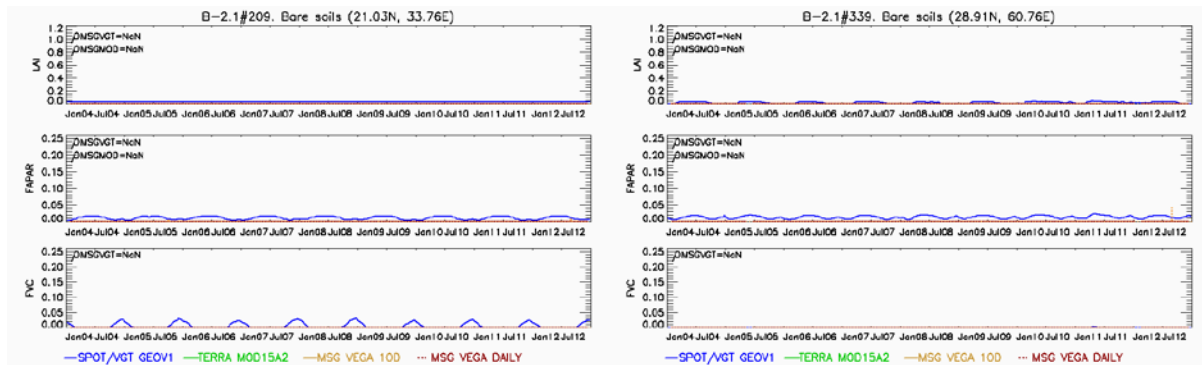
Figure 30: As in Figure 24 for Bare Areas.

- **Auto-Correlation distributions**

The auto-correlation of the temporal variations of MSG VEGA 10D and references SPOT/VGT GEOV1 and MODIS C5 (Figure 31) was assessed per biome type over MSGVAL sites. The computation was performed comparing temporal trajectories during two consecutive years (2009 versus 2008).

➢ For FVC, distributions of auto-correlation towards higher values were found for MSG VEGA 10D, very similar to that for GEOV1. Typically, auto-correlation was higher than 0.8 in more than 70% of cases for all biome types except for EBF.

➢ For LAI, auto-correlation was typically higher than 0.8 in more than 60% of cases for all biome types except for EBF and NLF. Note the higher percentage in EBF (22.4%) as compared to GEOV1 and MODIS C5 (9.9% and 4.9%), and the opposite trend in NLF (53.6% as compared to 100% and 86%).

➢ Histograms of the auto-correlation of MSG VEGA 10D for FAPAR provide worse results than LAI and FVC. Auto-correlation was typically higher than 0.8 in around 70%

of cases for NLF and cultivated, and in around 50% of cases for NLF and Herbaceous. However poor performance was found for EBF and SBA, mainly explained on the typical low variability of temporal trajectories over these biomes.
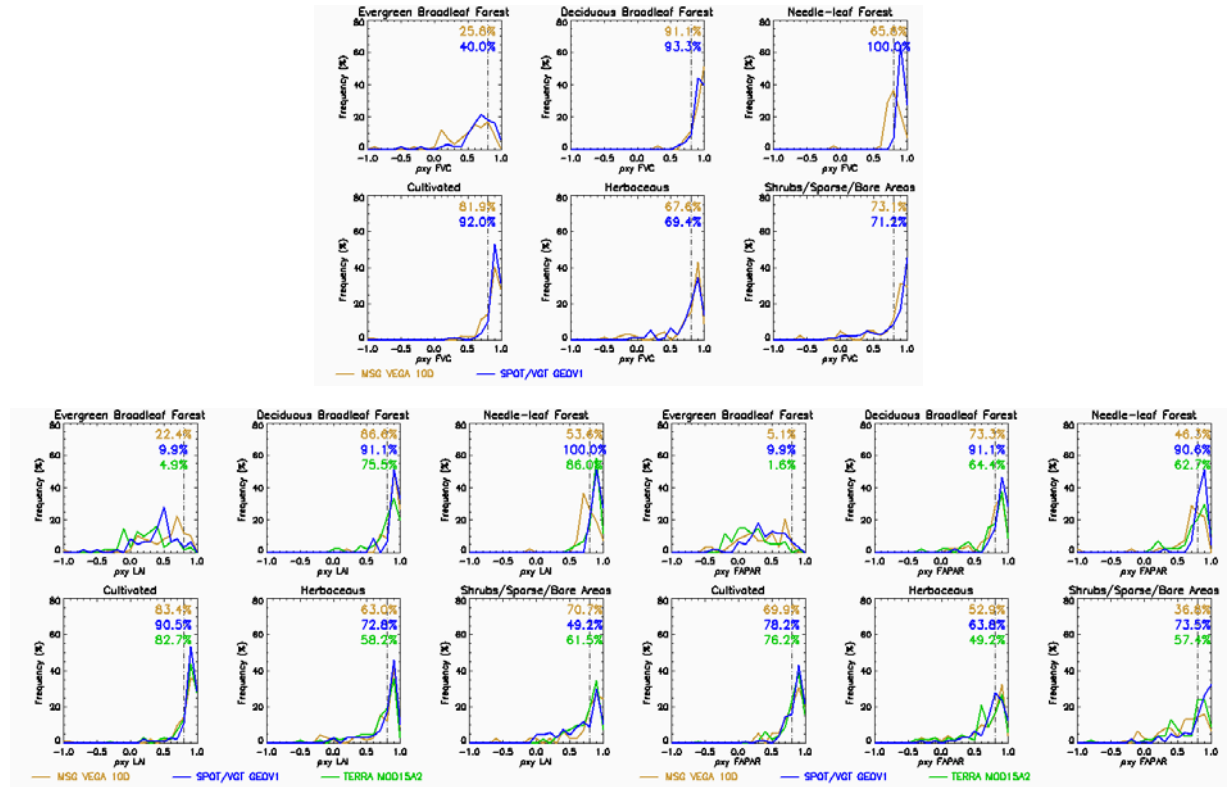
Figure 31: Auto-correlation distributions (ρXX) of MSG VEGA 10D, SPOT/VGT GEOV1 and MODIS C5 temporal profiles for MSGVAL sites for each biome type for FVC (top), LAI (bottom-left) and FAPAR (bottom-right). 2009 versus 2008 years are used in the computation. The values in the plot shows the percentage of cases with correlations higher than 0.8.

- **Cross-Correlation distributions**

The cross-correlation of the temporal variations between MSG VEGA 10D and reference SPOT/VGT GEOV1 and MODIS C5 products (Figure 32) was assessed per biome type over MSGVAL sites considering the 2008-2009 period.
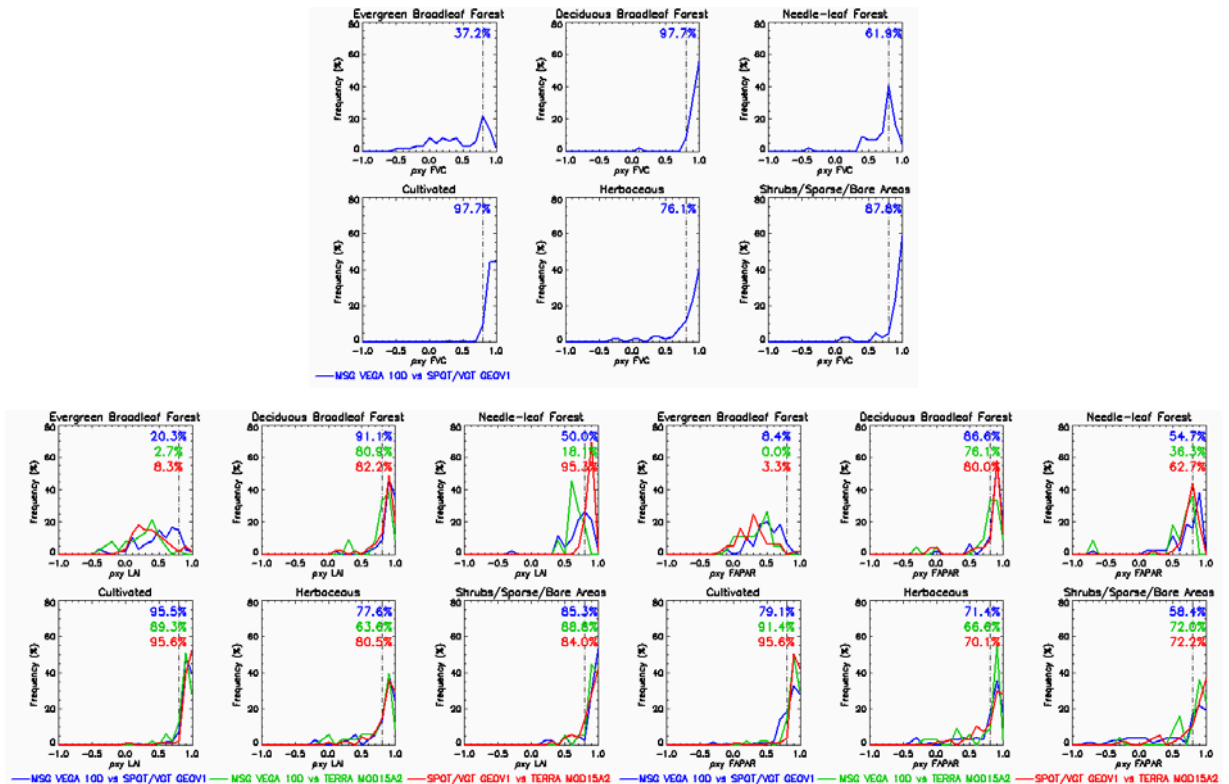
Figure 32: Cross-correlation distributions (ρXY) between MSG VEGA 10D, SPOT/VGT GEOV1 and MODIS C5 temporal profiles for MSGVAL sites during 2008-2009 period for each biome type for FVC (top), LAI (bottom-left) and FAPAR (bottom-right). The values in the plot shows the percentage of cases with correlations higher than 0.8.

For FVC:

➢ Very good agreement was obtained between MSG VEGA 10D and SPOT/VGT GEOV1 for all biome types except for EBF, with cross-correlation higher than 0.8 in more than 60% of cases for NLF and higher than 75% of cases for the rest of biomes, with up to 97.7 of samples for Cultivated.

For LAI:

➢ Very good agreement between VEGA 10D and GEOV1 was obtained for all biome types except for EBF, with cross-correlation higher than 0.8 in more than 50% of cases for NLF and more than 77% for the rest of biomes. Slight degraded performance was found as compared to MODIS C5, but satisfactory.

➢ For EBF and DBF, the best agreement was found in the comparison between MSG VEGA 10D and SPOT/VGT GEOV1. In case of NLF the best performance was found when comparing GEOV1 with MODIS, whereas for non-forest types similar agreement

was found for all the combinations.

➢

For FAPAR:

➢ Good cross-correlation consistency was found between MSG VEGA 10D and GEOV1 for all biome types except for EBF. Similar results were found in the comparison with MODIS, showing generally slightly degraded agreement.

5.4 INTRA-ANNUAL PRECISION

The smoothness of the products (Weiss et al., 2007) was used as indicator of the intra-annual precision as the CEOS LPV best practices for global LAI products recommends (Fernandes et al., 2014). Figure 33 shows the cumulative histograms of the δLAI, δFAPAR and δFVC for the products under study, which is an indicator of the noise of the temporal profiles.

➢ The cumulative histograms fit a negative exponential function, showing the best results for MSG VEGA 10D and GEOV1 (almost the same), with lower decay constant (τ) than MODIS for all the variables.
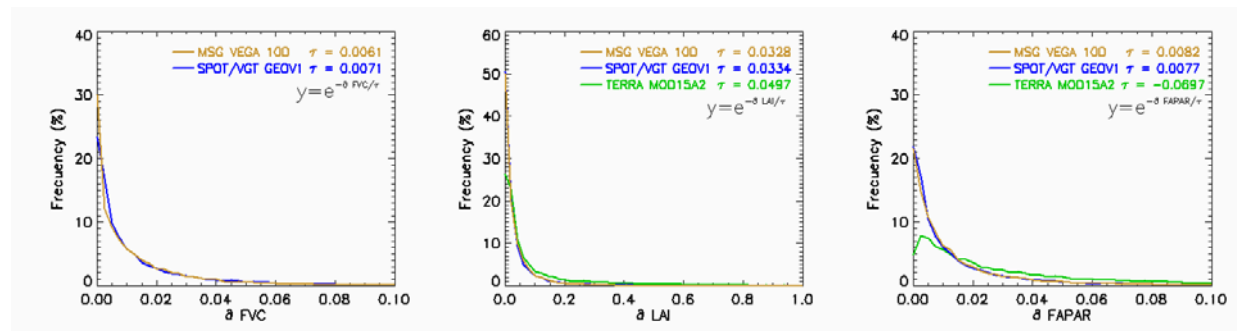
Figure 33: Histograms of the delta function (smoothness) for LAI, FAPAR and FVC MSG MSG VEGA 10D, GEOV1 and MODIS C5 products for MSGVAL sites during the 2008-2009 period. The curves are adjusted to an exponential function and the exponential decay constant (τ) is presented in the figure.

5.5 INTER-ANNUAL PRECISION

To investigate the inter-annual precision of the products, box-plots of absolute inter-annual anomalies (year 2009 versus 2008) of SPOT/VGT GEOV1 and MODIS C5 products, using the upper 95th and lower 5th percentiles over MSGVAL sites, have been computed (Figure 34 to Figure 35). Note that Cultivated sites were not considered in this analysis due to the large inter-annual variability in this land cover type due to agricultural practices (e.g., crop rotation). Broadleaf Evergreen Forest sites were also removed from this computation to avoid typically

noisy temporal trajectories, as observed in section 6.3.

➢ For the FVC, median absolute anomaly of 0.011 (3.7%) was found for MSG VEGA 10D, with slightly better overall performance than SPOT/VGT GEOV1, 0.014 (4.7%). This is well within the GCOS requirements in terms of stability (Max [3%; 0.2]). Median values per bin are lower than 0.05 for all FVC ranges except for the range between 0.5 and 0.6.

➢ Very good results were found for LAI. MSG VEGA 10D provides median absolute anomaly of 0.044 (3.5%), fulfilling the GCOS requirements for stability (Max [10%; 0.25]). Median absolute anomalies are lower than 0.2 for all LAI ranges except for values between 3 and 6. Slight degraded inter-annual precision was found, in overall, for GEOV1 and MODIS C5 although they clearly perform better for high LAI values (>4).

➢ For the FAPAR, SPOT/VGT GEOV1 provides inter-annual precision (median absolute anomaly of 0.18) within the GCOS requirement for stability (Max [3%; 0.2]). MSG VEGA 10D provides better overall performance (median absolute anomaly of 0.18) than MODIS (median absolute anomaly of 0.22) but higher scattering in the distribution of values.
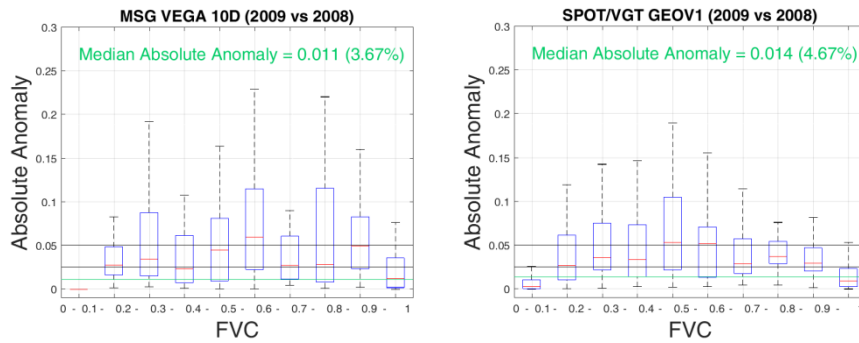
Figure 34: Box-plots of inter-annual absolute anomalies of MSG VEGA 10D and GEOV1 (year 2009 versus year 2008) per bin FVC value. Anomalies calculated over the 95th and 5th percentiles of MSGVAL sites during the January to December period. Red bars indicate median residuals, blue boxes stretch from the 25th percentile to the 75th percentile the data and whiskers include 99.3% of the coverage data (±2.7σ). Outliers are not displayed. Green line corresponds to the median absolute anomaly including all FVC ranges.
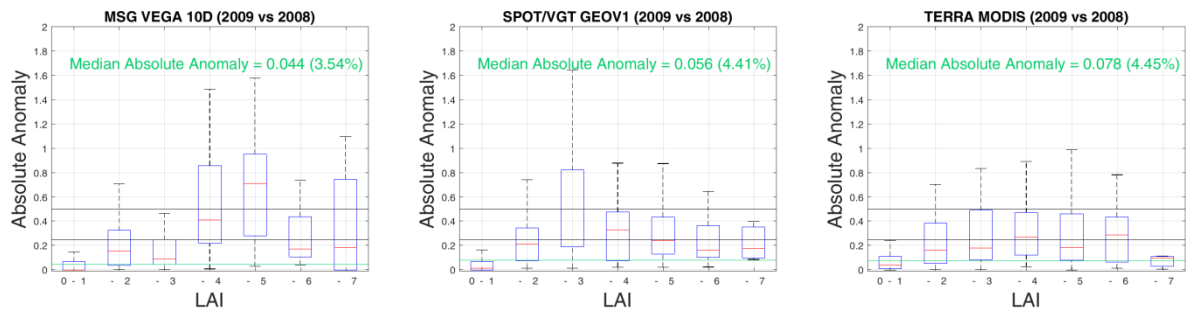
Figure 35: As in Figure 34 for MSG VEGA 10D, GEOV1 and MODIS C5 LAI products.
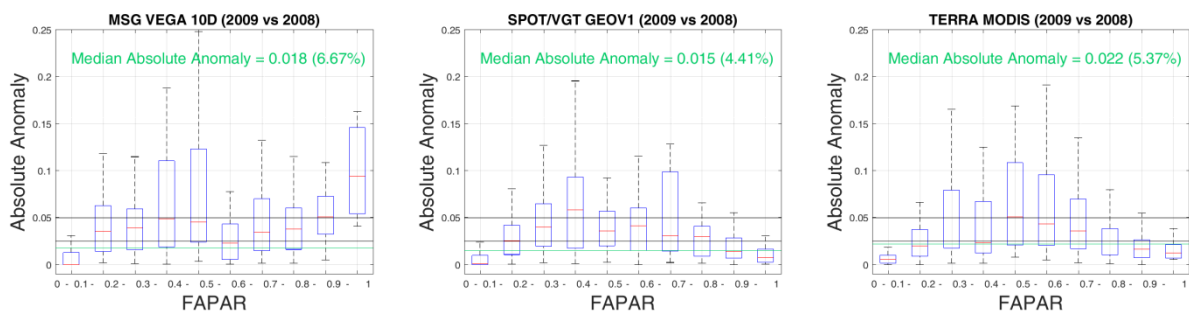
Figure 36: As in Figure 34 for MSG VEGA 10D, GEOV1 and MODIS C5 FAPAR products.

