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Collection 1km

Version 2

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List of Acronyms

AD	Applicable Document
AFRI	AFRIca
AOI	Area Of Interest
ATBD	Algorithm Theoretical Basis Document
ANN	Artificial Neural Network
B	Mean Bias
BELMANIP	BEenchmark Land Multisite ANalysis and Intercomparison of Products
BioPar	Biophysical Parameters
BS	Bare Soil
C	Cultivated
CAL/VAL	Calibration and Validation group of CEOS
CEOS	Committee on Earth Observation Satellite
CEOS LPV	CEOS Land Product Validation Subgroup
CESBIO	Centre d'Etudes Spatiales de la BIOSphere (France)
CFIA	Agri-Food Canada
CGLS	Copernicus Global Land Service
CNR-IREA	Italian National Research Council - Istituto per il rilevamento elettromagnetico dell'ambiente
CRA-SCA	The Research Unit for Cropping Systems in Dry Environments (Italy). Unità di ricerca per i sistemi colturali degli ambienti caldo aridi
CV	Coefficient of Variation
CYC	CYCLOPES
CYCLOPES	Carbon cYcle and Change in Land Observational Products from an Ensemble of Satellites
DBF	Deciduous Broadleaf Forest
DHP	Digital Hemispherical Photographs
EBF	Evergreen Broadleaf Forest
Environet	Environmental Network
EOLAB	Earth Observation LABoratory
EURO	EUROpe
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCOVER	Fraction of Vegetation Cover
FP7	Seventh Framework Programme
GCOS	Global Climate Observing System
GEOV1	Version 1 of LAI, FAPAR, FCOVER 1km products
GEOV2	Version 2 of LAI, FAPAR, FCOVER 1km products
GIO	GMES Initial Operations
GLC	Global Land Cover
GMES	Global Monitoring for Environment and Security
GSD	Ground Sampling Distance
H	Herbaceous
HIST	HISTorical mode of GEOV2 products
HLAT	Higher LATitudes
IFAPA	Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica (Spain)
ImagineS	Implementation of Multi-scale Agricultural Indicators Exploiting Sentinels
INTA	Instituto Nacional de Tecnología Agropecuaria (Argentina)
ITAP	Instituto Técnico Agronómico Provincial de Albacete (Spain)

JRC	Joint Research Centre
LAI	Leaf Area Index
LSA SAF	Land Surface Analysis Satellite Applications Facility
LUT	Look Up Table
MAR	Major Axis Regression
MI	Moran's Index
MOD	MODIS
MODIS	Moderate Resolution Imaging Spectroradiometer
MODC5	MODIS Collection 5
MOD15A2	MODIS global LAI and FAPAR
N	Number of samples
NAS	National Academy of Sciences (Ukraine)
NDVI	Normalized Difference Vegetation Index
NLF	Needle Leaf Forest
NNT	Neural Network Technique
NOAM	NOOrth of America
NOBS	Number of daily OBServations used in the GEOV2 compositing
NRT	Neal Real Time
OCEA	OCEAnia
OLIVE	On Line Validation Exercise
PAR	Photosynthetically Active Radiation
PDF	Probability Density Function
PROBA-V	Project for On-Board Autonomy satellite, the V standing for vegetation.
PUM	Product User Manual
PV	PROBA-V
QA	Quality Assessment
QAR	Quality Assessment Report
QFLAG	Quality Flag
R2	Correlation coefficient
RMSE	Root Mean Square Error
RTx	Various consolidation modes of Version 2 products
RTM	Radiative Transfer Model
SBA	Sparse vegetated and Bare Areas
SEMI-PER	length in days of the semi-period
SOAM	SOUth of AMERICA
SPOT	Satellite Pour l'Observation de la Terre
SPOT /VGT	Satellite Pour l'Observation de la Terre / VEGETATION
SSAU	Space Agency of Ukraine
SVP	Service Validation Plan
SZA	Sun Zenith Angle
TOC	TOp of Canopy
TSGF	Temporal Smoothing and Gap Filling
UNFCCC	United Nations Framework Convention on Climate Change
UV	University of Valencia
VALERI	VALidation of Land European Remote sensing Instruments
VGT	VeGeTation sensor
WGCV	Working Group on Calibration and Validation (CEOS)
WGS84	World Geodetic System 1984
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

The Copernicus Global Land Service (CGLS) is earmarked as a component of the Land Monitoring service to operate “a multi-purpose service component” that provides a series of bio-geophysical products on the status and evolution of land surface at global scale. Production and delivery of the parameters take place in a timely manner and are complemented by the constitution of long term time series.

The Version 2 of algorithm (Verger et al., 2014), initially defined for the estimation of LAI, FAPAR and FCOVER products from the VEGETATION (VGT) series of observations, has been applied to daily top-of-canopy reflectance provided by the PROBA-V sensor. Two specific adaptations are done to achieve good consistency in the time series from SPOT/VGT to PROBA-V: a spectral conversion applied on PROBA-V TOC reflectances to get SPOT/VGT-like reflectances, and a rescaling of the PROBA-V neural network (NNT) outputs with regard to SPOT/VGT NNT outputs (fitting a polynomial function over BELMANIP2.1 sites and overlap period). As Version 2 applies temporal smoothing and gap filling (TSGF) methods, it improves the spatial coverage and temporal precision of previous Version 1 products. Moreover, the Version 2 provides a near real time estimate (RT0) which is derived only with past-time observations. A number of consolidations (RT1-RT6) are provided once a new dekad of observations is available. RT6 should be very close to the HIST Version 2 product (offline processing). The details of the Version 2 algorithm are given in the ATBD [GIOGL1_ATBD_LAI1km-V2]

This report shows the quality assessment results of the PROBA-V LAI, FAPAR, FCOVER Version 2 products over one year period (September 2013 - October 2014) concomitant with SPOT/VGT observations (October 2013 - March 2014). The analysis is performed in agreement with guidelines of the CEOS LPV for validation of global LAI products, and with several recommendations of the CGLS review board. Inter-comparison exercises between the different modes (RT0 vs RT6), sensors (VGT vs PROBA-V), and products (Version 2 vs Version 1, MODISC5) are presented. Accuracy assessment was achieved against matchups with ground-based reference maps coming from FP7 ImagineS project (<http://fp7-imagines.eu>) and CEOS OLIVE portal.

Overall good results are obtained despite the differences that are still observed between different satellite products. The Version 2 near real time estimate (RT0) is consistent with RT6 within GCOS requirements for ~90% of cases. PROBA-V Version 2 products shows complete spatial coverage and very smooth profiles which improves notably the spatio-temporal continuity and the precision of the reference products (Version 1, MODIS). Moreover, several artefacts affecting Version 1 products over northern latitudes or desertic areas are properly removed in Version 2. An overall accuracy of 1 for LAI products, 0.1 for FAPAR and 0.17 for FCOVER is obtained, with a tendency to slightly overestimate FAPAR and mainly FCOVER ground references. The percentage of retrievals within GCOS requirements are 65% for LAI, 57% for FAPAR, and 35% for FCOVER. However, discrepancies between SPOT/VGT and PROBA-V Version 2 estimates (around 1.5 in LAI, 0.15 for FAPAR) have been observed over some specific regions and periods with vegetation at the maximum of the phenological cycle and high cloud occurrence. The impact that these

differences could have in anomalies, inter-annual precision or stability of the time series need to be investigated over a longer period as soon as the PROBA-V Version 1 time series expands.

With the current quality assessment report, PROBA-V Collection 1km LAI, FAPAR, FCOVER Version 2 products reach Validation Stage 1 in the CEOS LPV hierarchy.

1 BACKGROUND OF THE DOCUMENT

1.1 SCOPE AND OBJECTIVES

The scope of this document is to present the quality assessment results of PROBA-V Collection 1km LAI, FAPAR, FCOVER Version 2 products (hereafter called GEOV2), with emphasis on the consistency between modes (RT0 vs RT6), sensors (VGT vs PROBA-V) and with the PROBA-V Collection 1km Version 1 products (hereafter called GEOV1). The quality assessment is performed on test data set provided over the globe at 10 days frequency covering six months overlap period (October 2013 to March 2014) with SPOT/VGT, and 1 year of overlap with GEOV1/PROBA-V and MODIS (September 2013- October 2014).

The objective is to evaluate the scientific quality of PROBA-V Collection 1km LAI, FAPAR, FCOVER Version 2 products and to determine if they reach the required quality to be disseminated to users.

1.2 CONTENT OF THE DOCUMENT

This document is structured as follows:

- Chapter 2 recalls the user requirements, and the expected performance.
- Chapter 3 describes the methodology for quality assessment, the metrics and the criteria of evaluation.
- Chapter 4 presents the results of the scientific analysis.
- Chapter 5 summarizes the main results and presents the conclusions of the study.

1.3 RELATED DOCUMENTS

1.3.1 Applicable documents

AD1: Annex I – Technical Specifications JRC/IPR/2015/H.5/0026/OC to Contract Notice 2015/S 151-277962 of 7th August 2015

AD2: Appendix 1 – Copernicus Global land Component Product and Service Detailed Technical requirements to Technical Annex to Contract Notice 2015/S 151-277962 of 7th August 2015

AD3: GIO Copernicus Global Land – Technical User Group – Service Specification and Product Requirements Proposal – SPB-GIO-3017-TUG-SS-004 – Issue I1.0 – 26th May 2015.