● **Slope of the inter-annual variation**

In order to assess the stability of the time series, the variation of the inter-annual precision along

the period has been assessed. For this purpose, the median absolute anomaly as indicator of inter-annual precision for each year was computed using as a reference the first year of the time series (2004). Figure 37 to figure 39 show the inter-annual precision for LAI, FAPAR and FVC along the time series for the three products under study.

- ➢ For FVC, the two satellite products present almost identical slope of the inter-annual variation close to zero (0.018). In average, MSG VEGA MTFVC and GEOV1 provide the same mean values (0.0195) indicating good precision in both cases.
- ➢ For LAI, the three satellite products present a slope of the inter-annual variation close to zero. MSG VEGA 10D and SPOT/VGT GEOV1 provide slight positive inter-annual slope, which is lower in case of GEOV1, indicating higher stability of the time series. MODIS C5 provides slight negative slope. In average, MSG VEGA MTLAI provides higher mean values (0.094) than GEOV1 (0.085), indicating slight degraded precision, but improved precision as compared to MODIS C5 (0.115).
- ➢ For FAPAR, SPOT/VGT GEOV1 and MODIS C5 present a positive slope of the inter-annual variation close to zero, but MSG VEGA 10D provides higher positive inter-annual slope. This is explained due to the higher noise in the FAPAR mostly coming from the volumetric kernel parameter (k2) of the BRDF, whereas LAI and FVC use the more stable isotropic k0 parameter as input.
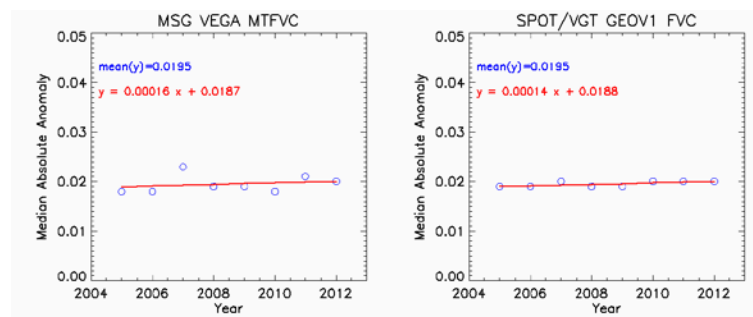
Figure 37:Inter-Annual Median Absolute Anomaly along the time series (2004-2012) for MSG VEGA 10D, and GEOV1 FVC products using as reference the first year of the value. Mean value and the slope of the fit are displayed.
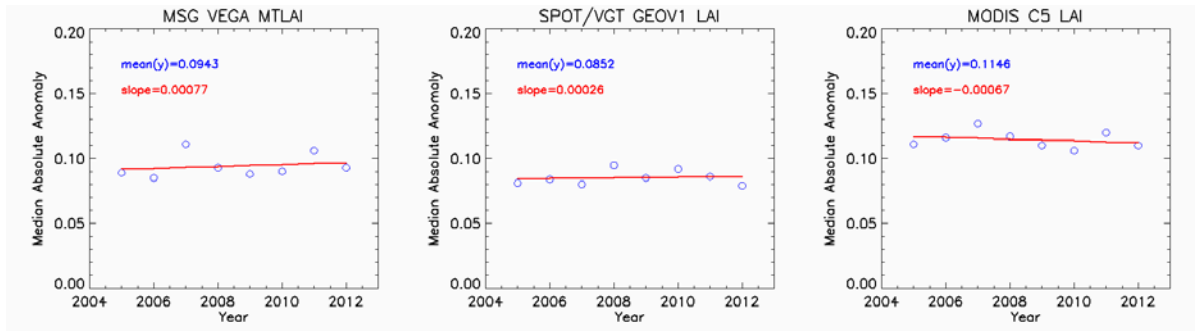
Figure 38: Inter-Annual Median Absolute Anomaly along the time series (2004-2012) for MSG VEGA 10D, GEOV1 and MODIS C5 LAI products using as reference the first year of the value. Mean value and the slope of the fit are displayed.
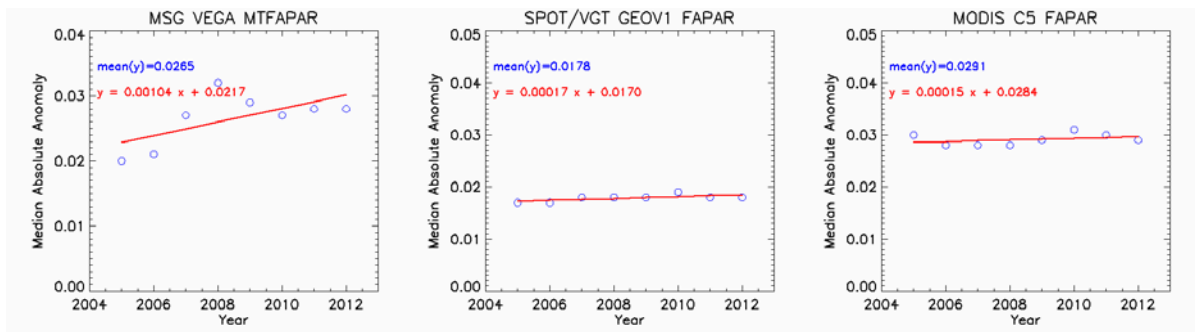
Figure 39: Inter-Annual Median Absolute Anomaly along the time series (2004-2012) for MSG VEGA 10D, GEOV1 and MODIS C5 FAPAR products using as reference the first year of the value. Mean value and the slope of the fit are displayed.

5.6 SPATIO-TEMPORAL CONSISTENCY OF THE TIME SERIES

This section presents the Hovmöller plots of the bias between MSG VEGA 10D and both reference products during the period from January 2004 to December 2012 (Figures 40 to 44). The central date of each month was selected to represent the temporal evolution along the whole time series.
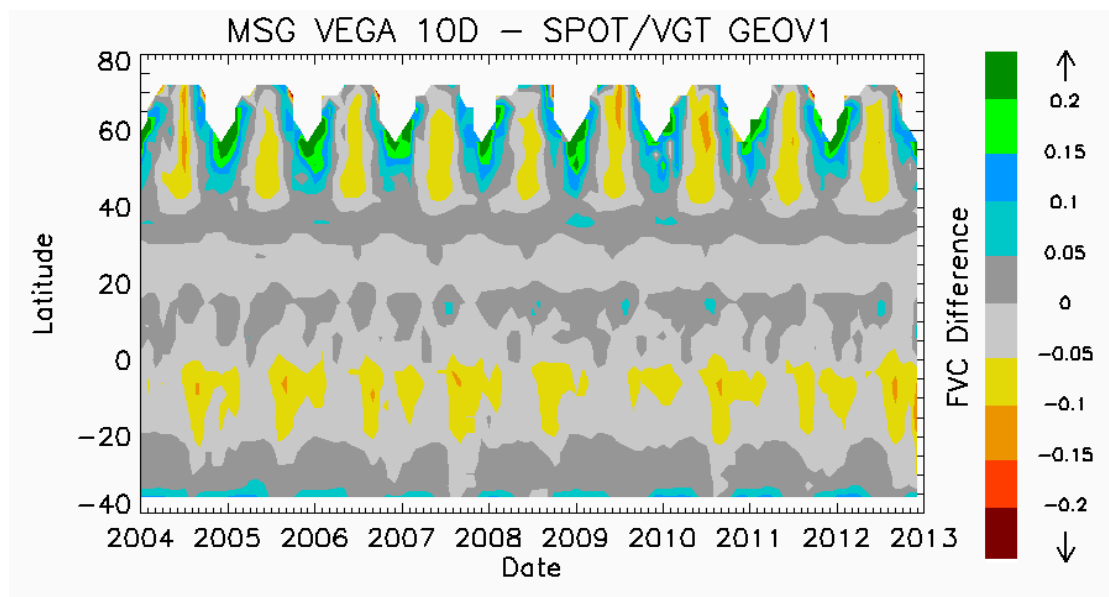
Figure 40: Hovmöller diagram of the Bias between MSG VEGA 10D and SPOT/VGT GEOV1 FVC products during the 2004-2012 period.
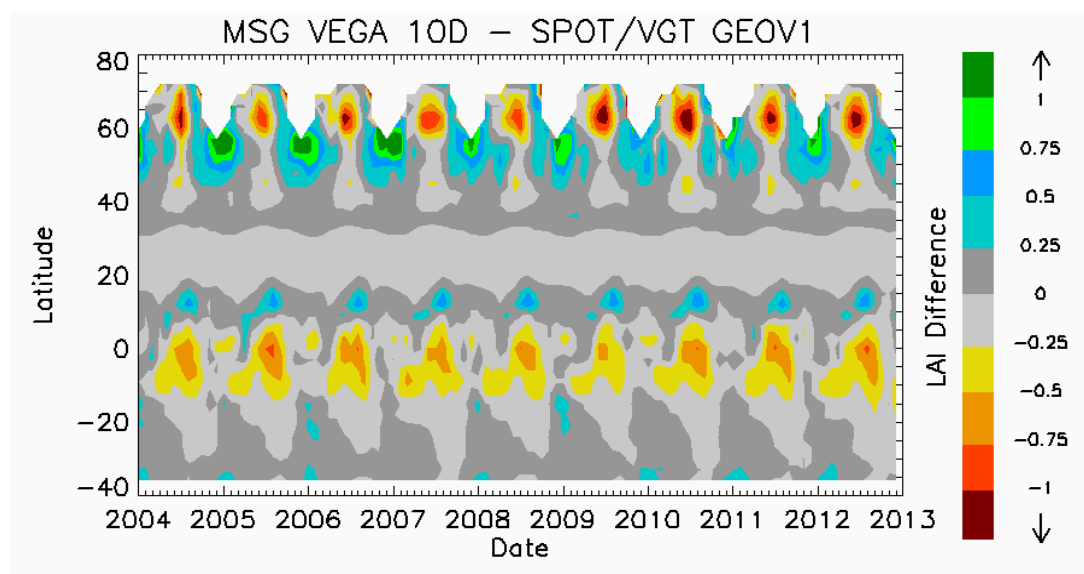
Figure 41: Hovmöller diagram of the Bias between MSG VEGA 10D and SPOT/VGT GEOV1 LAI products during the 2004-2012 period.
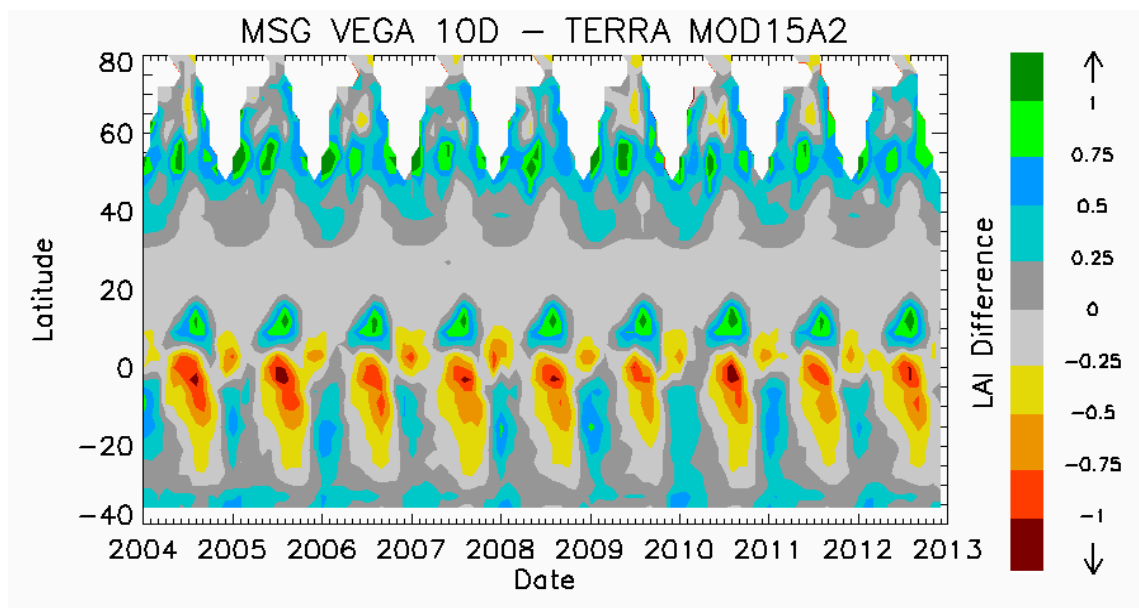
Figure 42: Hovmöller diagram of the Bias between MSG VEGA 10D and MODIS C5 LAI products during the 2004-2012 period.
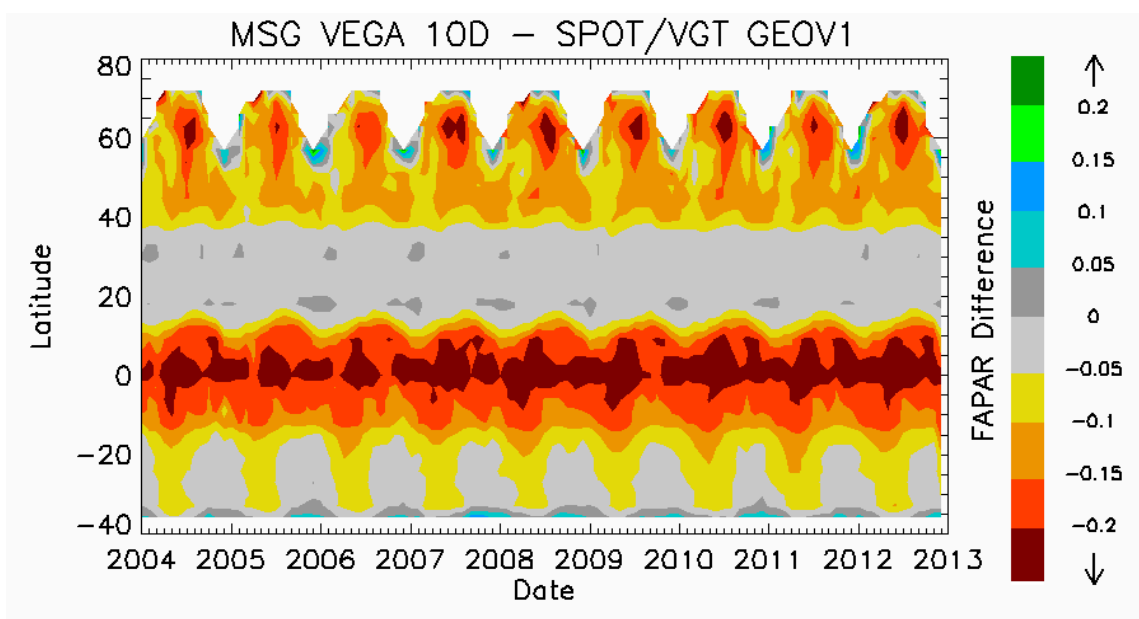
Figure 43: Hovmöller diagram of the Bias between MSG VEGA 10D and SPOT/VGT GEOV1 FAPAR products during the 2004-2012 period.
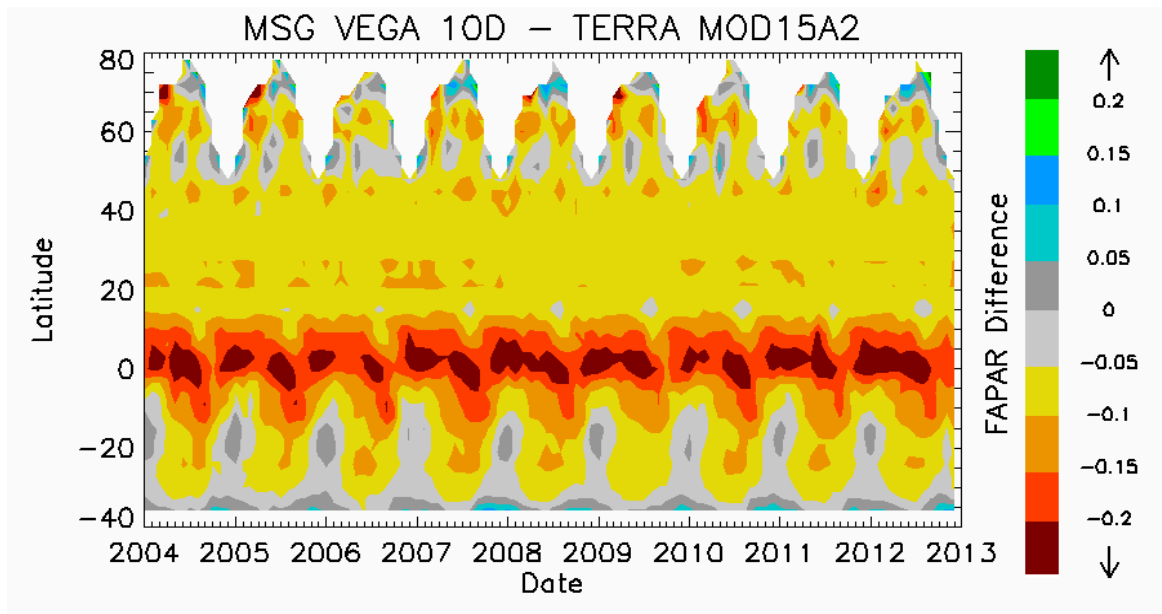
Figure 44: Hovmöller diagram of the Bias between MSG VEGA 10D and MODIS C5 FAPAR products during the 2004-2012 period.

The main results are:

➢ Very stable patterns of differences between MSG VEGA 10D and references products (SPOT/VGT GEOV1 and MODC5) were found along the whole time series for the three variables (LAI, FAPAR, FVC). No trends are observed which indicates the good stability of the MSG CDR of LAI, FAPAR and FVC.

➢ Main differences are observed around the equatorial belt and northern latitudes. The higher differences are found for FAPAR, whereas for FVC and LAI the bias is consistently low.

5.7 OVERALL STATISTICAL CONSISTENCY

5.7.1 Overall statistics

● **Global scatter plots**

To evaluate the overall consistency of MSG VEGA products, scatter-plots and relevant metrics

with reference products (SPOT/VGT GEOV1 and MODIS C5) were examined over MSGVAL sites during the 2008-2009 period. Note that VEGA pixels with error estimate higher than 1.5 in case of LAI, and higher than 0.15 in case of FVC/FAPAR have been discarded from this computation in order to avoid unreliable estimations. In case of GEOV1 and MODIS C5, only good quality pixels according to Table 7 were used. Figure 45 and Table 10 show the scatter-plots and relevant statistics between MSG VEGA 10D and SPOT/VGT GEOV1 and the comparison with MODIS is shown in Figure 46 and Table 11.
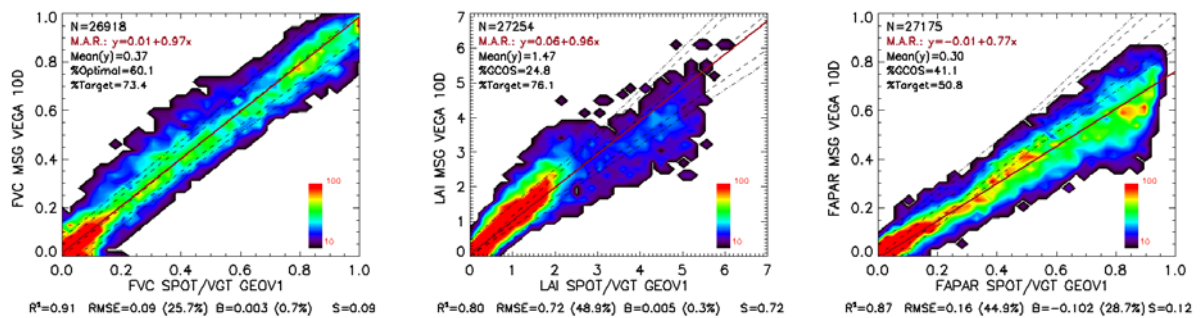
Figure 45: MSG VEGA 10D FVC, LAI and FAPAR products versus SPOT/VGT GEOV1 similar product scatter-plots over all MSGVAL sites for the 2008-2009 period. Dashed lines correspond to the 1:1 line, optimal (GCOS) and target uncertainty levels.

The results between MSG VEGA 10D and SPOT/GEOV1 shows that:

➢ For the FVC, acceptable results were found with overall discrepancies of 0.09 and more than 60% within the optimal level of consistency (73.4% including the Target level). Almost no mean bias was found (<1%) whereas some scattering was observed mainly for medium values of FVC. Remarkably good is the major axis regression between both products, very close to the 1:1 line.

➢ For the LAI, good consistency was found for LAI values up to 3 whereas some negative bias was observed for LAI values greater than 3. The overall discrepancies are RMSE=0.72 with 76% of samples within the target level of consistencies.

➢ For the FAPAR a clear tendency to provide lower values (MSG VEGA 10D< GEOV1) for higher FAPAR values was observed,with a mean bias of -0.102. Furthermore, almost no offset and slope of 0.77 were obtained. Overall discrepancies of RMSE=0.16 were found with 41.1 of pixels within the target level of consistencies. Note however that GEOV1 shows a positive bias (≈0.06) with ground truth data (Doña et al., 2017).

Table 10: Relevant statistics between MSG VEGA 10DFVC, LAI and FAPAR products versus SPOT/VGT GEOV1 over all MSGVAL sites for the 2008-2009 period. p-value corresponds to the test on whether the slope is significantly different to 1. Percentage of samples laying the uncertainty levels of optimal, target and threshold are displayed.

	MSG VEGA 10D vs SPOT/VGT GEOV1 (2008-2009)		
	FVC	LAI	FAPAR
R^2	0.91	0.80	0.87
Bias	0.003	0.005	0.102
RMSE	0.09	0.72	0.16
Offset	0.01	0.06	-0.01
Slope	0.97	0.96	0.77
p-value	0.013	0.702	0.001
%optimal	60.1	24.8	41.1
%target	73.4	76.1	50.8
%threshold	83.5	83.5	58.8

The comparison between MSG VEGA 10D and MODIS C5 indicate that:

➢ For LAI a tendency to provide higher values than MODIS was observed for LAI values lower than 3 whereas the opposite trend was observed for LAI values higher than 3. Overall discrepancies of RMSE=1.10 were found, mean bias of 0.062 (3.6%) and 59% of pixels within the target level of consistency.

➢ For the FAPAR, MSG provides lower values for all the ranges, with mean bias of -0.104, an offset of -0.06 and overall discrepancies of RMSE=0.16. Note here that MODIS presents positive bias for very low values as compared to ground truth and other reference products as it is reported by Camacho et al., (2013b), Seixas et al. (2006) or Martínez et al., (2013). Thus, MSG VEGA 10D shows reasonable results for very low FAPAR values (close to zero).
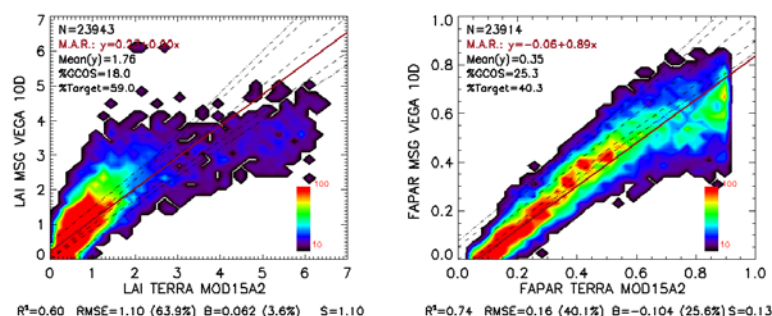
Figure 46: MSG VEGA 10D LAI and FAPAR products versus MODIS C5 similar products scatter-plots over all MSGVAL sites for the 2008-2009 period. Dashed lines correspond to the 1:1 line, optimal (GCOS) and target uncertainty levels.

Table 11: Relevant statistics between MSG VEGA 10DFVC, LAI and FAPAR products versus MODIS C5 over all MSGVAL sites for the 2008-2009 period. p-value corresponds to the test on whether the slope is significantly different to 1. Percentage of samples laying the uncertainty levels of optimal, target and threshold are displayed.

	MSG VEGA 10D vs MODIS C5 (2008-2009)	
	LAI	FAPAR
R^2	0.60	0.74
Bias	0.062	-0.104
RMSE	1.10	0.16
Offset	0.23	-0.06
Slope	0.90	0.89
p-value	0.001	0.001
%optimal	18.0	25.3
%target	59.0	40.3
%threshold	68.6	56.0

● **Box-plot of uncertainties per bin**

The analysis of the discrepancies (bias and RMSE) between MSG VEGA 10D and SPOT/VGT GEOV1 products per range of values over MSGVAL sites are presented in Figure 47. The benchmarking with MODIS C5 is presented in Figure 48.
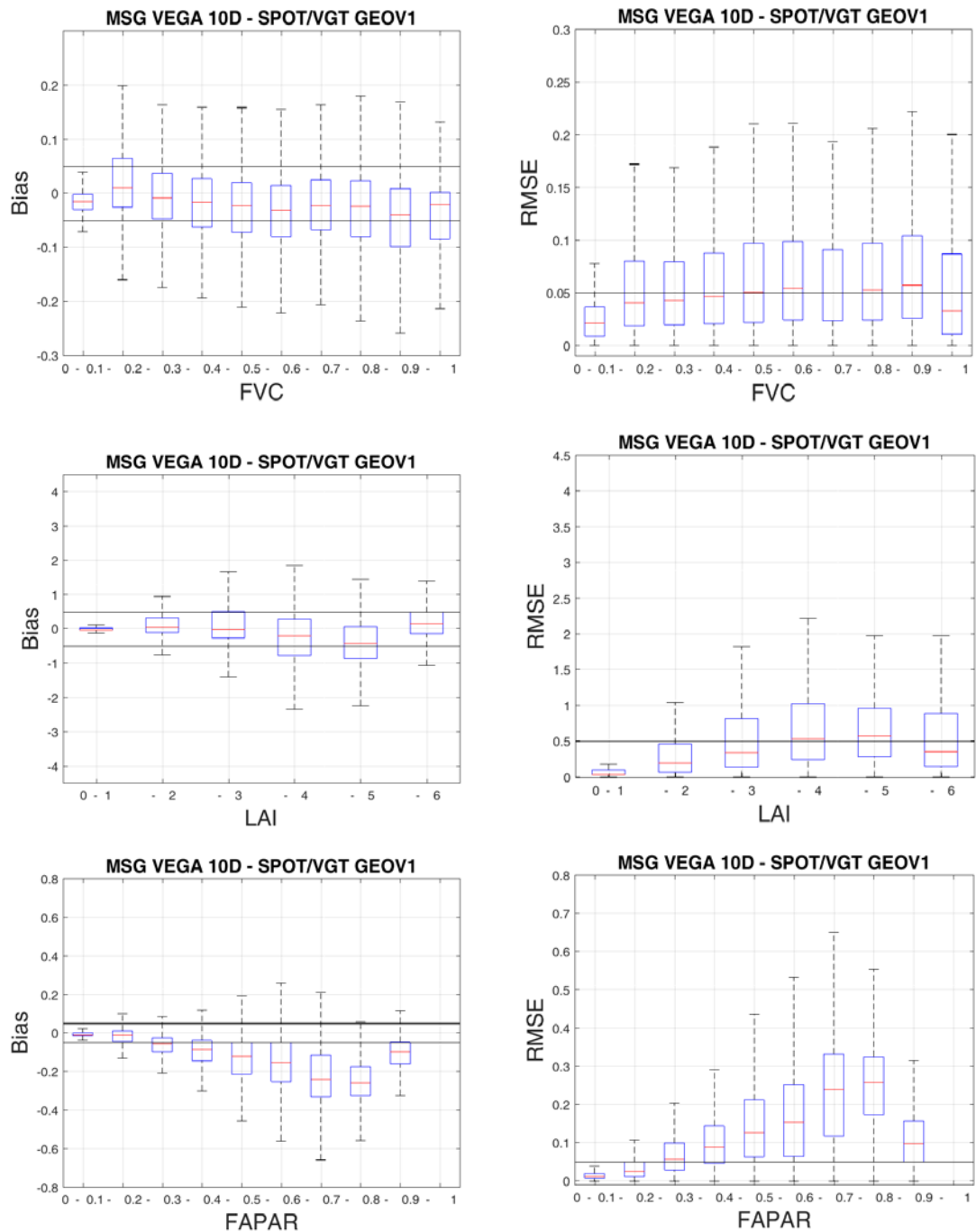
Figure 47: Box-plots of uncertainty statistics between MSG VEGA 10D and SPOT/VGT GEOV1 (Bias: left side, absolute Bias: right side) per bin for FVC (top), LAI (middle) and FAPAR (bottom) over MSGVAL sites during 2008-2009 period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.
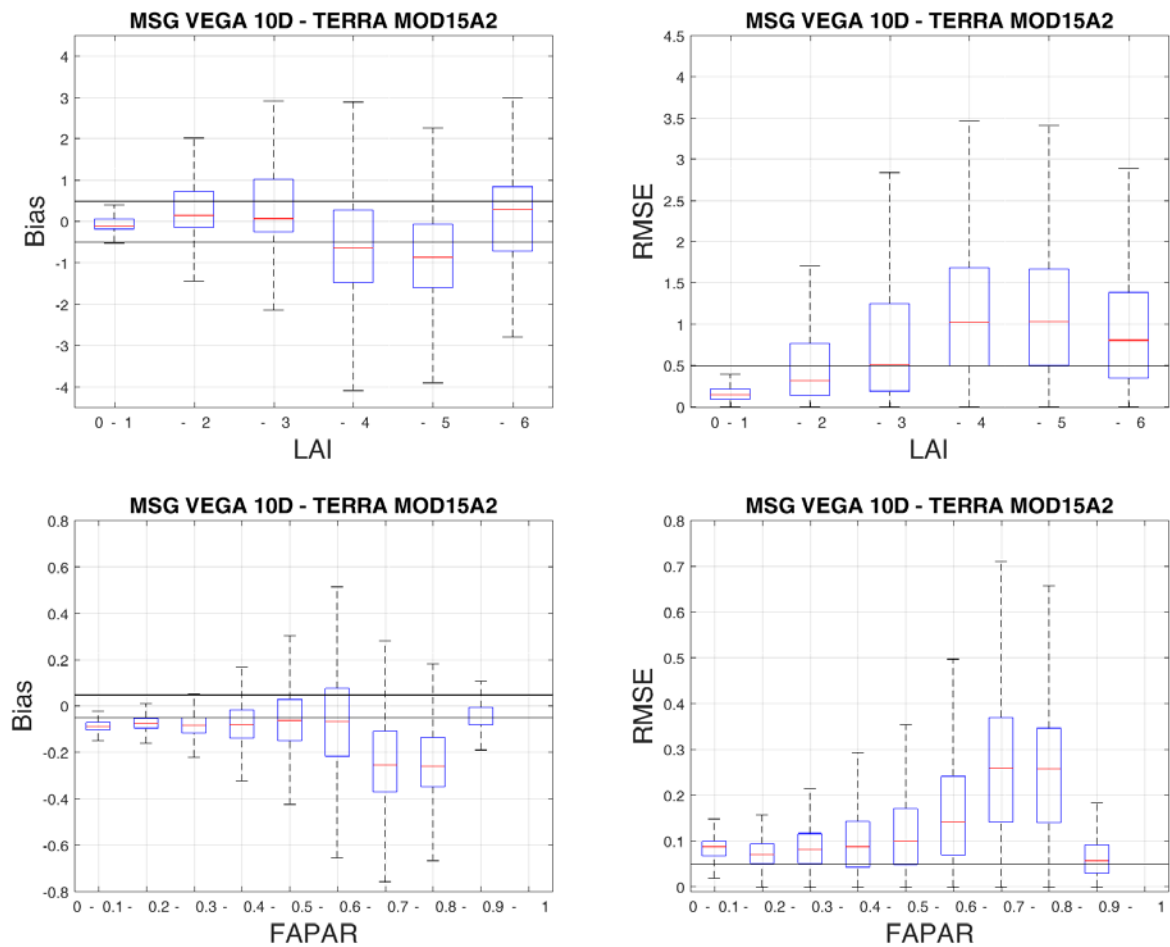
Figure 48: Box-plots of uncertainty statistics between MSG VEGA 10D and MODIS C5 (Bias: left side, absolute Bias: right side) per bin for LAI (top) and FAPAR (bottom) over MSGVAL sites during 2008-2009 period. Red bars indicate median values, blue boxes stretch from the 25thpercentile to the 75thpercentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.

For the comparison between MSG VEGA 10D and SPOT/VGT GEOV1, the following are the main findings:

➤ For FVC, MSG presented a slight negative bias across all the FVC values except for the range between 0.1 and 0.2, with median values typically between -0.04 and 0. For the RMSE, median values generally did not exceed 0.05.

➤ For LAI median values are around zero for all ranges except for LAI values between 3 and 5 (slight negative bias). In more than 50% of cases RMSE lower than 1 was found across all LAI values.

➤ For the FAPAR, larger discrepancies for medium values were observed and a negative

bias was found for ranges of FAPAR greater than 0.2. Large median overall discrepancies were found for FAPAR ranges between 0.6 and 0.8. As explained above, the large discrepancies observed for FAPAR can be partly explained due to the different definition of the FAPAR product (e.g., Martinez et al., 2013; Camacho et al., 2013b)

In case of MSG VEGA 10D versus MODIS C5:

➢ For LAI, very similar results were found than in the comparison with GEOV1. Median bias is close to zero for all ranges except for LAI values between 3 and 5, where negative mean bias around 1 was found

➢ In case of FAPAR, negative bias was found across all FAPAR ranges with large scattering for values between 0.5 and 0.8. This is clearly observed in the RMSE, where median values are up to 0.25 for values between 0.6 and 0.8, with 50% of data typically between 0.15 and 0.35. Note that this figure shows also the tendency of MODIS to overestimate very low FAPAR values (Camacho et al., 2013).

5.7.2 Analysis per biome type and continental region

This section presents the analysis of the discrepancies between MSG VEGA 10D and both references (SPOT/VGT GEOV1 and MODIS C5) across the three main continental region covered at the MSG disk: Europe (Figure 49), Africa (Figure 50) and South of America (Figure 51). For each continental region box-plots of the bias as a function of the main biome type are presented. The results were computed using the MSGVAL sites from each continental region during the 2008-2009 period.

For Europe:

➢ Median bias close to zero was found for all biome types except for Herbaceous (around 0.15), and 50% of cases are typically ranging between 0 and 0.12, which implies that MSG VEGA FVC 10D overestimates the FVC values provided by GEOV1 product.

➢ For LAI, a very good agreement was found between MSG VEGA 10D and both references, with typically median bias close to zero for all biome types except for Herbaceous in case of VEGA 10D versus GEOV1 (~0.6). Slight trend to provide positive bias between MSG VEGA 10D and both references was found, with 50% of cases ranging between -0.1 and 0.5.

➢ In case of FAPAR, a clear tendency to provide negative bias was found for all biomes (VEGA 10D < both references). In the comparison between VEGA 10D and GEOV1 median bias are typically close to zero except for NLF (around -0.05) whereas in the

comparison with MODIS C5 mean bias are typically ranging between -0.05 and -0.1.

In case of the African continent:

➢ Good agreement was generally found between MSG VEGA 10D and SPOT/VGT GEOV1 FVC products. As shown for Europe, tendency towards positive bias (VEGA D10> GEOV1) was observed, but these differences are less significant. Median bias was close to zero for all biome types with almost 50% of differences ranging between -0.05 and 0.12.

➢ For LAI, median differences around zero and almost 50% of cases lower than 0.5 were found between VEGA 10D and GEOV1 products. In case of MSG VEGA 10D versus MODIS slight degraded results were found, but still satisfactory, with slight trend towards positive bias and median bias lower than 0.5.

➢ For FAPAR, remarkably good is the consistency between VEGA 10D and GEOV1 over forest cases, with almost all cases within the ±0.05 threshold and very low scattering. For Herbaceous, Sparse and Bare Areas slight negative bias was found whereas large discrepancies were found for Cultivated. On the other hand, similar distribution of negative bias between MSG VEGA 10D and MODIS C5 was found for all biome types, with median values typically between -0.1 and -0.05.

Finally, for the South of America region:

➢ Different trend of the sign of the bias between MSG VEGA 10D and GEOV1 FVC products was found for forest sites as compared to Europe and Africa, showing slight tendency towards negative sign. For the rest of non-forest types, similar trend was found between both products than in the comparison over Europe and Africa.

➢ Good performance was found between MSG VEGA MTLAI and GEOV1 with slight negative bias over forest types and positive over non-forest cases. Large discrepancies were found between VEGA 10D and MODIS C5 LAI products, mainly for BDF, with median bias around -0.6 and large scattering (50% of differences ranging between -1.8 and 0.8).

➢ For FAPAR, larger discrepancies (negative sign) were found for forest types and Herbaceous. The higher discrepancies were found for BDF with almost all cases showing negative bias and differences up to -0.55. Regarding the comparison between MSG VEGA 10D and MODIS C5 FAPAR products, large discrepancies were found for all biomes with typically negative bias except for SBA.