1.3.2 Input

Document ID

Descriptor

Document-No.	CGLOPS1_QAR_LAI1km-PROBAV-V2	© C-GLOPS Lot1 consortium
Issue: I1.40	Date:14.02.2019	Page: 20 of 153

GIOGL1_SSD	Service Specifications of the Global Component of the Copernicus Land Service.
GIOGL1_SVP	Service Validation Plan of the Global Land Service
GIOGL1_ATBD_LAI1km-V1_I1.10	Algorithm Theoretical Basis Document of the Collection 1km LAI, FAPAR, FCOVER and NDVI Version1 derived from SPOT/VGT data
GIOGL1_ATBD_LAI1km-V1_I2.00	Algorithm Theoretical Basis Document of the Collection 1km LAI, FAPAR and FCOVER Version 1 derived from PROBA-V data
GIOGL1_PUM_LAI1km-V1_I1.10	Product User Manual of Collection 1 LAI, FAPAR, FCOVER Version 1 derived from SPOT/VGT
GIOGL1_VR_LAI1km-V1_I1.10	Validation Report of the Collection 1km LAI, FAPAR and FCOVER Version 1 derived from SPOT/VGT data
GIOGL1_QAR_LAI1km-V1_I3.10	Quality Assessment Report of the Collection 1km LAI, FAPAR and FCOVER Version 1 derived from PROBA-V data
GIOGL1_ATBD_LAI1km-V2	Algorithm Theoretical Basis Document of the Collection 1km LAI, FAPAR and FCOVER Version 2 derived from SPOT/VGT and PROBA-V data
GIOGL1_QAR_LAI1km-VGT-V2_I2.00	Quality Assessment Report of the Collection 1km LAI, FAPAR and FCOVER Version 2 derived from SPOT/VGT

These documents are available on the Global Land service website (<http://land.copernicus.eu/global>), in the respective LAI, FAPAR and FCOVER pages.

1.3.3 Output

Document ID

GIOGL1_PUM_LAI1km-V2

Descriptor

Product User Manual of the Collection 1km LAI, FAPAR and FCOVER Version 2 derived from SPOT/VGT and PROBA-V data

1.3.4 External documents

Document ID

Descriptor

ImagineS_RP7.5_FielCampaign_Pshenichne2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_Merguellil2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_25Mayo2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_Rosasco2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_LaReina2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_Barrax2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_Albufera2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_Ottawa2014	Field campaign and data processing report
ImagineS_RP7.5_FielCampaign_Capitanata2014	Field campaign and data processing report
ImagineS_RP7.5_FieldCampaign_Collelongo2015	Field campaign and data processing report

These documents are available on the website of the FP7 ImagineS project (<http://fp7-imagines.eu>).

2 REVIEW OF USERS REQUIREMENTS

According to the applicable document [AD2], the user's requirements relevant for LAI, FAPAR, FCOVER products are:

- **Definition:**

- Fraction of absorbed PAR (FAPAR): Fraction of PAR absorbed by vegetation for photosynthesis processes (generally around the "red": PAR stands for Photosynthetically Active Radiation).
- Leaf Area Index (LAI): One of half of the total projected green leaf fractional area in the plant canopy within a given area. Representative of total biomass and health of vegetation (CEOS).
- Fractional cover (FCOVER): Fractional cover refers to the proportion of a ground surface that is covered by vegetation

- **Geometric properties:**

- The baseline pixel size shall be 1km or 300m.
- The target baseline location accuracy shall be 1/3 of the at-nadir instantaneous field of view.
- Pixel co-ordinates shall be given for the centre of pixel

- **Geographical coverage:**

- Geographic projection: lat long, geodetical datum: WGS84
- Pixel size: 1/112° - accuracy: min 10 digits
- Coordinate position: pixel centre
- Global window coordinates UL: 180°W-75°N, BR:180°E, 56°S (40320 col, 14673 lines)

- **Time definitions:**

- As a baseline, the biophysical parameters are computed by and representative of dekad, i. E. for ten-day periods ("dekad") defined as follows: days 1 to 10, days 11 to 20 and days 21 to end of month for each month of the year.
- As a trade-off between timeliness and removal of atmosphere-induced noise in data, the time integration period may be extended to up to two dekads for output data that will be asked in addition to or in replacement of the baseline based output data.
- The output data shall be delivered in a timely manner, i.e. within 3 days after the end of each dekad.

- **Accuracy requirements:**

- **Baseline:** wherever applicable the bio-geophysical parameters should meet the internationally agreed accuracy standards laid down in document "Systematic Observation Requirements for Satellite-Based Products for Climate". Supplemental details to the satellite based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS-154, 2011)" (see Table 1)
- **Target:** considering data usage by that part of the user community focused on operational monitoring at (sub-) national scale, accuracy standards may apply not on averages at global scale, but at a finer geographic resolution and in any event at least at biome level.

Table 1: GCOS Requirements for LAI and FAPAR as Essential Climate Variables [GCOS-154, 2011].

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
LAI	250 m	N/A	2- weekly averages	Max(20%; 0.5)	Max(10%; 0.25)
FAPAR	250 m	N/A	2- weekly averages (based on daily sampling)	Max(10%; 0.05)	Max(3%; 0.02)

Note however that the uncertainty associated to LAI reference maps is expected to be around 1 LAI units for forest (Fernandes et al., 2003) or around 0.5 for croplands (Martínez et al., 2009). Therefore, with the available ground truth reference data we cannot achieve the GCOS target requirement on accuracy for LAI satellite-based products. Further research on FAPAR should be conducted to evaluate the uncertainty attached to ground reference maps, which could be also slightly higher than the GCOS requirement for satellite-based products.

- **Additional user requirements**

The GCOS requirements are supplemented by application specific requirements identified by the WMO (Table 2). These specific requirements are defined at goal (ideal), breakthrough (optimum in terms of cost-benefit), and threshold (minimum acceptable). In most cases the GCOS requirements satisfy threshold levels (especially considering that GCOS requirements greatly exceed threshold spatial resolution requirements so random errors will cancel during spatial aggregation).

Table 2: WMO Requirements for Global LAI and FAPAR products(*). G=goal, B=breakthrough, T=threshold.

Application	Variable	Accuracy (%)			Spatial Resolution (km)			Temporal Resolution (days)		
		G	B	T	G	B	T	G	B	T
Global Weather Prediction	LAI	5	10	20	2	10	50	1	5	10
	FAPAR									
Regional Weather Prediction	LAI	5	10	20	1	5	40	0.5	1	2
	FAPAR						20			
Hydrology	LAI	5	8	20	0.01	0.1	10	7	11	24
Agricultural Meteorology	LAI	5	7	10	0.01	0.1	10	5	6	7
	FAPAR		8	20						
Seasonal and Inter-annual Forecasts	FAPAR	5	7	10	50	100	500	7	12	30
Climate-Carbon Modelling	LAI	5	7	10	0.25	0.85	10	1	3	30
	FAPAR					0.5	2			

(*) <http://www.wmo-sat.info/oscar/requirements>

3 QUALITY ASSESSMENT METHOD

3.1 OVERALL PROCEDURE

The Quality Assessment follows the procedures described in the GL Service Validation Plan [GIOGL1_SVP]. The protocols and metrics were defined to be consistent with the Land Product Validation (LPV) group of the Committee on Earth Observation Satellite (CEOS) for the validation of satellite-derived land product. Several criteria of performance were assessed in agreement with previous global LAI validation exercises (Camacho et al., 2013, 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), and with the recent CEOS LPV Global LAI product validation good practices (Fernandes et al., 2014).

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). As GEOV2 has no missing values, we focused here on the analysis of quality flags associated to the gap filling method.

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 zoom over sub-continental areas (20° latitude x 30° longitude) at full resolution (see Figure 1), and the visualization of animations of global maps at a reduced (1/6 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. Global maps of residuals, at a reduced (1/6 pixels) resolution, between the product under study and reference products are analyzed in order to identify regions showing spatial inconsistencies for further analysis (e.g. temporal profiles). Furthermore, histograms of residuals and percentage of residuals laying under the uncertainty levels (Table 3) are analyzed. This analysis is complemented by the analysis of Probability Density Function (PDFs) and distribution of residuals per biomes and continents.

Furthermore, the spatial autocorrelation of the products is analyzed over surfaces that are known to be homogeneous and stable on a global scale. For this purpose, two spatial indicators were used: the coefficient of spatial variation (CV) and the Moran's Index (MI). The CV is defined by the ratio of the standard deviation to the mean. It is a useful measure of the relative spread in the data and provides an estimate of overall variability that is independent of spatial scale (Román et al., 2009). The MI is a measure of spatial autocorrelation (Moran, 1948), which is close to 0 for random spatial pattern, and ranges from -1 to 1 indicating negative or positive spatial autocorrelation.