Europe
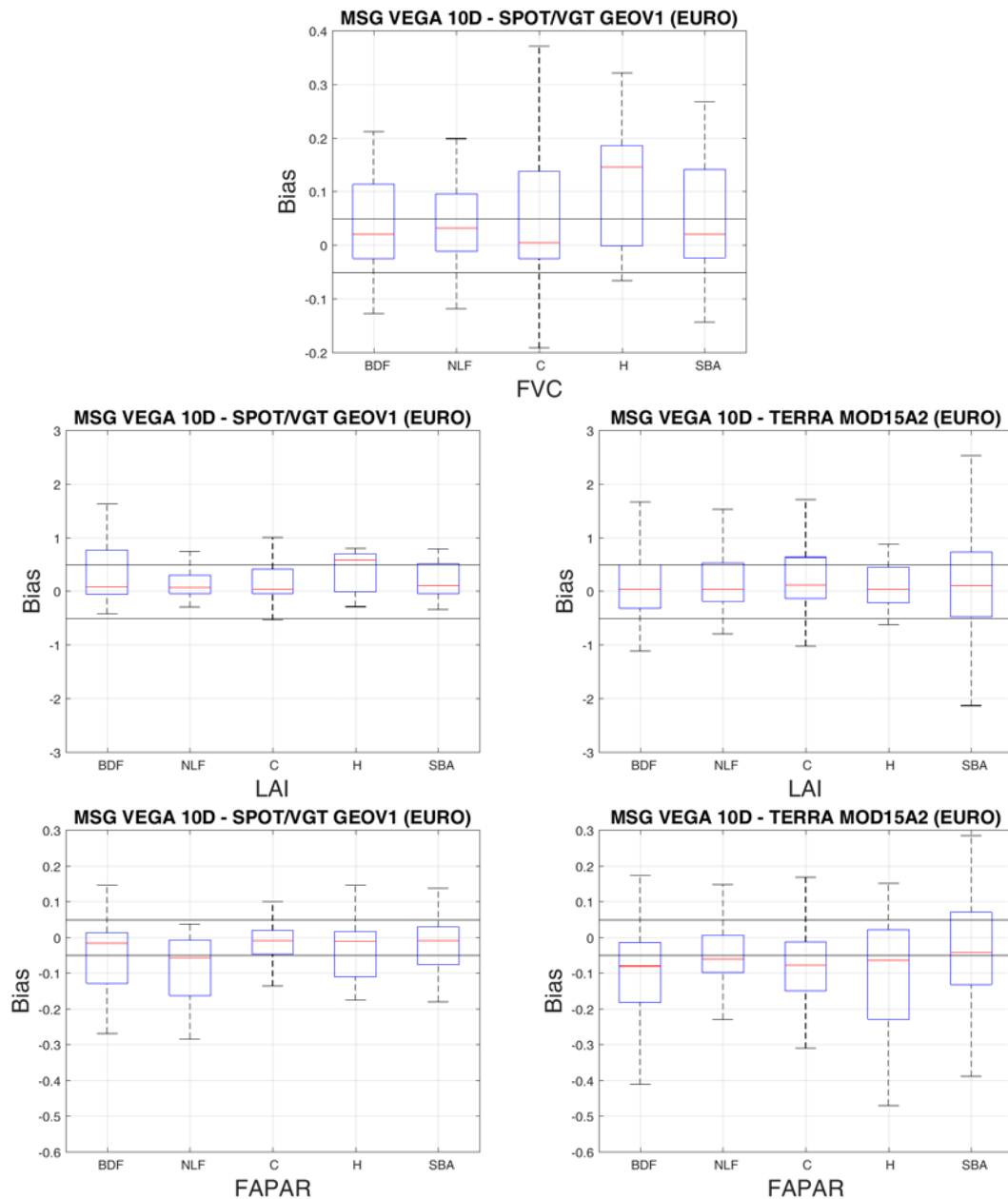
Figure 49: Box-plots of Bias between MSG VEGA 10D and SPOT/VGT GEOV1 (left side) and between MSG VEGA 10D and MODIS C5 (right side) FVC (Top), LAI (Middle) and FAPAR (Bottom) products per biome type over MSGVAL sites located over Europe during 2008-2009 period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.
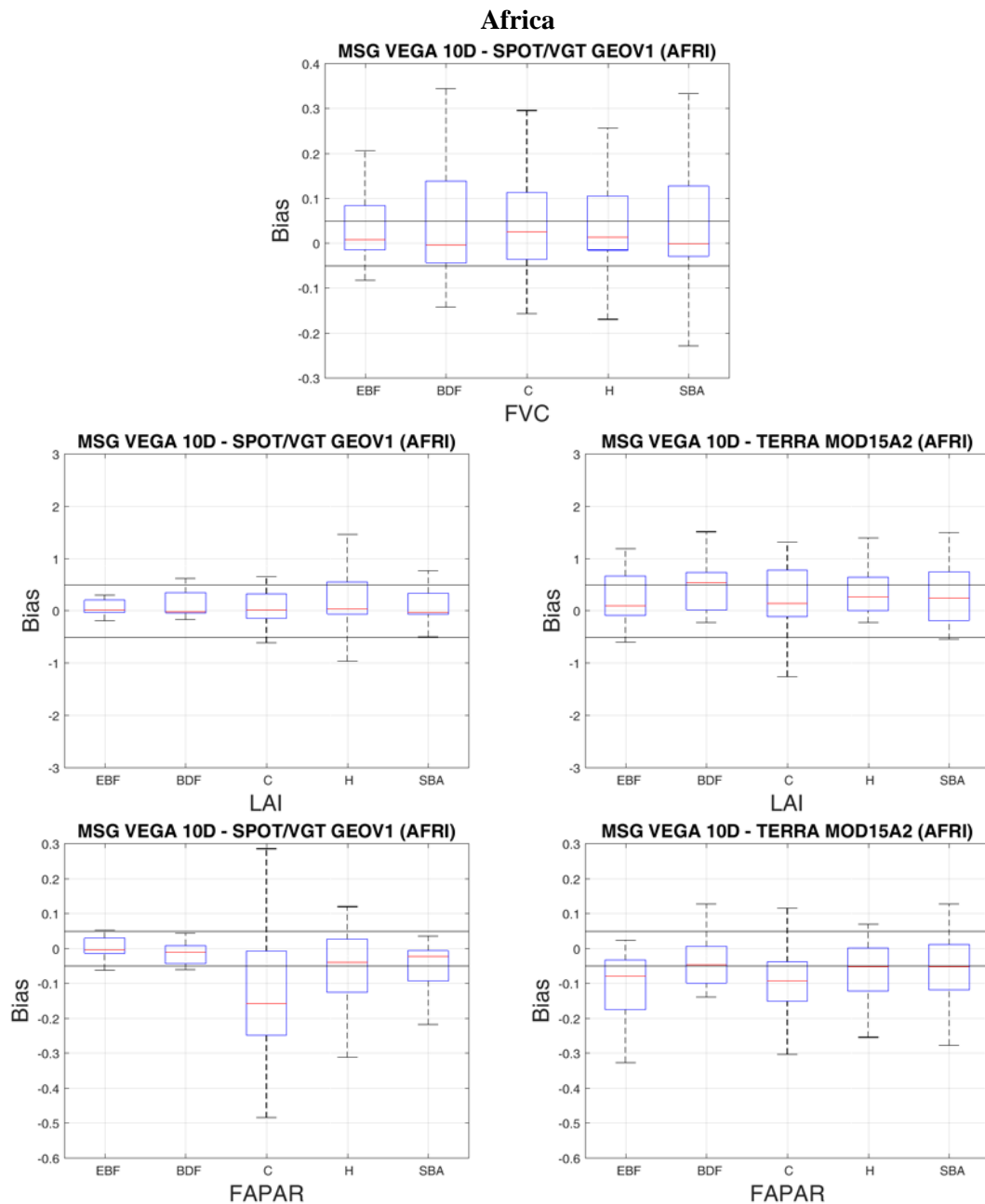
Africa

Figure 50: Box-plots of Bias between MSG VEGA 10D and SPOT/VGT GEOV1 (left side) and between MSG VEGA 10D and MODIS C5 (right side) FVC (Top), LAI (Middle) and FAPAR (Bottom) products per biome type over MSGVAL sites located over Africa during 2008-2009 period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.
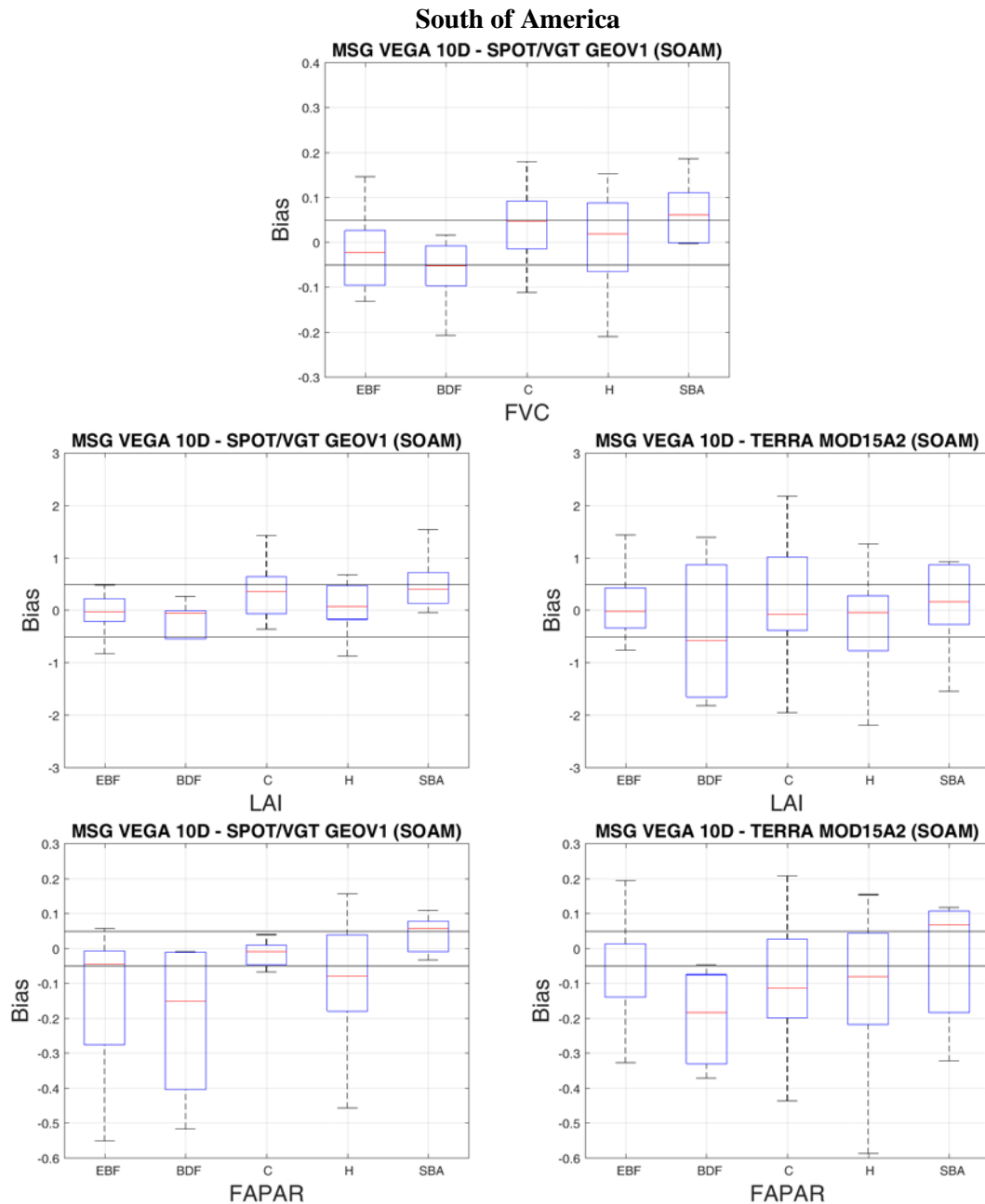
South of America

Figure 51: Box-plots of Bias between MSG VEGA 10D and SPOT/VGT GEOV1 (left side) and between MSG VEGA 10D and MODIS C5 (right side) FVC (Top), LAI (Middle) and FAPAR (Bottom) products per biome type over MSGVAL sites located over South of America during 2008-2009 period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.

5.8 ACCURACY ASSESSMENT

The relevant statistics of the accuracy assessment of MSG VEGA Daily (MDLAI, MDFAPAR, MDFVC), GEOV1 and MODIS C5 are presented in Table 12. Figures 52, 53 and 54 show the scatter-plots between the three satellite products under study and in-situ reference maps (as described in Section 4.3). Table 13 and Figure 55 and 56 show the accuracy assessment for MSG CDR for the period 2004-2012 for LAI and FVC but with much lower amount of reference datasets. MTFAPAR-R has not been evaluated due to the very limited number of references during this period. In case of GEOV1 and MODIS C5, pixels flagged as 'low quality' according to Table 6 were not included in the scatter-plot. In case of MSG LSA SAF product, pixels with error estimate higher than 1.5 in case of LAI, and higher than 0.15 in case of FAPAR/FVC were not included in the computation of relevant statistics. No samples were identified in FVC, whereas 2 to 5 samples were identified and removed for LAI and FAPAR, respectively. In addition, the ground data of Chimbolton in UK and Guyaflux in French Guiana were discarded due to the persistent cloud coverage over these two sites, which make them not adequate to assess the compliance against LSA SAF PR requirements. The compliance against LSA SAF PR requirements (see Table 1) is shown in Table 12 for daily products and Table 13 for CDR products. It should be noted than the results for the daily products mainly refer to croplands (>30 sites), with some forest references and few grasslands and bare soils. Additional temporal profiles over sites with ground data available can be found in Annex V.
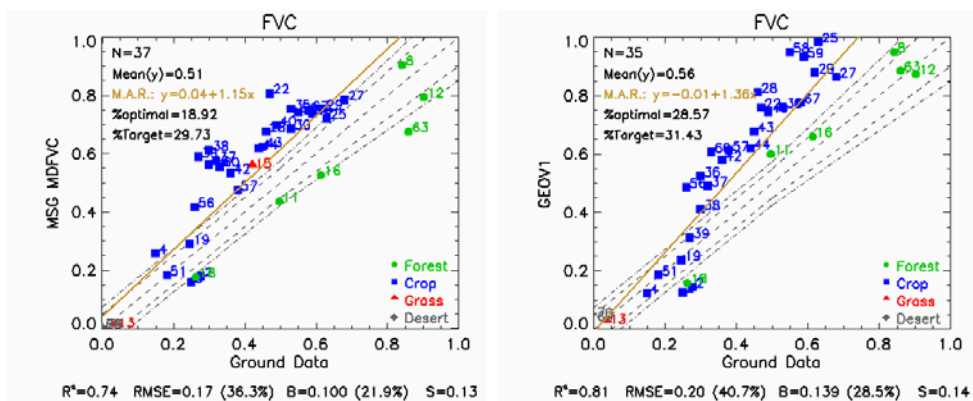
Figure 52: Comparison of satellite FVC product (MDFVC and GEOV1) with the ground-based maps. Forest stands for Broadleaf Evergreen, Broadleaf Deciduous and Needle-leaf Forests, Crops stands for Cultivated and Grass refers to Herbaceous, Shrubs and Sparse, Desert refers to Bare Areas. Numbers identify the ground data (section 4.3). Dashed lines correspond to the 1:1 line, optimal and target LSA SAF PR accuracy levels, and continuous yellow line to the linear fit using Major Axis Regression (MAR).
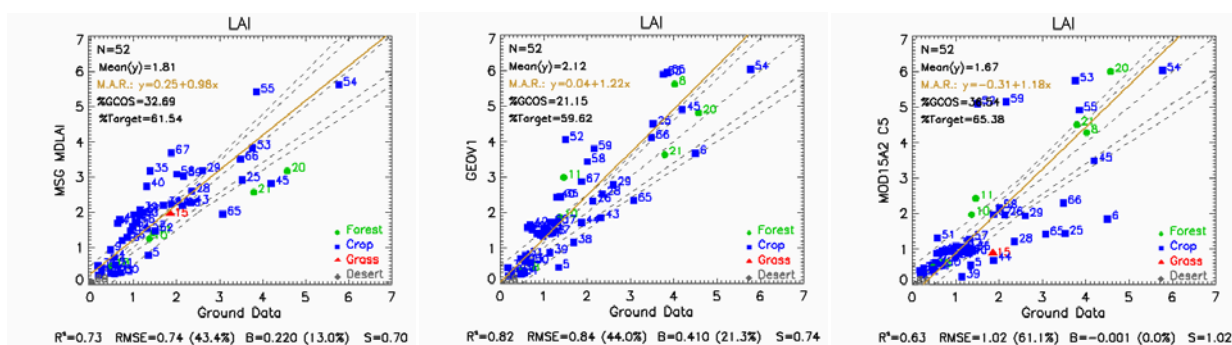
Figure 53: As in Figure 52 for satellite LAI products (MDLAI, GEOV1 and MODIS C5).
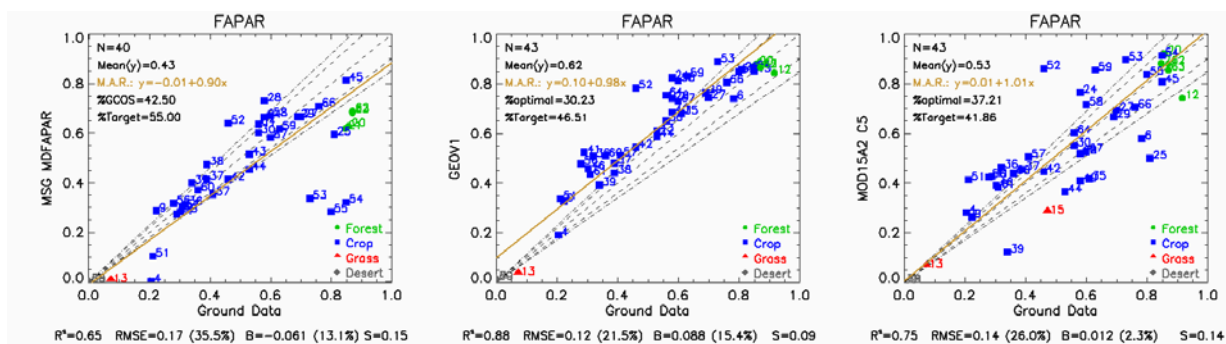
Figure 54: As in Figure 52 for satellite FAPAR products (MDLAI, GEOV1 and MODIS C5).

Table 12: Performance of MSG VEGA Daily (MDLAI, MDFAPAR, MDFVC), GEOV1 and MOD15A2 C5 products against reference ground based maps.

		Concomitant data		
		FVC	**LAI**	**FAPAR**
MSG VEGA Daily vs Ground Data	**N**	37	52	40
	R²	0.74	0.73	0.65
	Bias	0.1	0.22	-0.061
	RMSE	0.17	0.74	0.17
	Offset	0.04	0.25	-0.01
	Slope	1.15	0.98	0.90
	p-value	0.11	0.855	0.052
	%optimal	18.9	32.7	47.5
	%target	29.7	61.5	65
	%threshold	45.9	71.2	70
GEOV1 vs Ground Data	**N**	35	52	43
	R²	0.81	0.82	0.88
	Bias	0.139	0.41	0.088
	RMSE	0.20	0.84	0.12
	Offset	-0.01	0.04	0.10
	Slope	1.36	1.22	0.98
	p-value	0.005	0.015	0.716
	%optimal	28.6	21.2	39.5
	%target	31.4	59.6	53.5
	%threshold	34.3	71.2	65.1
MOD15A2 C5 vs Ground Data	**N**	N/A	52	43
	R²	N/A	0.63	0.75
	Bias	N/A	-0.001	0.012
	RMSE	N/A	1.02	0.14
	Offset	N/A	-0.31	0.01
	Slope	N/A	1.18	1.01
	p-value	N/A	0.158	0.868
	%optimal	N/A	35.5	41.8
	%target	N/A	65.4	53.5
	%threshold	N/A	73.1	62.8

Figure 55: Comparison of satellite FVC product (MTFVC-R and GEOV1) with the ground-based maps. Forest stands for Broadleaf Evergreen, Broadleaf Deciduous and Needle-leaf Forests, Crops stands for Cultivated and Grass refers to Herbaceous, Shrubs and Sparse, Desert refers to Bare Areas. Numbers identify the ground data (section 4.3). Dashed lines correspond to the 1:1 line, optimal and target LSA SAF PRD accuracy levels, and continuous yellow line to the linear fit using Major Axis Regression (MAR).
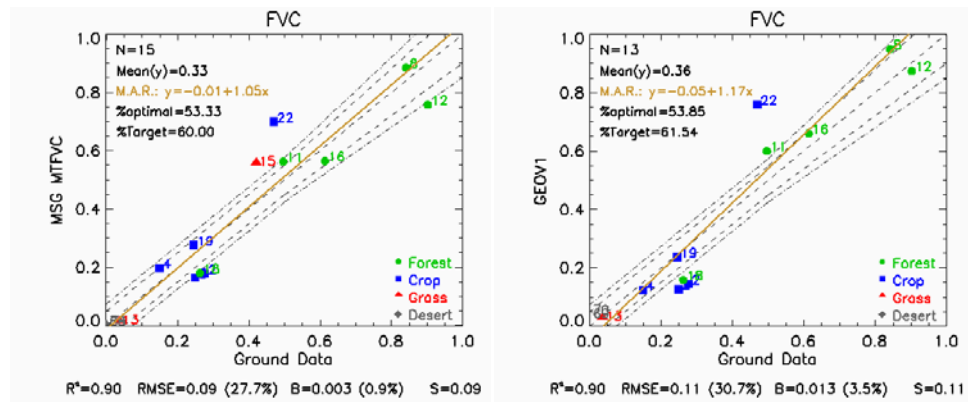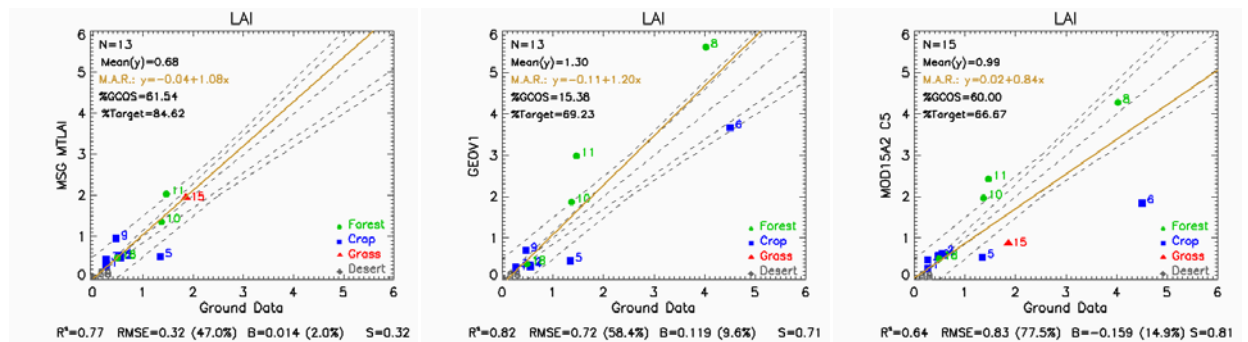

Figure 56: As in Figure 55 for satellite LAI products (MTLAI-R, GEOV1 and MODIS C5).

Table 13: Performance of MSG VEGA CDR, GEOV1 and MOD15A2 C5 products against reference ground based maps.

		Concomitant data	
		FVC	**LAI**
MSG VEGA CDR vs Ground Data	N	15	13
	R²	0.9	0.77
	Bias	0.003	0.014
	RMSE	0.09	0.32
	Offset	-0.01	-0.04
	Slope	1.05	1.08
	p-value	0.623	0.475
	%optimal	53.3	61.5
	%target	60	84.6
	%threshold	80	92.3
GEOV1 vs Ground Data	N	13	13
	R²	0.9	0.82
	Bias	0.013	0.119
	RMSE	0.11	0.72
	Offset	-0.05	-0.11
	Slope	1.17	1.2
	p-value	0.144	0.354
	%optimal	53.8	15.4
	%target	61.5	69.2
	%threshold	69.2	76.9
MOD15A2 C5 vs Ground Data	N	N/A	15
	R²	N/A	0.64
	Bias	N/A	-0.159
	RMSE	N/A	0.83
	Offset	N/A	0.02
	Slope	N/A	0.84
	p-value	N/A	0.336
	%optimal	N/A	60
	%target	N/A	66.7
	%threshold	N/A	75.3

The accuracy assessment shows:

For FVC:

➢ MTFVC-R shows over a limited number of samples (N=15) an overall accuracy RMSE of 0.09 with no mean bias. 53.3% of the samples are within optimal requirements and 60% fits the target level.

➢ MDFVC shows over a larger ground dataset (N=37) an overall accuracy (RMSE) of 0.17 and a mean bias of 0.106 with a clear tendency to overestimate croplands and to underestimate forest measurements. However, GEOV1 provides slightly degraded overall accuracy over this dataset with RMSE of 0.20 and higher slope of the linear fit, but more accurate estimations were observed over forest sites. Part of these differences could be partly attributed to the ground references, but the large positive bias seems to indicate an overestimation of the MDFVC ground values over cropland sites. Only 18.9% of the samples are within the PR optimal requirement level, and 29.7% of the samples are within the PR Target level.

For LAI:

➢ MTLAI-R shows an overall accuracy (RMSE) of 0.32 over limited sampling (N=13) with almost no mean bias, 61.5% of the samples in optimal requirement and 84.6% within target accuracy.

➢ MDLAI shows an overall accuracy (RMSE) of 0.74 (N=52), with slight positive mean bias (0.22). MDLAI shows better overall accuracy than MODIS (1.02) and GEOV1 (0.84), both with better spatial resolution. Note that in a few cases ground measurements correspond to LAIeff (which tends to underestimate actual LAI), This fact could explain part of the MDLAI positive bias.

➢ As for FVC, for forest sites MDLAI tends to underestimate ground values.

For FAPAR:

➢ For MDFAPAR, RMSE is 0.17 (N=40), with 47.5% of the estimates within the optimal requirement level, and 65% within target requirement, in both cases better than GEOV1 and MODISC5.

➢ Better overall accuracy was observed in GEOV1 (RMSE=0.12) and MODIS C5 (RMSE=0.14) as compared to MDFAPAR (RMSE=0.17), mainly affected with the poor estimations in Albufera site (#53, #54, #55). As observed in the temporal profile of Albufera (Annex V), MDFAPAR clearly underestimate FAPAR measurements during the peak of the season. However, for the rest of cropland sites,

MDFAPAR provide accurate measurements with bias close to zero, whereas GEOV1 slightly overestimate ground measurements, and MODIS C5 provides large scattering due to its noisier retrievals.

➢ The reason for failure of the MDFAPAR in Albufera is not well understood, but as MDFVC and MDLAI works fine, it seems to be related to the use of k1 and k2 BRDF parameters. Albufera is a site close to inland and coastal water, and could be contaminated to some extent by water, which could has a strong effect on k1 or k2, than on the more stable k0 BRDF parameter, used as input for FVC and LAI. This fact deserves further investigations.

➢ MDFAPAR tends to underestimate ground values over forest sites since measurements are more affected by non-photosynthetically elements (NPV) of the canopy, and overestimate green FAPAR in about 0.1 units at the peak season over deciduous forest (Zhang et al., 2013). The differences between canopy FAPAR (including NPV) and green FAPAR partly explain the differences observed between ground estimates (canopy FAPAR) and satellite product (green FAPAR) (Nestola et al., 2017).

6 CONCLUSIONS

The quality assessment of MSG/SEVIRI VEGA FVC, LAI and FAPAR V3.0 Climate Data Record of VEGA 10D products, reprocessed for the period 2004-2012, was conducted in agreement with the CEOS LPV best practices for validation of LAI products. The quality assessment has been focused on evaluating several criteria of performance, including completeness, spatial consistency, temporal consistency, precision, stability, overall assessment of discrepancies among similar products per biome type, and continental region, and the accuracy as compared to ground data collected and up-scaled according to CEOS LPV guidelines. This study was focused on the consistency of MSG VEGA 10D products as compared to references (GEOV1 and MODIS C5) products mainly for the 2008-2009 period. Moreover, for the analysis of the time series (temporal consistency, and stability) and for the accuracy assessment, the period was expanded using the whole available period (2004-2016) using MSG VEGA Daily products.

The summary of results and main conclusions are given below per main criteria:

Product Completeness

➢ MSG VEGA 10D completeness is very good over Africa and the South of America region along the MSG disk, improving the completeness of polar orbiting products (GEOV1) mainly during north hemisphere summer. However, a large fraction of missing values was found over Europe, mainly over northern latitudes in winter-time, due to the snow cover and/or persistent cloudiness at these latitudes in winter.

➢ Around 50% of gaps are shorter than 30 days.

Spatial Consistency

➢ MSG VEGA products show reliable spatial distributions of retrievals around the MSG disk without detecting anomalous patterns.

➢ The spatial consistency between VEGA 10D and GEOV1 shows:

o For FVC, around 70% of the samples shows optimal level of consistency (differences<Max[0.05,10%]), and up to 80% in the target level (differences<Max[0.075,15%]), with some spatial discrepancies observed over some regions: MSG tends to provide higher values over arid regions, and lower values over Europe.

o For LAI, around 55% of pixels shows optimal consistency (differences < 15%; i.e., GCOS requirement) and 90% of the pixels are within target consistency (differences

<Max [0.5, 20%]). Poor consistency was found over equatorial regions (Amazonia Forest, West Africa) and northern latitudes.

- o For FAPAR, there are large discrepancies in term of magnitude over all vegetated surfaces (up to -0.4). However, this is a systematic trend that does not imply inconsistent spatial features, but a different magnitude of the value. Nevertheless, around 55%-60% of samples shows optimal level of consistency (differences<Max[0.05,10%]; GCOS requirement).

➢ Difference maps between VEGA 10D and MODIS C5 LAI products show good spatial consistency over large areas, with histograms of differences centered at zero and 73.5% within the target level of consistency. Poor consistency was found for FAPAR in more than 50% of cases, showing systematic negative bias along the vegetated areas, and positive bias over semi-desertic regions.

➢ The analysis of PDFs of retrievals and differences per biome type shows the following:

- o VEGA 10D and GEOV1 show similar FVC and LAI distributions for all biome types except for EBF and NLF. Good agreement was found for FAPAR for non-forest sites.

- o VEGA 10D and MODIS C5 LAI products show the main discrepancies for EBF. For the non-forest areas MODIS LAI displays slightly larger values. Large discrepancies were found between VEGA 10D and MODIS C5 FAPAR for all biome types, mainly for EBF.

Temporal Consistency

➢ MSG VEGA temporal variations were found temporally consistent with those of GEOV1 and MODIS C5 products for all biome types, showing similar trends. The main discrepancies were found for forest sites at the peak of the season, where VEGA FAPAR and LAI tend to provide lower values than GEOV1 and MODIS. Very good consistency was found for the rest of biomes.

➢ Inconsistent values were found over sites located over the border of the MSG disk, and the retrievals over these areas should be carefully taken into account.

➢ Acceptable auto-correlation values were found for MSG VEGA 10D FVC and LAI products for all biome types, with typically more than 70% and 60% of cases greater than 0.8 for all biome types except for EBF. For FAPAR lower auto-correlation values were found.

➢ Cross-correlations between MSG VEGA 10D and reference products (GEOV1 and MODIS C5) show typically more than 50% of cases higher than 0.8 for all biome types except for EBF.

Intra-Annual Precision

➢ MSG VEGA 10D products shows very similar histograms of smoothness than SPOT/VGT GEOV1 products, and much better than MODIS. These results confirm the good intra-annual precision (at short time scale) for MSG VEGA 10D products.

Inter-Annual Precision

➢ MSG VEGA 10D shows similar inter-annual precision than GEOV1 and MODIS C5 products. For the FVC, median absolute anomaly of 0.011 (3.7%) was found. For the LAI MSG VEGA 10D provides median absolute anomaly of 0.044 (3.6%). Finally, for FAPAR MSG provides inter-annual precision of 0.18 (6.7%).

➢ Median absolute anomaly values of the percentile 5th and 95th, as indicator of inter-annual precision, match GCOS requirement on stability for the three variables.

➢ No trend in observed in the inter-annual variability from 2004 to 2012 period, similar mean values during the period than GEOV1 and better than MODIS products.

Stability of the Time Series

➢ Very good stability of the MSG VEGA 10D time series was found as compared to GEOV1 and MODC5. No trends were detected during the period 2004-2012.

Overall Statistical Consistency

➢ Scatter-plots and uncertainty statistics between MSG VEGA 10D and SPOT/VGT GEOV1 over MSGVAL sites show overall good consistency for FVC and LAI with overall discrepancies (RMSE) of 0.09 and 0.72 and almost no bias (<0.7%). Around 60% and 30% of pixels are within optimal consistency (GCOS) for FVC and LAI, and more than 73% including the target level of consistency. For the FAPAR, mean negative bias of -0.10 was found, with overall discrepancies of RMSE=0.16 and 41.1 of pixels within GCOS uncertainty levels.

➢ The overall comparison between MSG VEGA 10D and MODIS C5 LAI products over MSGVAL sites shows overall discrepancies of RMSE=1.1 with slight bias of 0.06. For FAPAR negative bias of -0.1 was found with overall discrepancies of RMSE=0.16. 18% and 25% of pixels are within GCOS uncertainty level for LAI and FAPAR respectively (59% and 40%) considering target level.

➢ Per continental region:
  o For Europe and Africa, good agreement was found between MSG VEGA 10D and SPOT/VGT GEOV1 for FVC, with a tendency towards positive bias (VEGA D10> GEOV1) for almost all biome types. In the case of Europe, herbaceous areas showed

an overestimation of MSG VEGA 10D in comparison with GEOV1 FVC values, with a mean bias value of 0.15. For the South of America region, different trend of the sign of the bias between MSG VEGA 10D and GEOV1 FVC was found for forest sites as compared to Europe and Africa, showing slight tendency towards negative sign.

o In Europe and Africa, very good agreement was found between MSG VEGA 10D LAI product and both references (GEOV1 and MODIS C5). In the case of Europe was observed a slight trend towards positive bias for all biome types. For South America, slight negative bias over forest types and positive over non-forest cases were found between MSG VEGA and GEOV1. Large discrepancies were found between VEGA 10D and MODIS C5 LAI products, mainly for BDF.

o All the continental regions showed a clear tendency to provide negative bias (VEGA 10D < both references) for FAPAR values. Remarkably good is the consistency between VEGA 10D and GEOV1 over forest cases in the African region, with almost all cases within the ±0.05 threshold and very low scattering. Larger discrepancies were found between VEGA 10D and GEOV1FAPAR products, mainly for BDF and cultivate areas, in case of South America and Africa, respectively. In these cases, median bias values close to -0.2 were obtained. In the comparison between with MODIS C5 FAPAR products, larger discrepancies were found in South America, with negative median bias values ranging from -0.05 to -0.2, except for SBA.

➢ Finally, negative bias was found between MSG VEGA 10D and MODIS C5 FAPAR for all biome types, with median values typically between -0.1 and -0.05.

Accuracy Assessment

➢ The accuracy of MSG CDR FVC (MTFVC-R) shows good performance (RMSE=0,09) over a limited number of samples (N=15) but with similar weight between different biomes (5 forest, 5 crops, 5 grass and bare). 60% of the samples fits the target requirement level.

➢ The accuracy of MSG VEGA daily FVC shows however a systematic positive bias over cropland sites, a slight negative bias in forest sites with overall errors of RMSE=0.17 (N=37, mostly crops), with 29.7% of the samples within PR target requirement. The accuracy results were however better than for GEOV1 FVC (RMSE=0.2). It should be noted that part of these systematic discrepancies mainly over croplands could be also attributed to systematic uncertainties in the ground datasets that should be further investigated.

➢ For LAI, VEGA CDR shows an overall accuracy of RMSE= 0.32 (N=13) with 84.6% of the samples within Target levels. Regarding the daily product, the RMSE=0.74, better

than MODIS C5 (1.02) and GEOV1 (0.84). A tendency to underestimate LAI for forest sites is observed in the MDLAI as it was for MDFVC. 32.5% of samples are in the optimal level of accuracy, and 61.5% in the target level.

➢ For FAPAR (MDFAPAR), degraded overall accuracy (RMSE=0.17) was found as compared to GEOV1 (RMSE=0.12) and MODIS C5 (RMSE=0.14), which is mostly due to the poor performance over Albufera rice site, and THE underestimation observed for forest sites. However, for other cropland sites good accuracy was observed (better than MODIS and GEOV1). The underestimation for forest sites can be partly explained due to the impact of NPV elements in ground measurement of FAPAR.

➢ MDFAPAR has 47.5% and 65% of the estimates within the Optimal and Target requirements, better than MODIS and GEOV1.

➢ The accuracy assessment is performed over a limited database of ground references, so the conclusions have to be interpreted accordingly. Additional ground references should be considered to improve the significance of the accuracy assessment.

Concluding remarks

The validation results of the MSG VEGA CDR products show overall good results, with good spatial and temporal consistency as compared to validated satellite products. It is noticeable the good inter-annual precision of the products and the stability of the time series. The main discrepancy was found for the FAPAR product where MSG provides lower values than both references based on MODIS products, which is explained by the different definition of the FAPAR. However, MSG FAPAR shows better accuracy results than MODIS and GEOV1 products. Most of the criteria evaluated shows in overall positive results, with some limitations in the accuracy of FVC product that has been detected over croplands in the evaluation of daily FVC products over extended period of time. Table 14 provides a summary of results per main criteria. Table 15 shows the compliance matrix against LSA SAF Product Requirements.