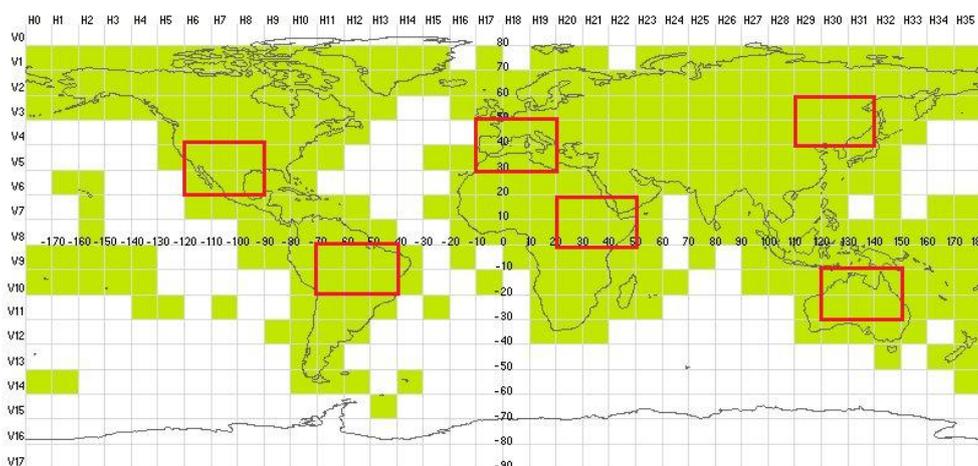


Figure 1: Location of the zoon areas displayed at full resolution for visual inspection of spatial consistency.

Two products are considered spatially consistent when the residual difference lays within GCOS accuracy requirements of the variable. The residual (ϵ) is estimated assuming a linear trend between two products ($Y = aX + b + \epsilon$), then the residual can be written as $\epsilon = Y - aX - b$, which represent the remaining discrepancies regarding the general trend between both products. In this way, systematic trends are not considered, depicting more clearly patterns associated to the spatial distribution of retrievals. The linear trend has been computed using BELMANIP2.1 sites for the period under study.

Here three levels of uncertainty (optimal, target and threshold) were defined, as described in Table 3. The percentage of land values within these uncertainty levels is quantified. Note that the optimal level of uncertainty has been selected according to the GCOS accuracy requirements for LAI and FAPAR (see Table 1). Figure 2 displays the selected uncertainty levels as a function of the product value.

Table 3: Uncertainty levels used for LAI, FAPAR and FCOVER products.

	Optimal (GCOS)	Target	Threshold
LAI	Max (0.5, 20%)	Max (0.75, 25%)	Max (1, 30%)
FAPAR / FCOVER	Max (0.05, 10%)	Max (0.075, 15%)	Max (0.1, 20%)

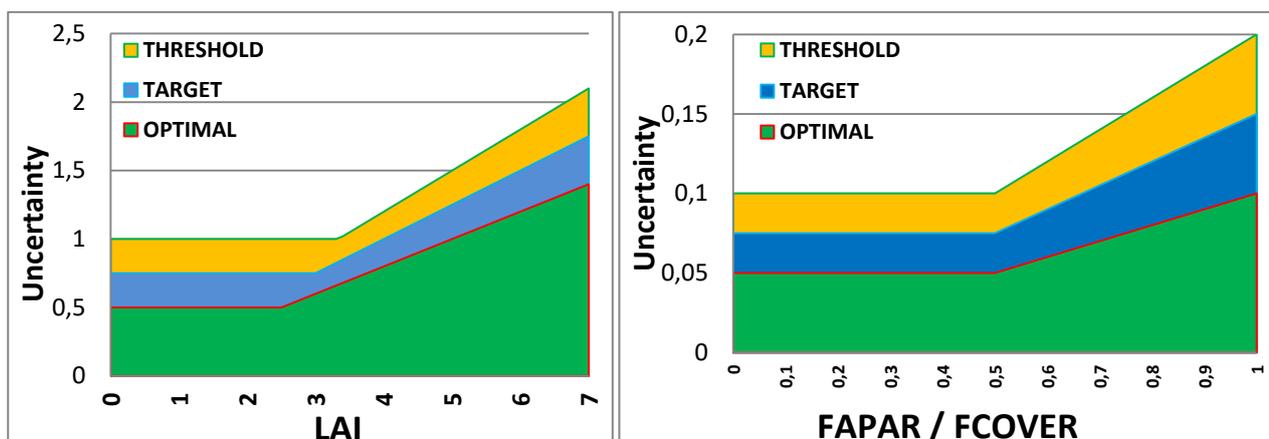


Figure 2: Uncertainty levels as a function of LAI (Left) and FAPAR/FCOVER (Right) products.

Temporal Consistency

The realism of the temporal variations and the precision of the products are assessed over the 445 BELMANIP 2.1 network plus the DIRECT network of sites (see section 3.3).

Firstly, the consistency of temporal variations for the different GEOV2 modes is investigated. Secondly, the temporal variations of the vegetation variables are qualitatively analyzed as compared to reference validated products.

The cross-correlation metric is included to analyse the temporal consistency of the products. 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 mean values of x and y series, respectively. The Auto-correlation is a particular case of the cross-correlation where $x=y$. The delay d considered is one year (36 dekads).

Histograms of cross-correlation between GEOV2 and reference products temporal variations per biomes over BELMANIP2.1 sites are evaluated.

Precision

Intra-annual precision (smoothness) corresponds to temporal noise assumed to have no serial correlation within a season. In this case, the anomaly of a product LAI value from the linear estimate based on its neighbours can be used as an indication of intra-annual precision (Fernandes et al., 2014), so-called smoothness (Weiss et al., 2007). 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 $P(d_{n+2})$ was computed:

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

Histograms of the smoothness for the different GEOV2 modes (from RT0 to RT6) are presented adjusted to a negative exponential function. The exponential decay constant is used as quantitative indicator of the typical smoothness value.

Global Statistical analysis

The inter-comparison of products offers a means of assessing the discrepancies (systematic or random) between products. The global statistical analysis is performed over a globally representative set of sites (BELMANIP 2.1) considering all the dates available. The BELMANIP-2.1 network of 445 sites was designed to represent globally the variability of land surface types. It is an improved version of the original BELMANIP sites (Baret et al., 2006). To allow comparison between the products, the same temporal (10-days) and spatial (3x3 pixels) supports are used. For the spatial support we used the GEOV2 *Plate carrée* projection over $1/112^\circ$ as a common grid. Reference products (e.g., MODIS) are re-sampled over the GEOV2 grid. The distribution of products values is then generated in the form of PDFs and distribution of the residuals (bias). The consistency between products under study and the reference products is further quantified based on uncertainties metrics associated to the scatter-plots between pairs of products (Table 4). These analyses are achieved per continents and per main land cover classes.

Accuracy Assessment

Accuracy is quantified by several metrics reporting the goodness of fit between the products and the corresponding ground measurements (Table 4). 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) were computed instead OLS because is specifically formulated to handle error in both of the x and y variables (Harper, 2014). Finally, the number of pixels within the GCOS requirements is quantified. The accuracy assessment is computed against ground data set up-scaled according with the CEOS LPV recommendations (Morissette et al., 2006). 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 4: Uncertainty metrics for product validation

Gaussian Statistics	Comment
N: Number of samples	Indicative of the power of the validation
RMSE: Root Mean Square Error	RMSE computed between ground and product values should be compared to the RMSE value corresponding to ground measurements. Indicates the Accuracy (Total Error). Relative values between the average of x and y were also computed.
B: Mean Bias	Difference between average values of ground and product. Indicative of accuracy and possible offset. Relative values between the average of x and y were also computed.
S: Standard deviation	Standard deviation of the pair differences. Indicates precision.
R²: Correlation coefficient	Indicates descriptive power of the linear accuracy test. Pearson coefficient was used.
Major Axis Regression (slope, offset)	Indicates some possible bias.
p-value	Test on whether the slope is significantly different to 1.
% GCOS requirements	Percentage of pixels matching the LAI/FAPAR GCOS requirements (*).

(*) For FCOVER, FAPAR GCOS requirements were considered.

Summary of Quality Assessment Procedure

Table 5 summarizes the number of validation metrics used for the validation of PROBA-V GEOV2 vegetation products.

Table 5: Summary of the QA procedure

Quality Criteria	Product evaluated	Reference Product	Coverage
Completeness	PROBA-V GEOV2	SPOT/VGT GEOV2	Global
	Global maps and temporal evolution of QFLAG Bit 3 (filling method) activation.		
Spatial Consistency	PROBA-V GEOV2 (RT6 and RT0)	SPOT/VGT GEOV2 PROBA-V GEOV1 MODIS C5	Global Sub-continental Regions
	Visual inspection of global maps and sub-continental regions Maps and histograms of residuals (global maps). Percentage of pixels within the uncertainty levels: optimal (GCOS), target and threshold. PDFs of retrievals & histograms of residuals per biome and region (BELMANIP 2.1). Moran Index		
Temporal Consistency	PROBA-V GEOV2 (all modes)	SPOT/VGT GEOV2 PROBA-V GEOV1 MODIS C5	445 BELMANIP2.1 + DIRECT sites
	Qualitative inspection of temporal variations. Histograms of Cross-correlation between GEOV2, GEOV1 and MODIS C5.		
Intra-annual Precision (smoothness)	PROBA-V GEOV2 (all modes)	SPOT/VGT GEOV2 PROBA-V GEOV1 MODIS C5	445 BELMANIP2.1
	Histograms of the smoothness.		
Statistical Analysis (Discrepancies)	PROBA-V GEOV2 (all modes)	SPOT/VGT GEOV2 PROBA-V GEOV1 MODIS C5	445 BELMANIP2.1 + Africa Region (20°X35°)
	Scatter-plots (R^2 , RMSE, Bias, Scattering, Major Axis Regression, p-value) per biomes (BELMANIP2.1).		
Accuracy Assessment (Error)	PROBA-V GEOV2 (RT6, RT0) PROBA-V GEOV1 MODIS C5	Ground-based maps	In-situ sites (see section 3.3)
	Scatter-plots, Pearson's coefficient. Root Mean Square Error (RMSE), mean bias (B), major-axis regression (offset, slope), p-value test, percentage of pixels within the GCOS accuracy levels.		

Satellite products must be compared over a similar spatial support area and temporal support period. The statistical analysis was conducted using an average value over 3x3 pixels and the temporal support period for the statistical assessment is 10-days. As different temporal compositing schemes are considered in the satellite product (Table 6) the following approach for comparison was followed: the closest dekad has been selected for comparing GEOV1 and GEOV2. In the case of MODIS products, with an 8 days temporal window, a weighted average of best quality retrievals was used, considering the closest date (weight of 0.5) to the reference date, and the two neighbours dates (before and after, with weight of 0.25).

Furthermore, due to the availability of the data for the different products under study, two periods have been considered for the statistical analysis:

- **Overlap period between PROBA-V and SPOT/VGT:** PROBA-V GEOV2 and SPOT/VGT GEOV2 were compared during the overlap period between both sensors. The 6-month period from October 2013 to March 2014 of GEOV2 RT6 modes was used. Note that this period corresponds to the fall and winter period in northern latitudes, in which vegetation activity is low.
- **One year of data:** The comparison between PROBA-V GEOV2 and references PROBA-V GEOV1 and MODIS C5 was performed during one year of data. Here, the period from October 2013 to September 2014 was considered, with full representation of vegetation phenological cycle in both hemispheres

Table 6: Temporal information where j is the first day of the temporal composite window

Product	Temporal window	Temporal frequency	Product date
GEOV2	variable(± 60)	10	j+60
GEOV1	30	10	j+17
MODIS	8	8	j

The following Quality Flag information on the reference products (GEOV1 and MODIS C5) was used to filter pixels flagged as out of range, saturated or invalid (Table 7) for the statistical analysis:

Table 7: 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/FCOVER 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, Fpar, Lai). Shore, freshwater, ocean (bit 1, 2,FparExtra), Cirrus detected (bit 5, FparExtra)

3.2 SATELLITE PRODUCTS

This section provides an overview of the retrieval algorithms of the satellite products used in this exercise. Table 8 summarizes the main characteristics of the several products inter-compared. Summary of retrieval algorithms and main validation results (if available) are provided hereafter.

Table 8: Characteristics of the global remote sensing products under study. GSD, ANN, CYC, MOD, and RTM stands for “Ground Sampling distance”, “Artificial Neural Network”, “CYCLOPES”, “MODIS” and “Radiative Transfer Model”, respectively.

Product	Sensor	GSD	Frequency	Compositing	Algorithm	Clumping	Reference
GEOV2	VGT/SPOT PROBA-V	1 km	10-days	Variable (± 60 -days)	ANN trained with CYC and MOD	Weighted of CYC and MOD	Verger et al., (2014)
GEOV1	PROBA-V	1 km	10-days	30-days	ANN trained with CYC and MOD	Weighted of CYC and MOD	Baret et al., (2013)
MODIS C5	MODIS/TERRA	1 km	8-days	8-days	Inversion RTM 3D	Plant, canopy & landscape	Knyazikhin et al., (1998)

3.2.1 PROBA-V Collection 1km Version 2 (GEOV2/PV)

The SPOT-VEGETATION (VGT) mission end in May 2014 and the provision of GEOV2 products in the Global Land Service continues based on PROBA-V (PV) 1 km observations. The GEOV2 algorithm (Verger et al., 2014) [GIOGL1_ATBD_LAI1km-V2] initially defined for the estimation of LAI, FAPAR and FCOVER from the VEGETATION series of observations (see SPOT/VGT GEOV2 below), was applied to daily top-of-canopy reflectance provided by the PROBA-V sensor. As the GEOV2 neuronal network (NNT) algorithm was trained with SPOT/VGT observations, two specific adaptations are applied to achieve good consistency when applied to PROBA-V data. First, a spectral conversion is applied on the actual PROBA-V TOC reflectances to get SPOT/VGT-like TOC reflectances values. Second, PROBA-V NNT outputs are rescaled with regard to SPOT/VGT NNT output using a polynomial function fitted over BELMANIP2.1 sites [GIOGL1_ATBD_LAI1km-V2].

The GEOV2 algorithm aims providing improved products as compared to GEOV1, although derived from the same sensors observations, with smoother retrievals and no missing values. GEOV2 products have the same temporal sampling frequency of 10 days than GEOV1. Similarly to GEOV1, GEOV2 capitalizes on the development and validation of already existing products: CYCLOPES version 3.1 and MODIS collection 5, and the use of neural networks (Baret et al. 2013; Verger et al. 2008). The basic underlying assumption is that a strong link exists between VEGETATION observations and the fused product resulting from CYCLOPES and MODIS products. Products are associated with quality assessment flags as well as quantified uncertainties.

The algorithm starts from the daily PROBA-V top-of-canopy reflectance products. The output is the instantaneous first guess of the three variables. Then, a temporal smoothing and gap filling (TSGF) method is applied, using several techniques including the Savitzky-Golay filter, a climatology (Verger et al., 2013) or interpolation methods to smooth the time profile and fill the gaps [see GIOGL1_ATBD_LAI1km-V2 for details]. Two different branches are processed depending on the time series considered:

- **The past-time series “HIST” (Offline processing of historical time series):** The past time series is defined as past observations where, for a given dekad, the ‘n’ dekads before and after are available, where ‘n’ is the number of dekads required for convergence, i.e. the length (in dekad) of the convergence period. HIST product is based on SPOT/VEGETATION observations, and is not released for PROBA-V.
- **The near real time products “RT_x”** are derived for the most recent limited season (around 2 months) using also similar principles as those for the past-time series. RT0 corresponds to the near real time guess. Note that each time a new dekad is processed (real time estimates), the recent past values of the products is updated. This results in successive updates of the products that converge towards the past time series value after the ‘convergence period’ (up to six dekads, RT₆). “RTx” products are based on PROBA-V observations, where RT₆ should be very close to the HIST product.

Product Content

The LAI, FAPAR, FCOVER products contain the following layers (for LAI, FAPAR, and FCOVER).

- LAI (or FAPAR, or FCOVER): variable value
- NOBS: number of daily observations used in the compositing
- QFLAG: quality flag
- RMSE-LAI: root mean square error with available daily observations.
- LENGTH_BEFORE: length in days of the semi-period before the decadal date of the compositing window.
- LENGTH_AFTER: length in days of the semi-period after the decadal date of the compositing window.

Quality Flag Information

The quality flag (QFLAG) is specified in Table 9. It is as consistent as possible with this used for GEOV1 products. However, due to the fact that GEOV2 results from the compositing of a number of daily PROBA-V reflectance observations, some differences have been introduced.

Table 9: Description of the quality flag provided for the GEOV2 LAI, FAPAR, FCOVER.

	Bit = 0	Bit = 1
Bit 1: Land/Sea	Land	Sea
Bit 2: Not used		
Bit 3: Filled	No filled	The number of valid observations at (at least) one side (the left side in the NRT case) of the ± 60 -day period is lower than 6 and a gap filling procedure (Bit 13-14) is applied
Bit 4 : Not used		
Bit 5: Not used		
Bit 6: Input status	OK	All reflectance data within ± 60 days (- 60 days in the NRT case) are out of range or invalid
Bit 7: LAI status	OK, in expected range including tolerance	Out of range or invalid
Bit 8: FAPAR status	OK, in expected range including tolerance	Out of range or invalid
Bit 9: FCOVER status	OK, in expected range including tolerance	Out of range or invalid
Bit 10: HLAT status	No specific correction for high latitudes is applied	A specific correction for high latitudes (lat > 55°) and SZA > 70° is applied
Bit 11: EBF status	Pixel is not recognized as Evergreen Broadleaf Forest	Pixel is recognized as Evergreen Broadleaf Forest
Bit 12: BS status	Pixel is not recognized as Bare Soil	Pixel is recognized as Bare Soil
Bit 13: Climatology	Not filled	Filled with climatology
Bit 14: Gap filling	Not filled	Filled with interpolation

3.2.2 Reference products

- **SPOT/VGT Collection 1km Version 2 (GEOV2/VGT)**

The Version 2 of algorithm was developed for SPOT/VEGETATION (VGT) observations. GEOV2/VGT uses as input daily top-of-canopy SPOT/VGT data. The algorithm principles, product outputs, including quality flags are the same as describe above (GEOV2/PV). The main differences with GEOV2/PV is that the spectral conversion (PV to VGT), the scaling of the outputs PV to VGT, and the near real time processing does not applies here. Only GEOV2/VGT HIST products are available.