Table 14: Summary of Product Evaluation (MSG VEGA). The plus (minus) symbol means that the product has a good (poor) performance according to this criterion.

QA Criteria	Performance	Comments
Product Completeness	+	Optimal coverage over Africa and South America. Missing values mostly over northern latitudes in Europe due to snow.
Spatial Consistency	±	Smooth spatial distribution of retrievals, with no artefacts detected over the two years analysed. VEGA 10D shows typically 80-85% of the samples within target level of consistency for LAI and FVC as compared to GEOV1 (smooth product), and only about 10% of the samples showing poor performance (typically in equatorial belt, northern latitudes or semi-desertic regions). For FAPAR, systematic differences are obtained over vegetated surfaces. As compared to MODIS there are more discrepancies, partly explained by the lower smoothness of MODIS (noisy retrievals).
Temporal Consistency	+	Good consistency of MSG VEGA temporal variations, as compared to SPOT/VGT GEOV1 and MODIS C5. The main discrepancies were found for forest sites at the peak of the season, where VEGA FAPAR and LAI tends to provide lower values than GEOV1 and MODIS. Auto-correlation >0.8 in more than 70% and 60% of cases for FVC and LAI for all biome types except for EBF. For FAPAR lower auto-correlation values were found. Cross-correlations>0.8 between PROBA-V and both references (GEOV1 and MODIS) in more than 50% of cases for all biome types except for EBF.
Intra-Annual Precision	+	Smooth temporal profiles, similar to GEOV1, better than MODIS.
Inter-Annual Precision	+	Median absolute anomalies (95th and 5th percentiles) matching the GCOS stability requirements (0.04, 3.5%) for LAI and FAPAR (0.018, 6.7%) for FAPAR. Similar results for FVC (0.011, 3.7%).
Stability	+	Very stable patterns of bias between VEGA and reference products along the period. No trend detected.
Overall Statistical Consistency	±	Overall consistency between MSG VEGA and GEOV1 of 0.09, 0.72 and 0.16 for FVC, LAI and FAPAR, showing negative bias of -0.10 for FAPAR. MSG VEGA versus MODIS C5 shows overall errors (RMSE) of 1.1 and 0.16 for LAI and FAPAR, respectively. Per continental region, larger discrepancies as compared to reference products over Europe with median bias values between MSG VEGA 10D and GEOV1 in herbaceous areas of 0.15. Optimal consistency over Africa, except for FAPAR products over cultivated areas with median bias of -0.2 for MSG VEGA 10D versus GEOV1. Good consistency over South of America, except for MSG VEGA with reference FAPAR products for BDF biome (median bias ≈ -0.2).
Accuracy	±	For CDR products, For MTLAI-R (+): N=13, RMSE=0.32, Bias=0.014; 85% fits Target level. For MTFVC-R (+) : N=15, RMSE=0.09, Bias=0.003; 60% fits Target level. For MTFAPAR-R: no enough ground data available. For daily products, For MDLAI (+): N=52, RMSE=0.74, Bias=0.22; 61% fits Target level. For MDFAPAR (±): N=40, RMSE=0.17, Bias=-0.061; 65% fits Target level. For MDFVC (-): N=37, RMSE=0.17, Bias=0.1; 30% fits Target level. General trend to overestimate in croplands but slightly underestimate in forest sites.

Table 15: Compliance matrix of MSG VEGA CDR (MTLAI-R, MTFVC-R, MTFAPAR-R) products against ground references over limited number of samples and against operational satellite products over a global network of validation sites and two year period (2015-2016). N stands for the number of samples.

MSG VEGA CDR	Ground References N=15			Copernicus GEOV1/VGT (N >26900)			NASA MODIS C5 (N > 23900)	
	LAI	FAPAR	FVC	LAI	FAPAR	FVC	LAI	FAPAR
% Optimal	61.5	No data	53.3	24.8	41.1	60.1	18.0	25.3
% Target	84.6	No data	60.0	76.1	50.8	73.4	59.0	40.3
% Threshold	92.3	No data	80.0	83.5	58.8	83.5	68.6	56.0

Table 16: Compliance matrix of MSG VEGA daily (MDLAI, MDFVC, MDFAPAR) products against ground references over limited number of samples (mainly croplands). N stands for the number of samples.

MSG VEGA CDR	Ground References 37< N <52		
	LAI	FAPAR	FVC
% Optimal	32.7	47.5	18.9
% Target	61.5	65	29.7
% Threshold	71.2	70	45.9

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ANNEX I. MAPS OF MSG VEGA 10D CDR