The validation results of the SPOT/VGT GEOV2 products [GIOGL1_QAR_LAI1km-VGT-V2_I2.00] show an overall quite good spatial and temporal consistency with the SPOT/VGT GEOV1 products. However, a negative bias (lower GEOV2 FAPAR values) was detected for low and medium FAPAR values at global scale. All the criteria evaluated, including precision and accuracy assessment, showed positive results. The main improvement of the GEOV2 product as compared

to GEOV1 is completeness of the product (no missing values) and precision of the products. GEOV2 provides smoother retrievals, which are also more consistent from year to year than the reference products. The filled retrievals appeared to be consistent and reliable all around the world, even if more ground data is needed to verify their accuracy. The accuracy assessment using CEOS OLIVE DIRECT sites showed an RMSE of 0.83 for LAI with 73% of samples (N=49) within GCOS requirements, similar to GEOV1/VGT LAI products (RMSE=0.95). For FAPAR, GEOV2/VGT showed an RMSE=0.12 with a slight negative bias (-0.04) mainly over grassland (non-concomitant) sites (whereas GEOV1/VGT FAPAR displayed no mean bias). Finally, for the FCOVER, GEOV2/VGT showed an RMSE=0.11 and a slight positive mean bias of 0.023, similar to GEOV1/VGT.

- **PROBA-V Collection 1km Version 1 (GEOV1)**

The Version 1 of algorithm was defined by INRA in the framework of the FP7/geoland2 project. It generates the Leaf Area Index (LAI), associated with the Fraction of absorbed PAR (FAPAR) and the fraction of vegetation cover (FCOVER). These products are known as the GEOV1 products (Baret et al., 2013). The algorithm of the 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 FCOVER 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 algorithm was first applied to the SPOT-1&2/VEGETATION-1&2 data for the production of SPOT/VGT GEOV1 products. GEOV1/VGT products are validated Stage 2 according to the CEOS LPV hierarchy, outperforming the quality of similar products (Camacho et al., 2013). To ensure the consistency of the time series when moving from SPOT/VGT to PROBA-V, a pre-processing module was added to the Version 1 processing line that performs a conversion from PROBA-V spectral bands to VGT-2 spectral bands and converts the format of the S1-TOA PROBA-V data into PROBA-V “VGT-like” P-segments. The details are described in the ATBD [GIOGL1_ATBD_LAI1km-V1_I1.10].

Based upon the results of the quality assessment, performed over the first year of PROBA-V data (November 2013 to December 2014) [GIOGL1_QAR_LAI1km-V1_I3.10], the PROBA-V GEOV1 products are currently disseminated as “pre-operational”. These validation results show a good spatial and temporal consistency with the SPOT/VGT GEOV1 products for the overlap period (November 2013 to May 2014). However, a positive bias as compared to SPOT/VGT was detected for the FCOVER mainly for values larger than 0.5 and forest biomes. This bias seems to be confirmed by the limited ground observations available. Note that GEOV1/VGT FCOVER already presented positive bias as compared to ground truth over croplands, as reported by Mu et al. (2015). The accuracy of PROBA-V GEOV1 LAI product, evaluated according to CEOS LPV guidelines, was very close to GCOS requirement using limited concomitant data (RMSE=0.54) or using additional non-concomitant references (RMSE=0.51). For the FAPAR, the accuracy was acceptable (RMSE=0.11 for all data), but a slight overestimation was observed mainly as

compared to concomitant data over croplands (bias=0.09). The FCOVER shows the worst performance, with a systematic positive bias (up to 0.15 for concomitant data) observed mainly for forest and cropland sites and overall error (RMSE) of 0.14.

- **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 (Knyazhikin et al., 1998). The MODIS red and NIR atmospherically corrected reflectances (Vermote et al., 1997) 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.

The MODIS LAI/FAPAR product has been used in many validation and inter-comparison studies (Cohen 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 (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., 2013). 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., 2013).

3.3 IN-SITU REFERENCE PRODUCTS

The accuracy assessment of PROBA-V GEOV2 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.

- **Dataset from ImagineS project**

19 LAI ground references over ten sites were made available coming from the FP7 ImagineS project during the year 2014 (Table 10): two dates in Pshenichne (Ukraine) and Merguellil (Tunisia), two sites in 25 Mayo (Argentina), one site in Rosasco (Italy), La Reina and Barrax (Spain), four dates in Albufera (Spain) and Ottawa (Canada), and two more dates in Capitanata (Italy). The ground data was collected by different institutions (NAS and SSAU, CESBIO, INTA and EOLAB, CNR-IREA, IFAPA and EOLAB, ITAP, UV and EOLAB, CFIA, CRA-SCA) using mainly digital hemispherical photos (DHP). Ground data was up-scaled by EOLAB using either SPOT-5 or

Landsat-8 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 (Morissette 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/>).

Table 10: Characteristics of the validation sites and associated ground biophysical values. round data provided by ImagineS. #Sample is the number to identify the validation site in the Accuracy Assessment results (see 4.7).

Site	Country	Lat (deg)	Lon (deg)	Land Cover	Dates (mm/yyyy)	LAI	FAPAR	FCOVER	#Sample
Pshenichne	Ukraine	50.07	30.23	Crops	06/2014	2014	0.64	0.55	#1
					07/2014	2.76	0.70	0.68	#2
Merguellil	Tunisia	35.5662	9.9122	Crops	01/2014	0.18*	N/A	N/A	#3
					04/2014	0.93*	N/A	N/A	#4
25Mayo_1	Argentina	-37.9065	-67.7459	Crops	02/2014	1.30	0.39	0.32	#5
25Mayo_2	Argentina	-37.9389	-67.7890	Shrub	02/2014	0.42	0.19	0.16	#6
Rosasco	Italy	45.253	8.562	Crops (Rice)	07/2014	4.2	0.85	N/A	#7
LaReina_1	Spain	37.8189	-4.8624	Crops	05/2014	1.08	0.30	0.29	#8
Barrax-LasTiasas	Spain	39.0544	-2.1007	Crops	05/2014	1.5*	0.36	0.37	#9
Albufera	Spain	39.2743	-0.316	Crops (Rice)	06/2014	0.58	0.21	0.18	#10
					06/2014	1.51	0.46	N/A	#11
					07/2014	3.77	0.73	N/A	#12
					08/2014	5.78	0.85	N/A	#13
Ottawa	Canada	45.3056	-75.7673	Crops	06/2014	1.03*	N/A	0.39	#14
					06/2014	1.46*	N/A	0.48	#15
					07/2014	1.82*	N/A	0.49	#16
					07/2014	2.79*	N/A	0.79	#17
Capitanata	Italy	41.4637	15.4867	Crops	03/2014	1.82	0.56	N/A	#18
					05/2014	3.08	N/A	N/A	#19

(*) LAleff

For most of the ImagineS campaigns ground data was collected with digital hemispherical photography (DHP) and processed with CAN-EYE software to retrieve green LAI, FAPAR and FCOVER. Note that DHP measures gap fractions, thus CAN-EYE provides Plant Area Index which is a good approximation of LAI values for these cropland sites without presence of yellow or woody material. For all these sites, the transfer functions reported good performances with RMSE typically lower than 1 for LAI, and 0.1 for FAPAR and FCOVER (see ground reports for details). The exception was the Rosasco site (rice fields), because the NDVI of the Landsat image was saturated for many samples due to the very high LAI ground values. Thus a slight underestimation

of the LAI map is expected [ImagineS_RP7.5_FielCampaign_Rosasco2014]. Also for Barrax, an overestimation of the LAI is expected, as clumping values for very homogeneous crops were found unreliable, which leads to LAI values up to 7.5 for alfalfa canopies [ImagineS_RP7.5_FielCampaign_Barrax2014]. Then, for Barrax, LAI effective values are selected for comparisons with satellite estimates.

Note that, in La Albufera, Ottawa and Capitanata other devices (LAI-2000, LAI-2200 and AccuPAR) were also used for LAI and FAPAR estimations. The mean value of the LAI or FAPAR estimation with the different devices was used for the up-scaling using the high resolution satellite imagery. The RMSE associated to the up-scaled map ranges from 0.35 to 1.16 for LAI, from 0.06 to 0.22 for FAPAR and from 0.07 to 0.18 for FCOVER.

- **Additional dataset**

Due to the limited number of concomitant ground measurements, the number of ground reference maps was increased by using data from a different year from Camacho et al. (2013) and available at CEOS OLIVE Cal/Val portal (<http://calvalportal.ceos.org/>). These sites have been filtered by analyzing the inter-annual stability of the MODIS C5 FAPAR products, as MODIS time series expands from 2000 till the most recent dates. Only stable forest and grassland sites have been used: a maximum difference of ± 0.05 in the MODIS FAPAR value between the concomitant date and the equivalent day of the current year was allowed. A total of 19 additional sites were finally considered, their main characteristics are presented in ANNEX I. Additional Validation Sites. Furthermore, an additional non-concomitant deciduous forest site located in Collelongo (Italy) coming from ImagineS dataset was included [ImagineS_RP7.5_FieldCampaign_Collelongo2015].

3.4 REGIONAL/BIOME ASSESSMENT

The 445 BELMANIP 2.1 sites were classified according to the main biome type as well as per continents to assess the product performance per regions and biomes (Figure 3).

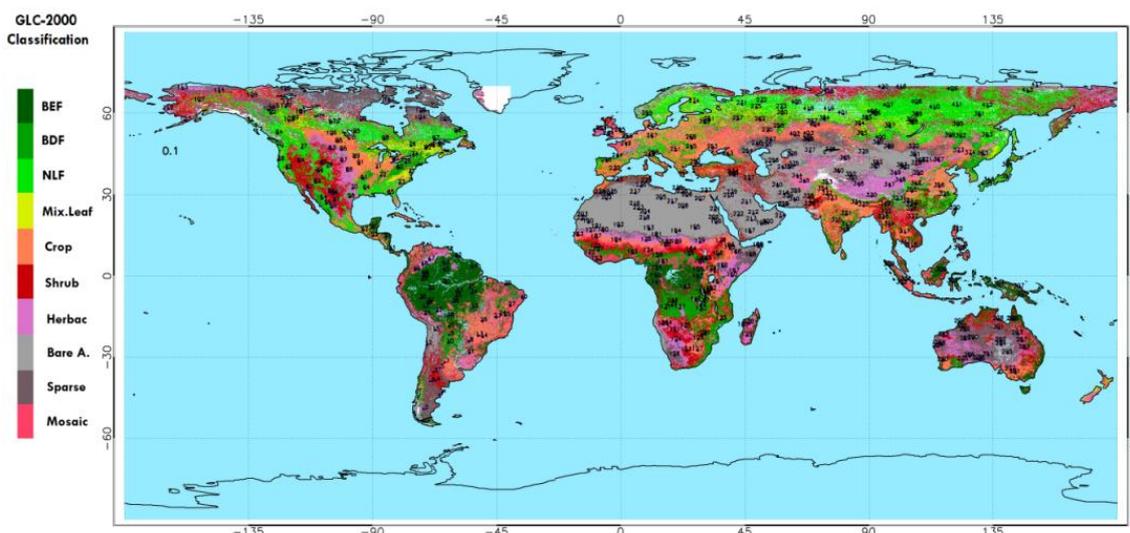


Figure 3: Location of the BELMANIP2.1 sites over an aggregated land cover (GLC-2000) map. All the classes are aggregated in the following main biomes (up to down in the legend): Evergreen Broadleaf Forest, Deciduous Broadleaf Forest, Needle-leaf Forest, Mixed leaf Forest, Croplands, Shrublands, Herbaceous, Bare Areas, Sparse vegetation and Mosaic.

Several performance metrics (Table 4) are evaluated over the BELMANIP-2.1 network of 445 sites (Figure 3) built to represent the global variability of vegetation types and vegetation conditions. Moreover, BELMANIP2.1 allows performing the analysis per continents and main biomes, aggregated based on the 7 generic classes derived from the GLC-2000 classification (Bartholomé and Belward, 2005): Evergreen Broadleaf Forest (EBF), Deciduous Broadleaf Forest (DBF), Needle-leaf Forest (NLF), Shrublands (S), Herbaceous (H), Cultivated (C), Sparse and Bare areas (SBA).

3.5 AREAS OF INTEREST (SPATIAL AUTOCORRELATION)

The spatial autocorrelation analysis was performed over 15 BELMANIP2.1 sites that are known to be homogeneous and stable up to ~50x50 km² (Table 11): 5 sites were selected to be representative of Evergreen Broadleaved Forest biome type, 5 of Deciduous Broadleaved Forest and 5 of Herbaceous and Shrublands.

Table 11: Central coordinates of the 15 selected BELMANIP2.1 sites for the Spatial Correlation analysis and Google Earth View of 50kmx50km.

EBF				
B2.1 #16	B2.1 #18	B2.1 #30	B2.1 #46	B2.1 #436
				
Lat=-10.3094 Lon= -70.0321	Lat=-14.8264 Lon=-62.1798	Lat=-2.6785 Lon= -63.648	Lat=0.7204 Lon=-71.3605	Lat=3.0485 Lon=-69.8396
DBF				
B2.1 #10	B2.1 #20	B2.1 #147	B2.1 #160	B2.1 #384
				
Lat=-24.7802 Lon=-62.3381	Lat=-18.7696 Lon=-62.0803	Lat=-9.5691 Lon=30.2923	Lat=5.7958 Lon=29.4051	Lat=57.5562 Lon=73.9674
Herbaceous/Shrublands				
B2.1 #299	B2.1 #135	B2.1 #138	B2.1 #178	B2.1 #301
				
Lat=-16.2663 Lon=141.917	Lat=-18.8817 Lon=23.598	Lat=-17.5573 Lon=46.5038	Lat=12.8954 Lon=9.2416	Lat=-19.4853 Lon=137.1787

4 RESULTS

4.1 PRODUCT CONTENT & VISUAL INSPECTION OF GLOBAL MAPS

Global maps of the three GEOV2/PV variables (modes RT0 to RT6) and its respective Quality Indicators (RMSE, NOBS, LENGTH_BEFORE, LENGTH_AFTER) have been checked during the period under study (from August 2013, first date of RT6, to December 2014, last date of RT0) at 1/16 of its original resolution.

4.1.1 Product Value

Figure 4, Figure 5, Figure 6 show global maps of the PROBA-V GEOV2 LAI, FAPAR and FCOVER estimates for RT0 (left) and RT6 (right) modes. ANNEX II. Global Maps of PROBA-V Version 2 Products displays the global maps (one example per month) of the PROBA-V GEOV2 during the period under study for RT6 mode. All global maps of GEOV2 RT0 and RT6 can be found in the digital annex (see ANNEX XII. Digital Annex). The global maps show:

- As observed for SPOT/VGT GEOV2 [GIOGL1_QAR_LAI1km-VGT-V2_I2.00], no missing values in the products were found, which is a clear improvement regarding previous GEOV1 version.
- Consistent distribution of values was found, without finding suspicious patterns for all the dates.

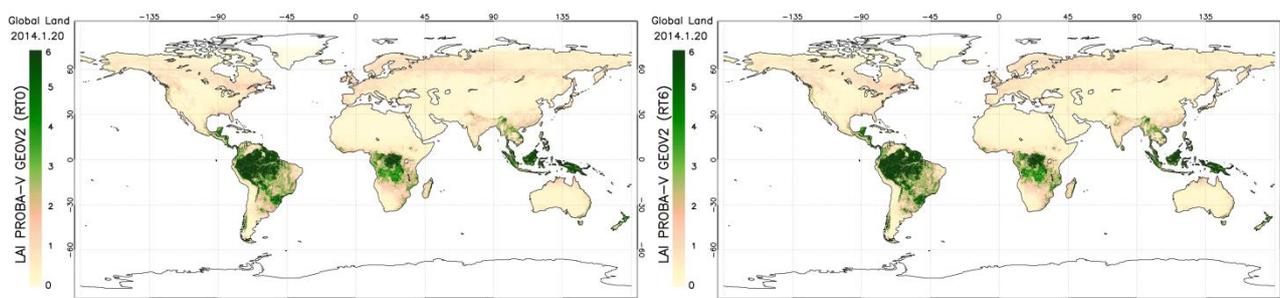


Figure 4: PROBA-V GEOV2 LAI global map for January 20th, 2014. Left: RT0. Right: RT6.

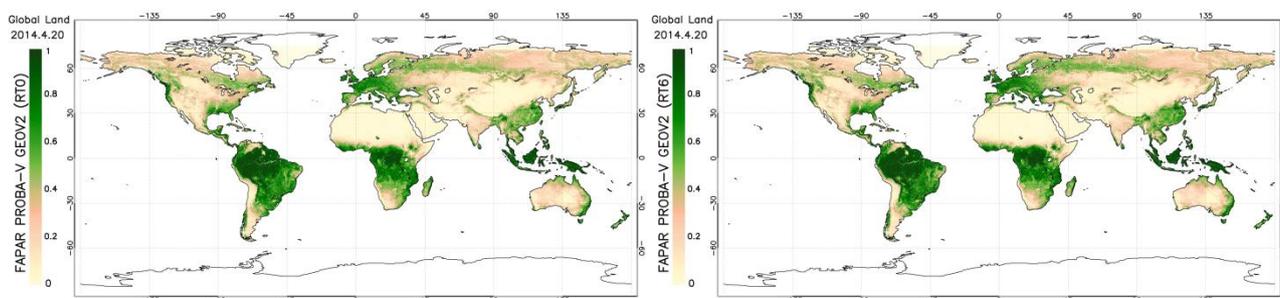


Figure 5: PROBA-V GEOV2 FAPAR global for April 20th, 2014. Left: RT0. Right: RT6.