FVC
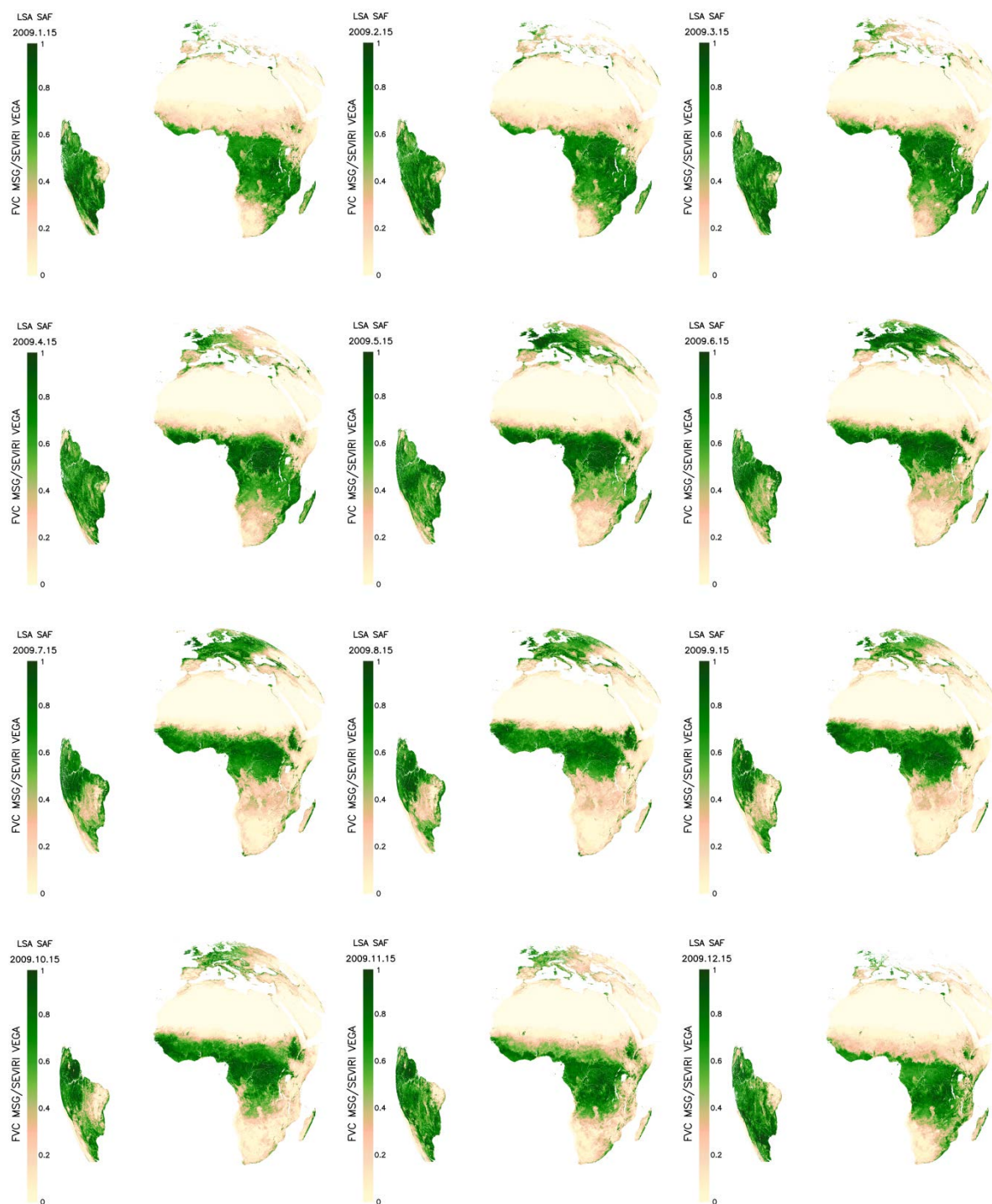
LAI
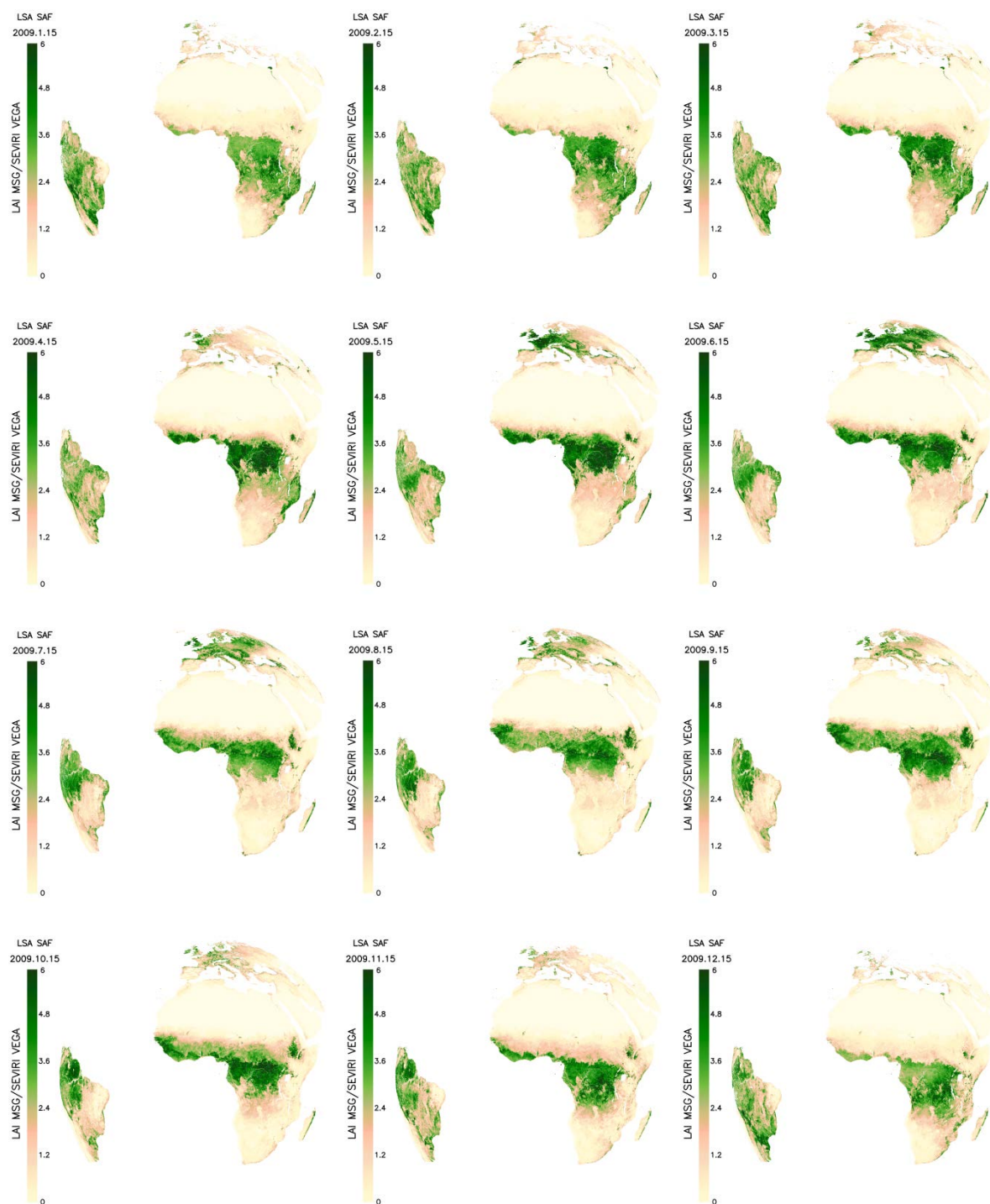
FAPAR
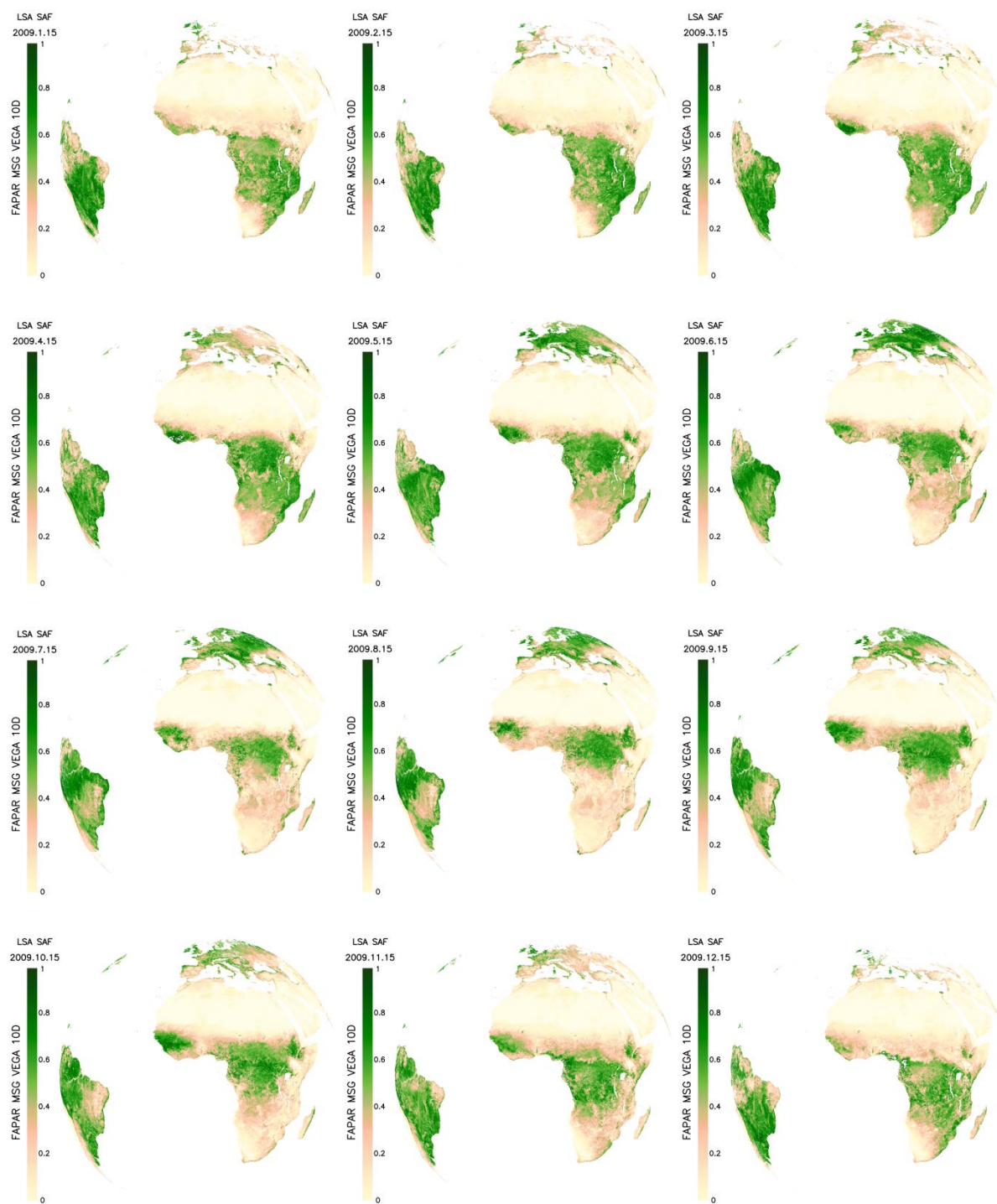
ANNEX II. MAPS OF DIFFERENCES VEGA 10D CDR VS GEOV1 FVC
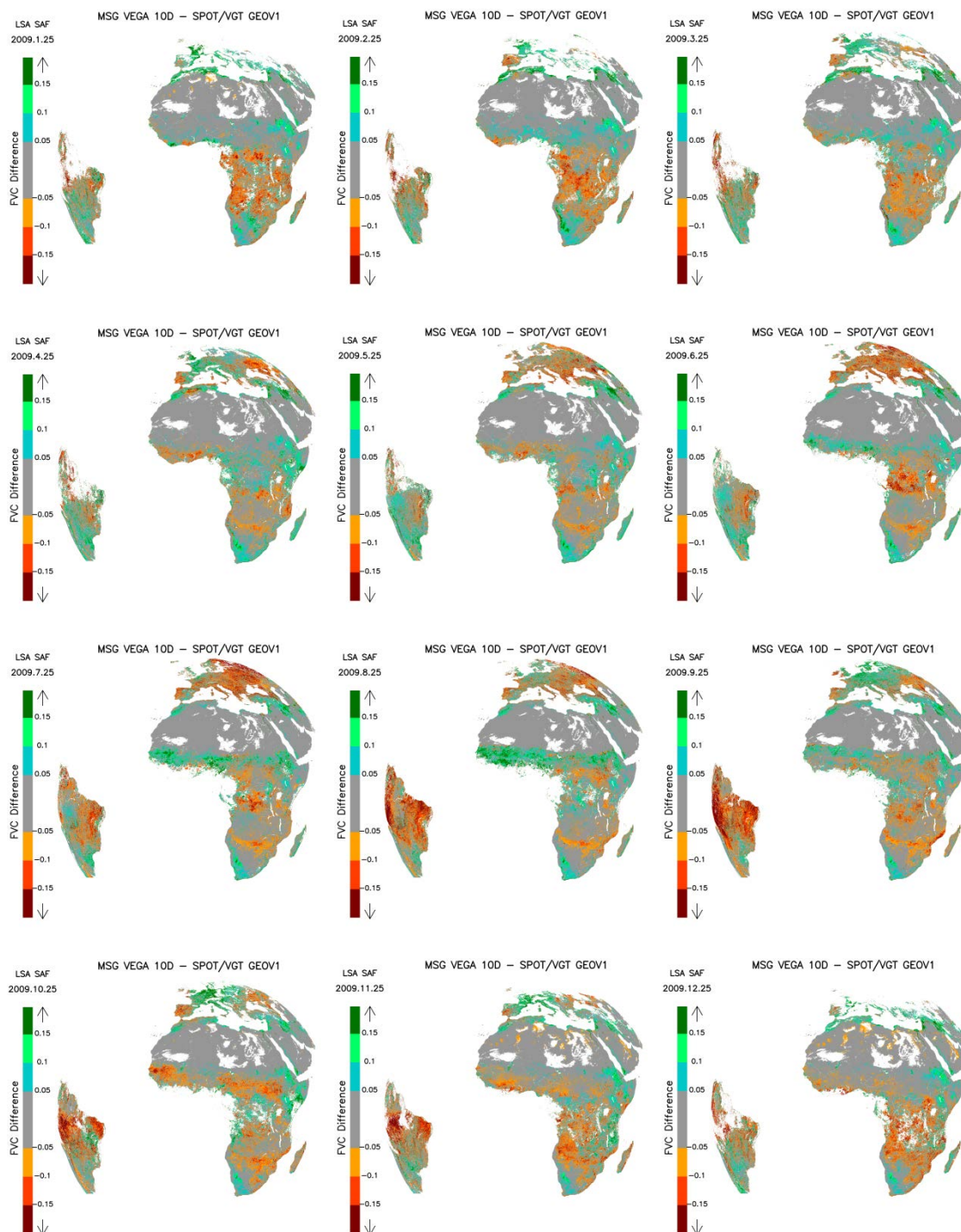
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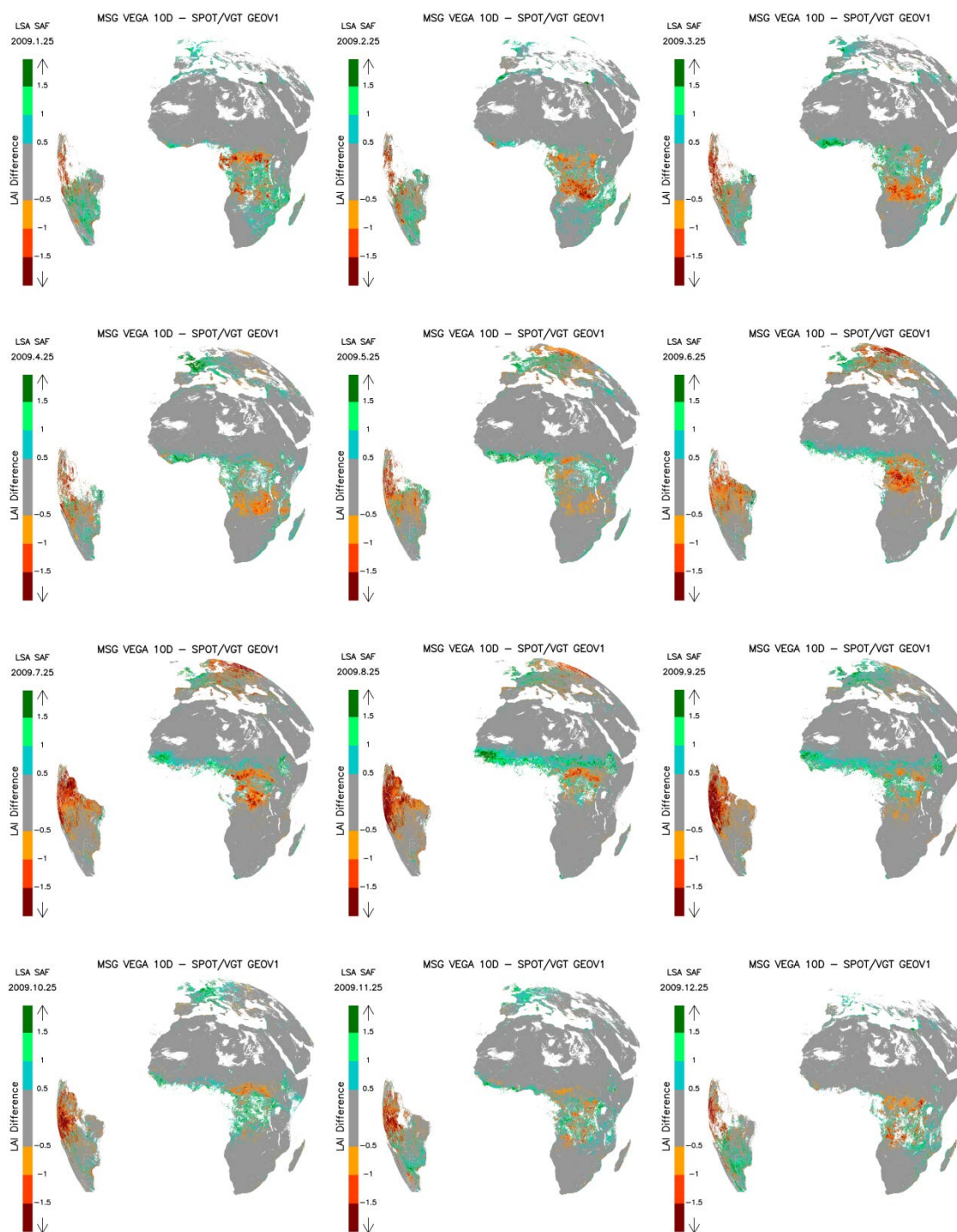
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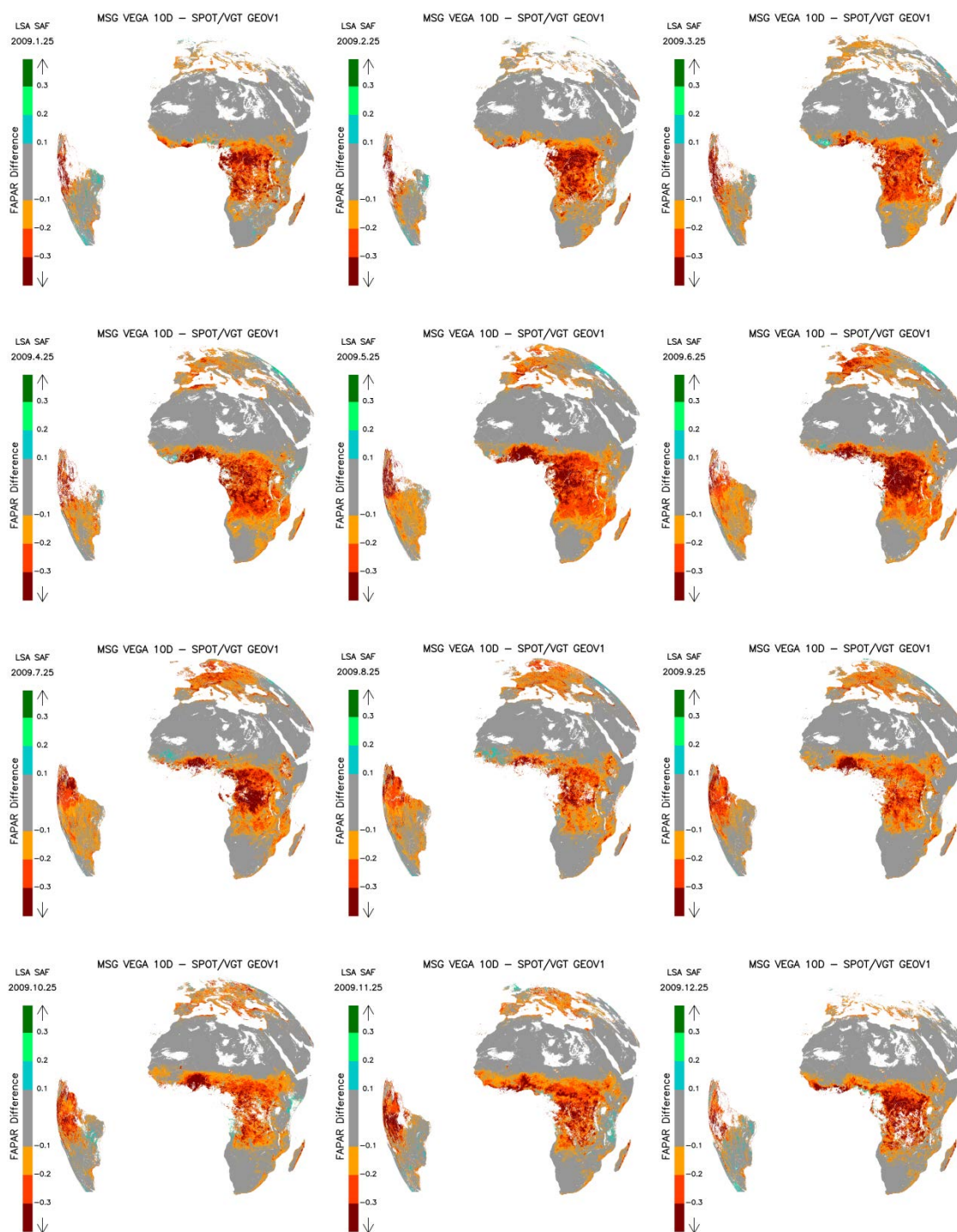
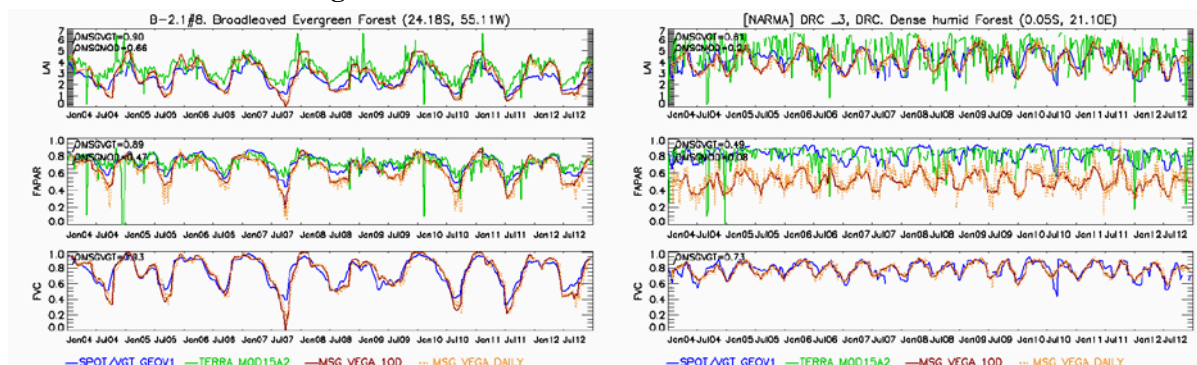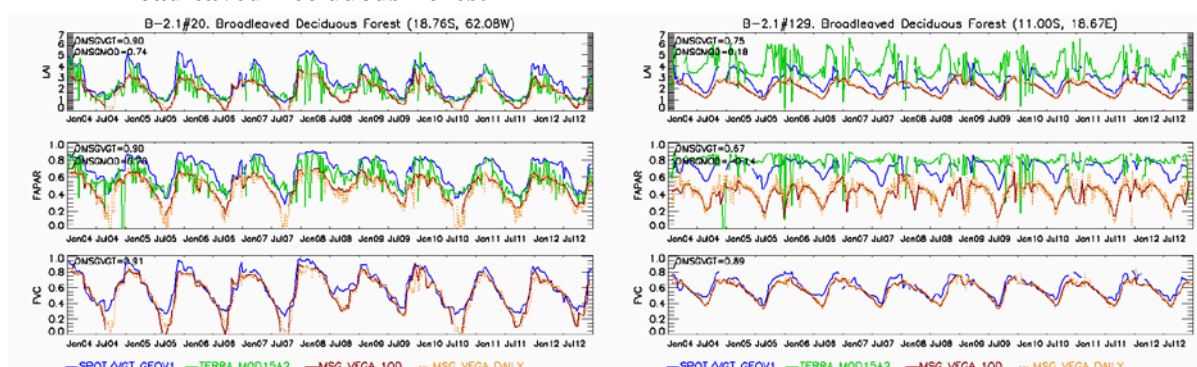# ANNEX III. MAPS OF DIFFERENCES VEGA 10D CDR VS MODIS C5 LAI
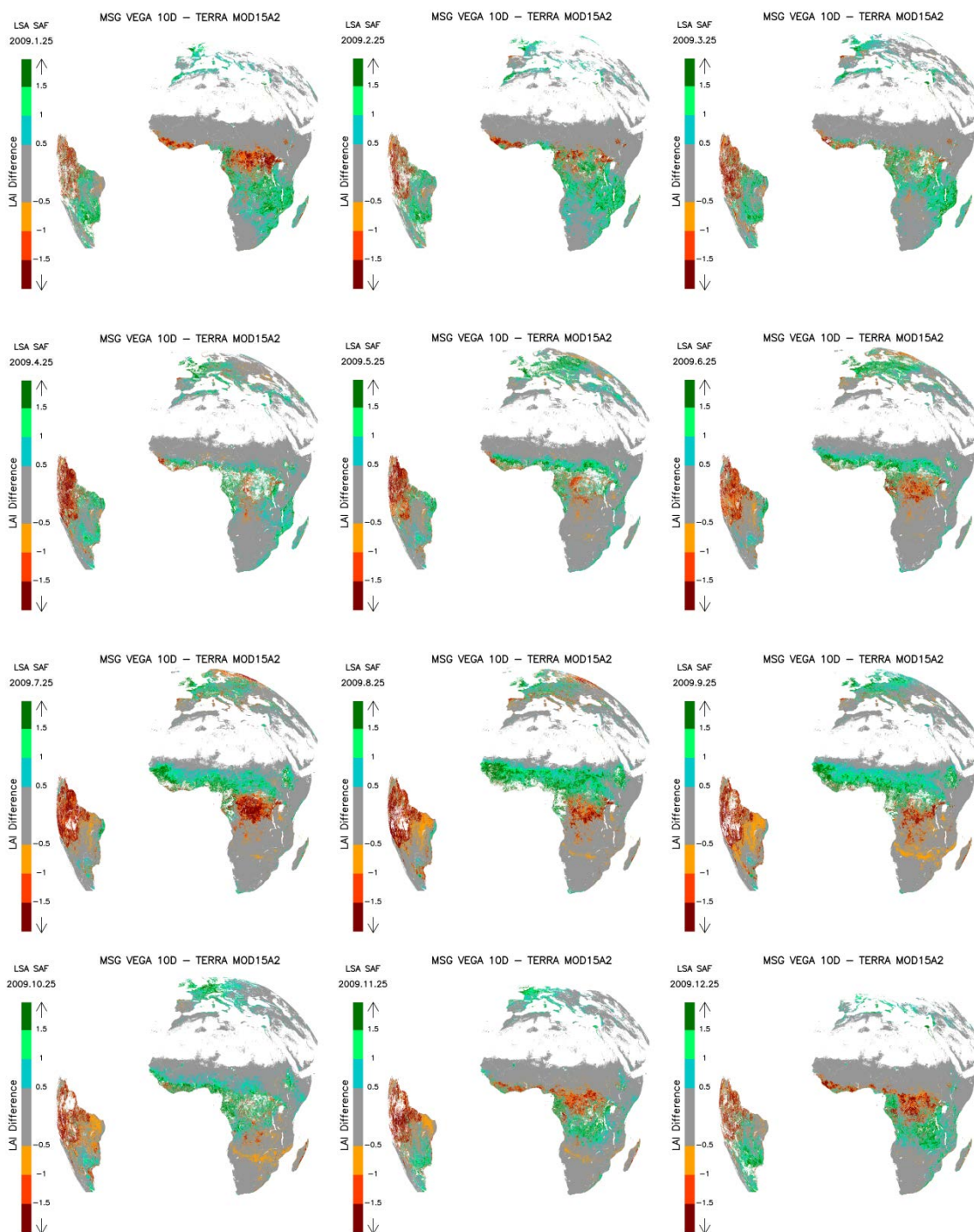
FAPAR
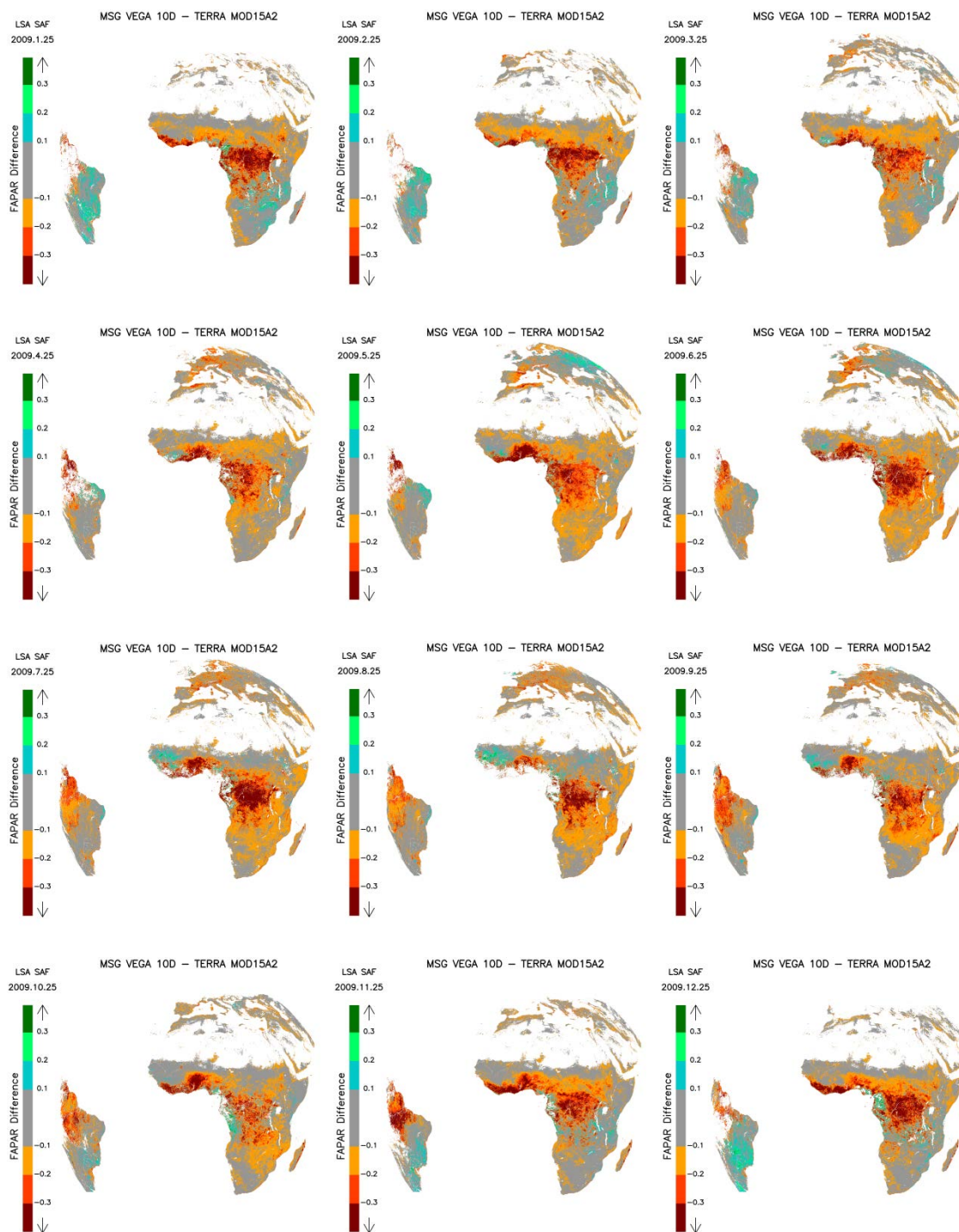
ANNEX IV. ADDITIONAL TEMPORAL PROFILES