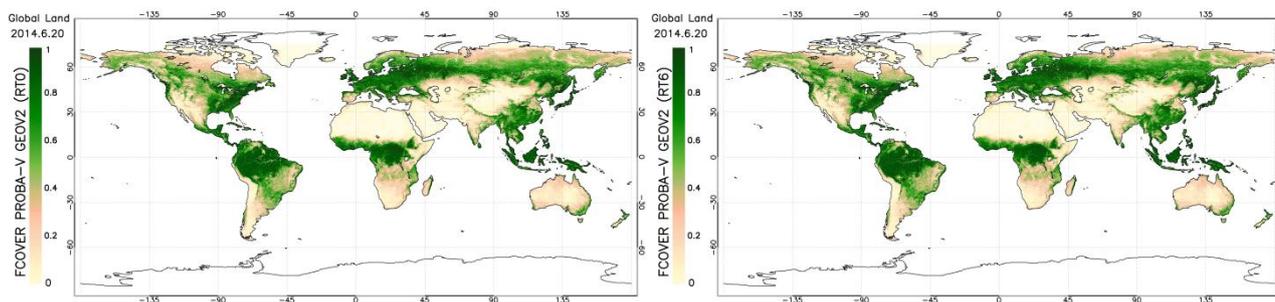


Figure 6: PROBA-V GEOV2 FCOVER global map for June 20th, 2014. Left: RT0. Right: RT6.

4.1.2 Quality Indicators

- **RMSE**

Global maps of the RMSE estimation for LAI, FAPAR and FCOVER PROBA-V GEOV2 (see section 3.2.1) have been checked for the whole period under study (all modes) and compared with GEOV2/VGT during the overlap period. RMSE maps for RT0 and RT6 modes can be found in the digital annex (see ANNEX XII. Digital Annex). Figure 7 shows examples for LAI RMSE estimates from RT0 mode to RT6 mode. Figure 8 shows examples of RMSE difference maps (PROBA-V GEOV2 *versus* SPOT/VGT GEOV2) for the three variables. For a better quantitative interpretation, scatter-plots of RMSE PROBA-V vs RMSE SPOT/VGT over BELMANIP-2 sites per month can be found in the Digital Annex.

These results show:

- Very similar RMSE estimations were observed for all modes. Slightly higher RMSE estimates for RT6 as compared to RT0 is appreciated locally over some areas where the RMSE is larger than 0.4 (e.g. Africa, South America)
- Missing values corresponds to filled values (bit 3 of QFLAG activated). Note that higher amount of missing values was found for RT0 as compared to RT6, as expected due to the higher number of available observations in RT6.
- Consistent values of PROBA-V GEOV2 RMSE estimates as compared to SPOT/VGT GEOV2 RMSE. GEOV2/PV RMSE displays higher values than GEOV2/VGT RMSE over densest vegetation areas, such as Amazonian forest or Central Africa for the three variables. In some cases, SPOT/VGT provides locally higher RMSE values than PROBA-V (e.g., FCOVER in Europe)

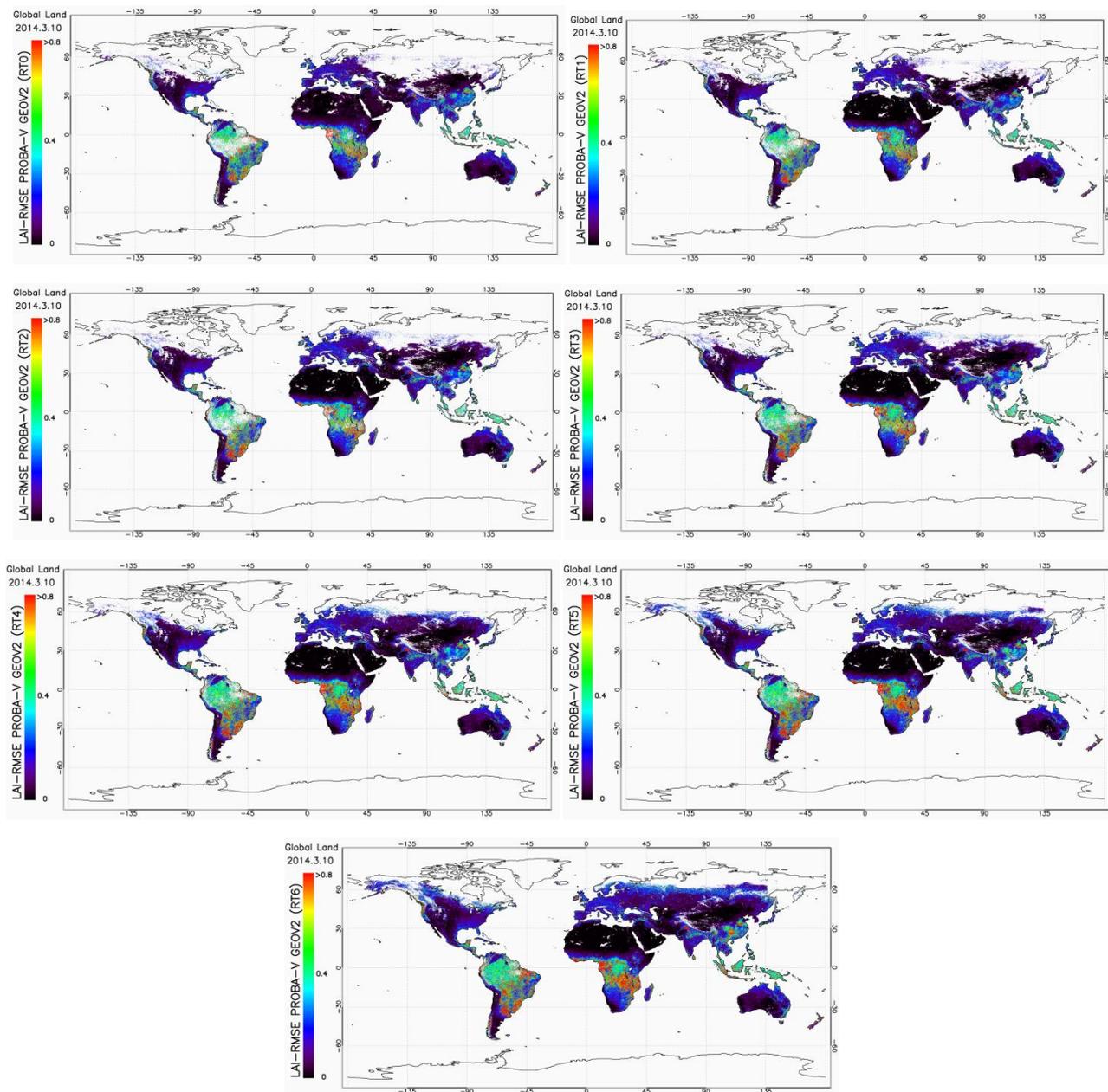


Figure 7: PROBA-V GEOV2 LAI RMSE maps for March 10th, 2014. Modes from RT0 to RT6 are displayed.