- **Broadleaved Evergreen Forest**
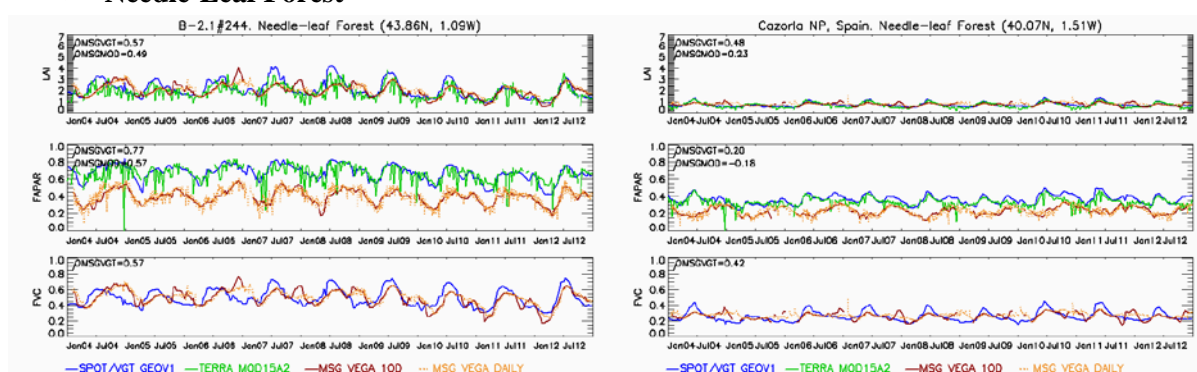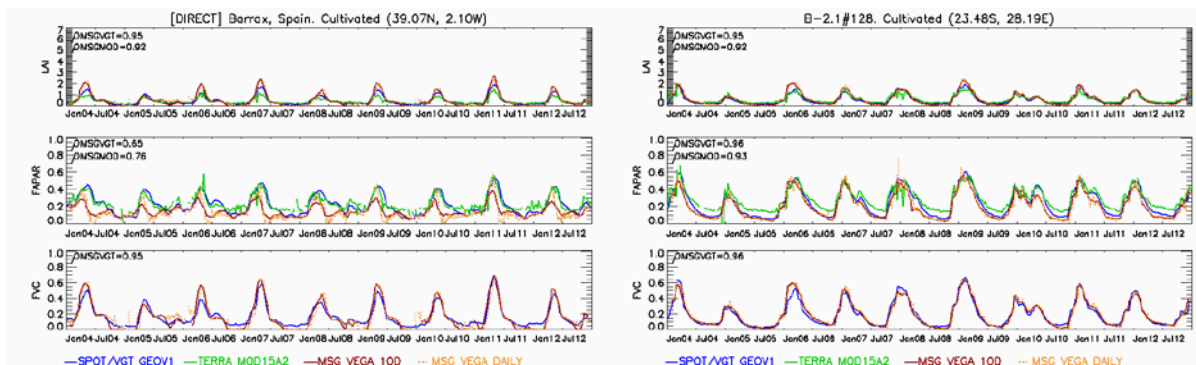

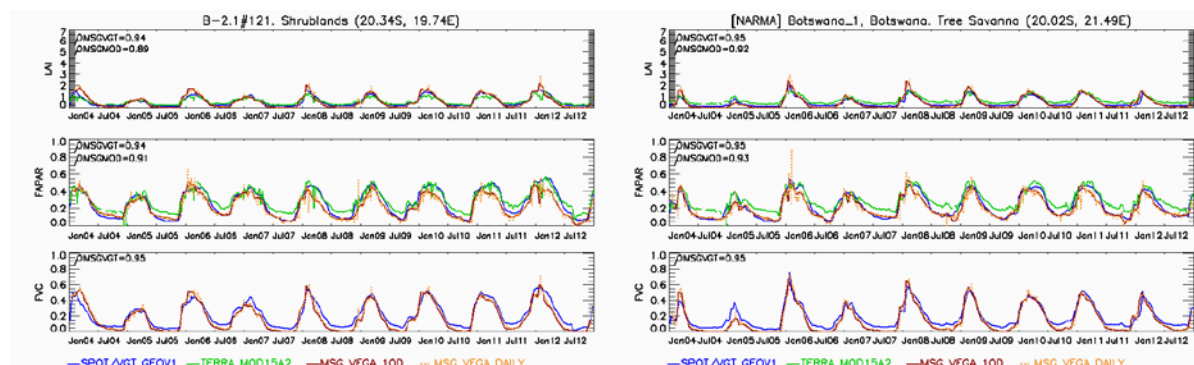- **Broadleaved Deciduous Forest**

- **Needle-Leaf Forest**

● **Cultivated**

● **Herbaceous**
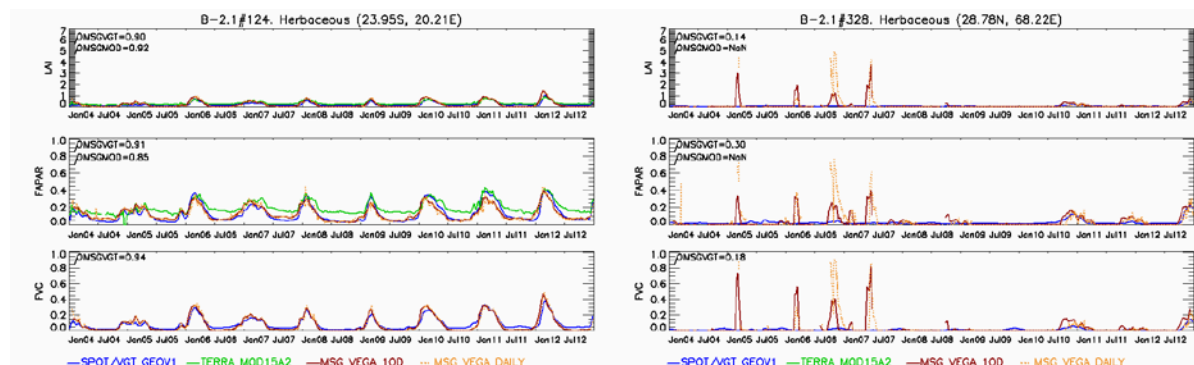
● **Shrublands**

- **Bare Soil**
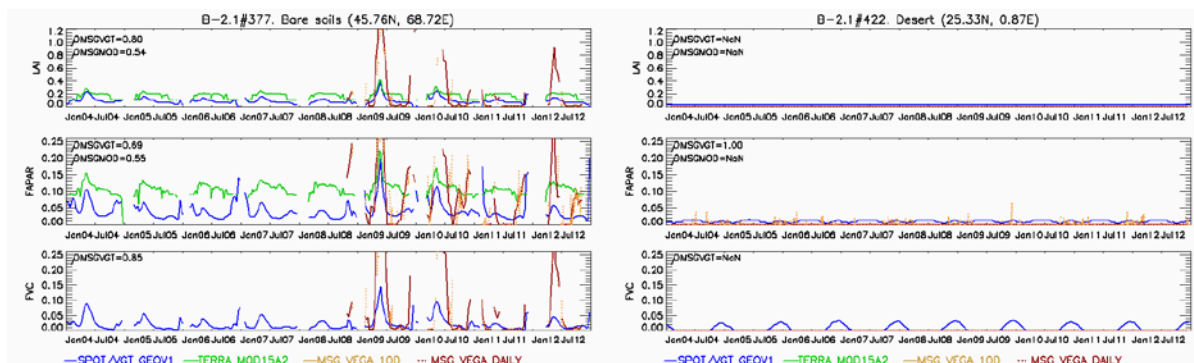
ANNEX V. ADDITIONAL TEMPORAL PROFILES WITH GROUND MEASUREMENTS

- **GuyaFlux (#17)**
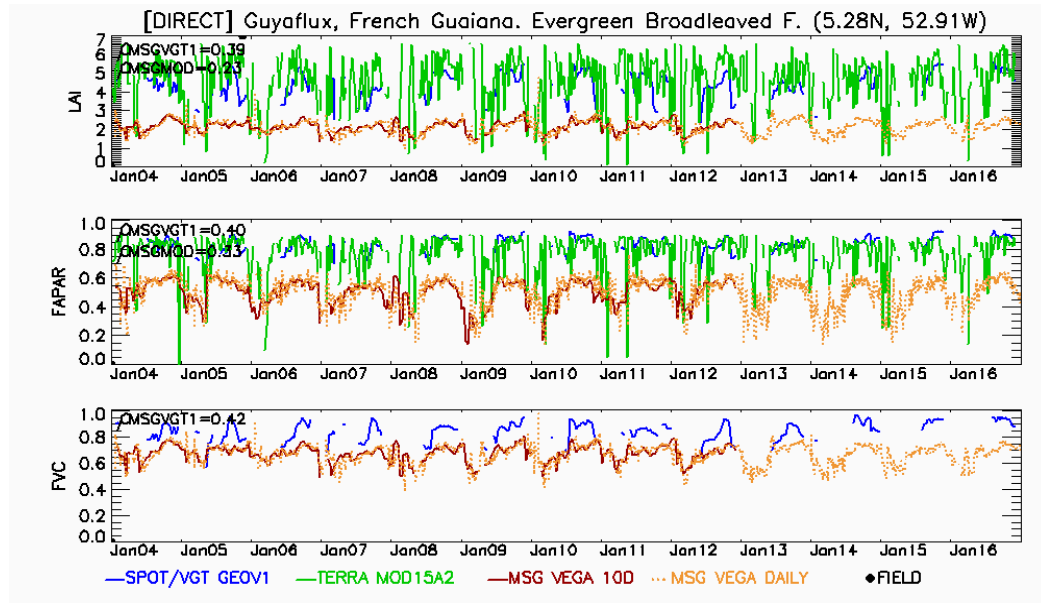
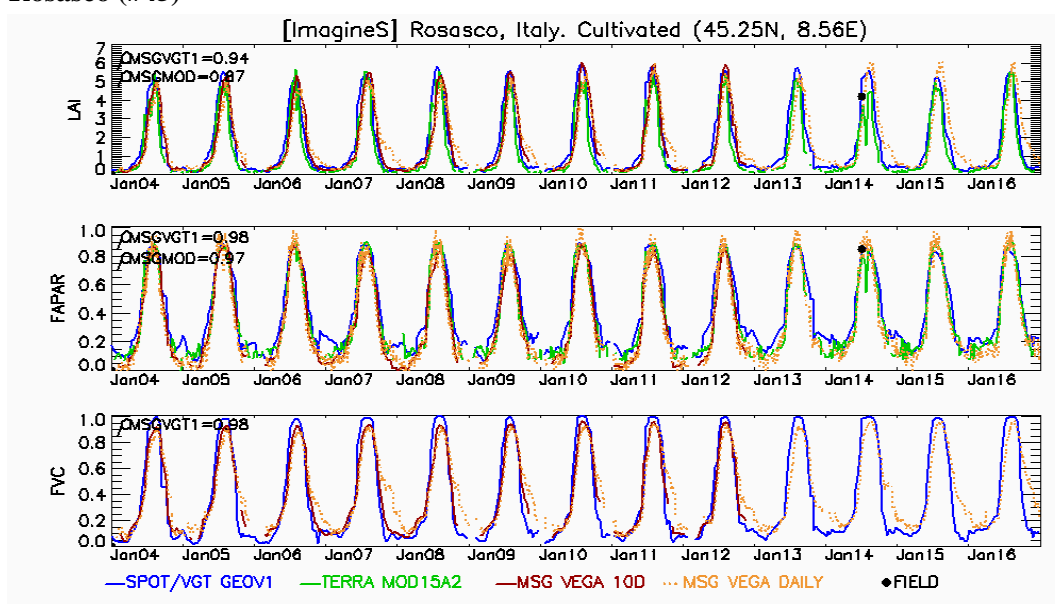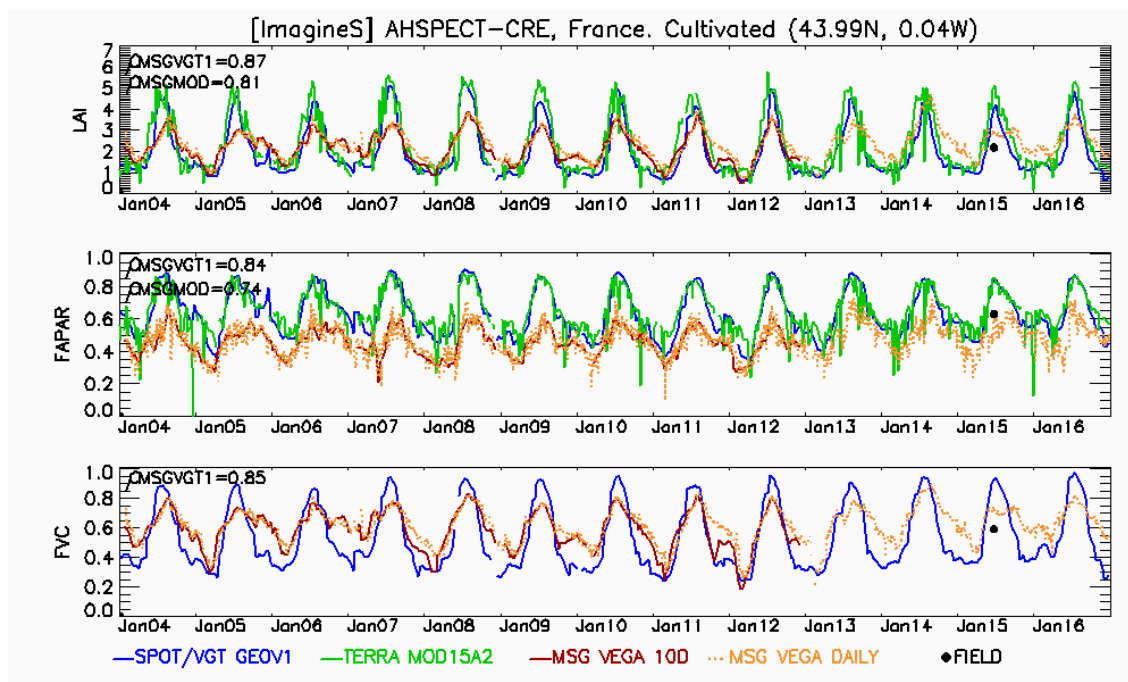- **HarthForest (#20, #21)**
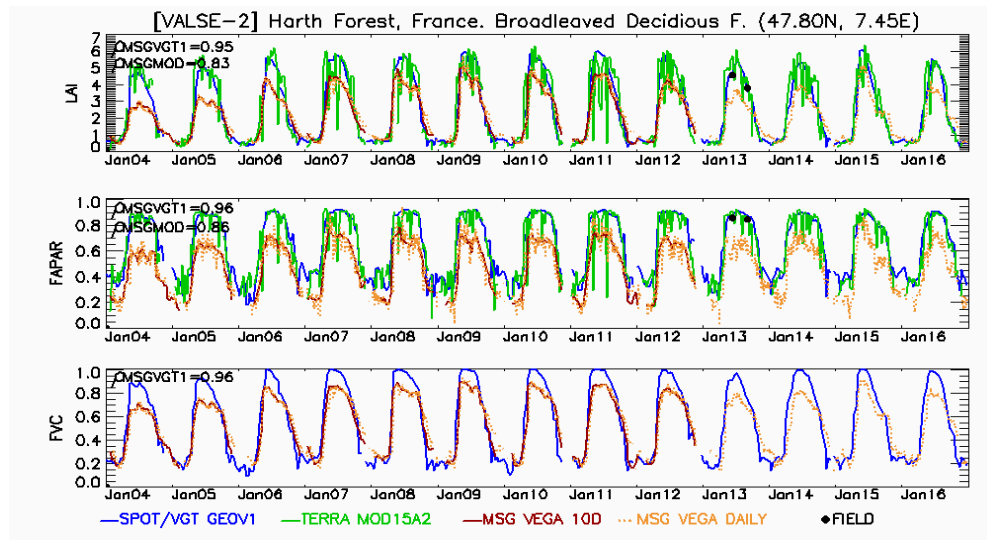
- **Albufera (#51, #52, #53, #54, #55)**
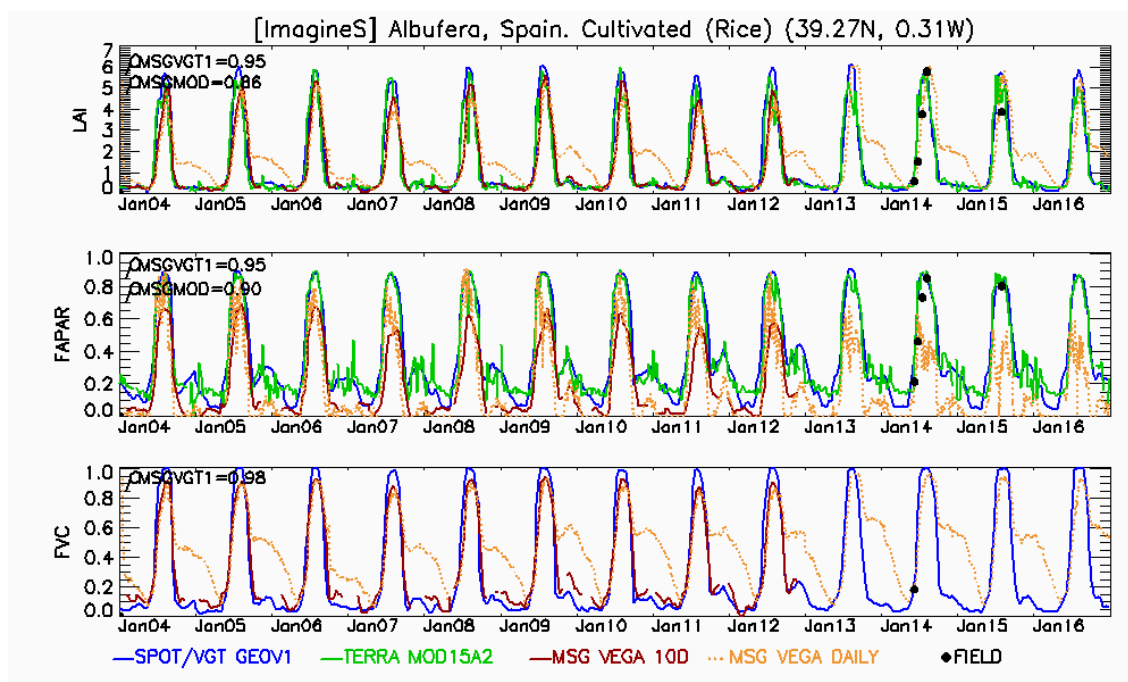
- **Rosasco (#45)**

- **AHSPECT-CRE (#59)**

- **LaReina_1 (#46)**