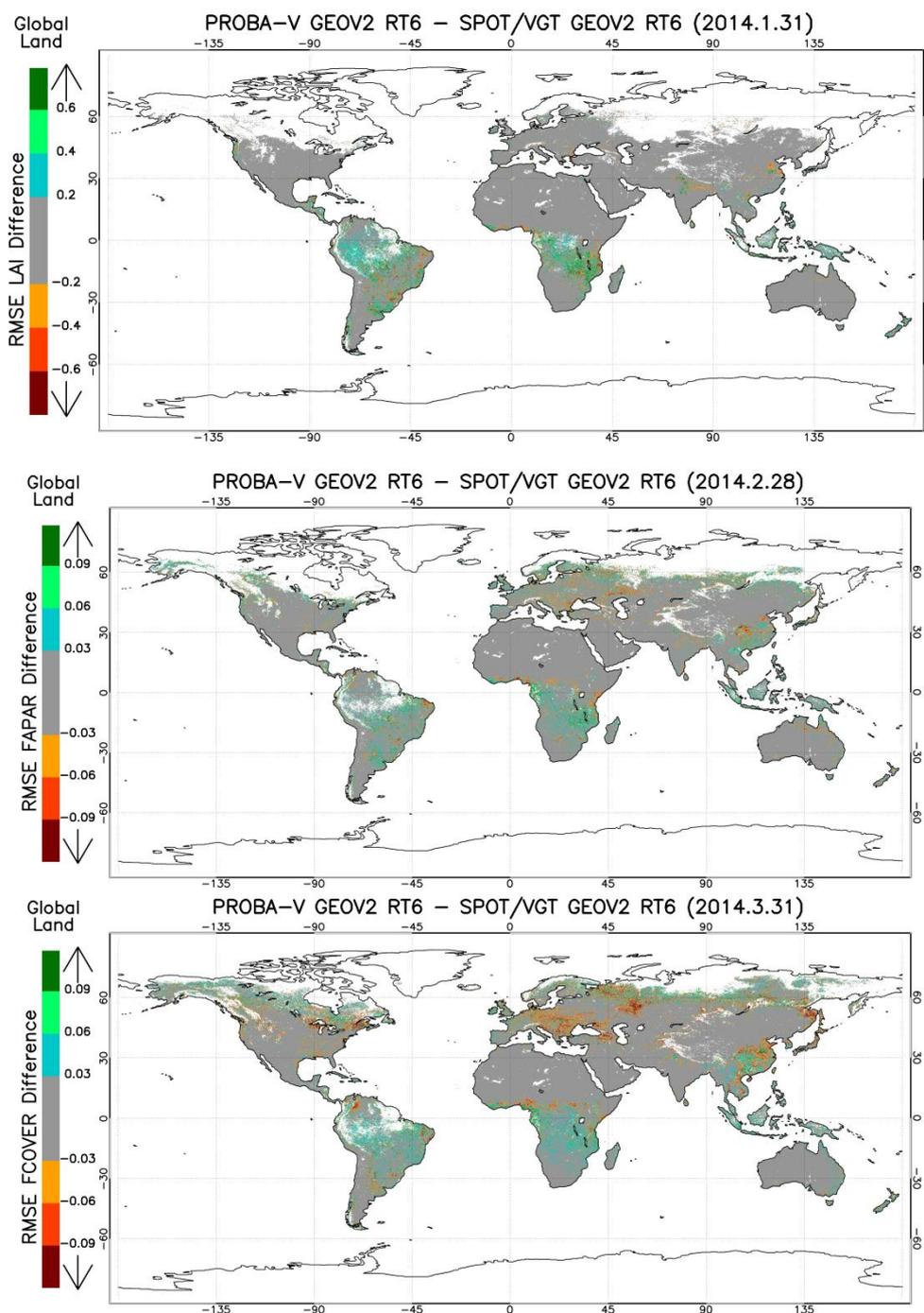


Figure 8: PROBA-V - SPOT/VGT RT6 RMSE maps for different dates. LAI RMSE 31.01.2014 (top), FAPAR RMSE 28.02.2014 (middle) and FCOVER RMSE 31.03.2014 (bottom).

- **NOBS, LENGTH_BEFORE & LENGTH_AFTER**

In this section, the number of daily observations used in the compositing (NOBS), and the length in days of the semi-period before (LENGTH_BEFORE) and after (LENGTH_AFTER) the decadal

date of the compositing window of GEOV2/PV products have been displayed for all modes and compared to the equivalent GEOV2/VGT layers. Figure 9-top shows an example of NOBS for RT0 and RT6 modes. To better display the differences between PROBA-V and SPOT/VGT the corresponding difference maps of NOBS are also displayed (Figure 9 bottom). Figure 10 shows the LENGTH_BEFORE and LENGHT_AFTER fields for RT0 and RT6 modes. To assess the consistency with SPOT/VGT difference maps of both fields (LENGHT_BEFORE, LENGHT_AFTER) are shown in Figure 11. Moreover, NOBS, LENGTH_BEFORE and LENGHT_AFTER scatter-plots between PROBA-V and SPOT/VGT over BELMANIP-2 sites has been computed for RT0 and RT6 modes at a monthly frequency (see ANNEX XII. Digital Annex).

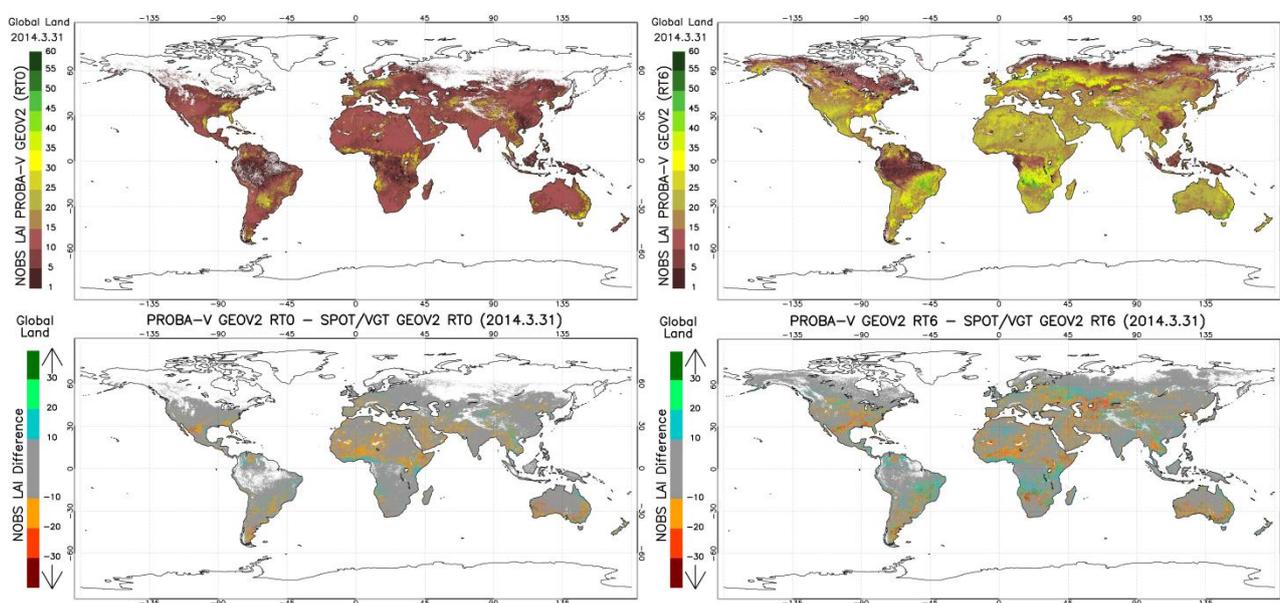


Figure 9: PROBA-V GEOV2 NOBS global maps (Top) and PROBA-V- SPOT/VGT NOBS global maps (Bottom) for 31th March, 2014. Left: RT0 mode. Right: RT6 mode. Gaps correspond to NOBS=0.

- The NOBS quality indicator of GEOV2/PV was generally found consistent to that of SPOT/VGT observations, with differences typically ranging between ± 10 observations (Figure 9). However, some regions depicted higher differences up to ± 20 observations mainly for RT6 with longer composite periods than RT0. PROBA-V tends to provide lower NOBS than SPOT/VGT over arid regions (e.g., Sahara desert). Note that white colour correspond to NOBS=0 (i.e., missing values in the product field. In these cases where NOBS=0, the bit 3 of the QFLAG (filled values) is activated. As expected, RT6 mode shows greater number of observations than RT0.
- The spatial pattern of semi-periods is consistent with NOBS maps. Consistent values with SPOT/VGT are observed globally (differences typically between ± 10) showing higher differences over some regions. We identified an issue with LENGTH_AFTER RT0 that should be equal to 60 (Figure 10, top-right) and identical for PROBA-V or SPOT/VGT input

data (Figure 11, top right). This issue was fixed, and the disseminated GEOV2 PROBA-V product delivers the correct LENGTH-AFTER RT0 value (globally equal to 60) and identical to that of GEOV2 SPOT/VGT).

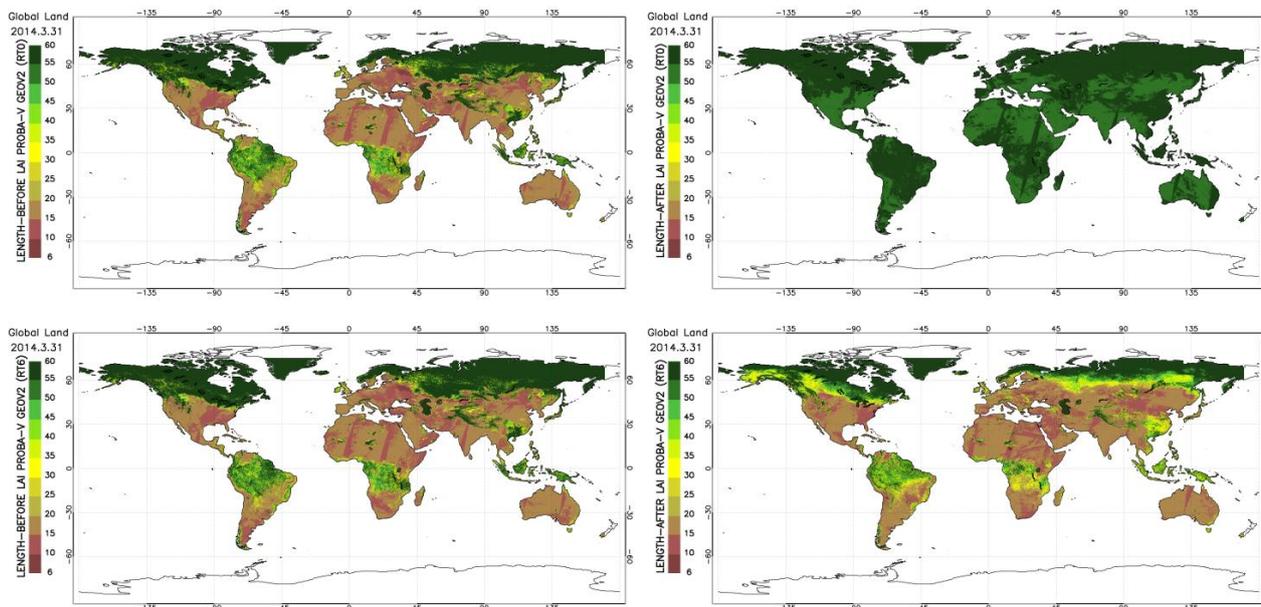


Figure 10: PROBA-V GEOV2 LENGTH_BEFORE (left) and LENGTH_AFTER global maps (right) global maps for 31th March, 2014. Top: RT0 mode. Bottom: RT6 mode.

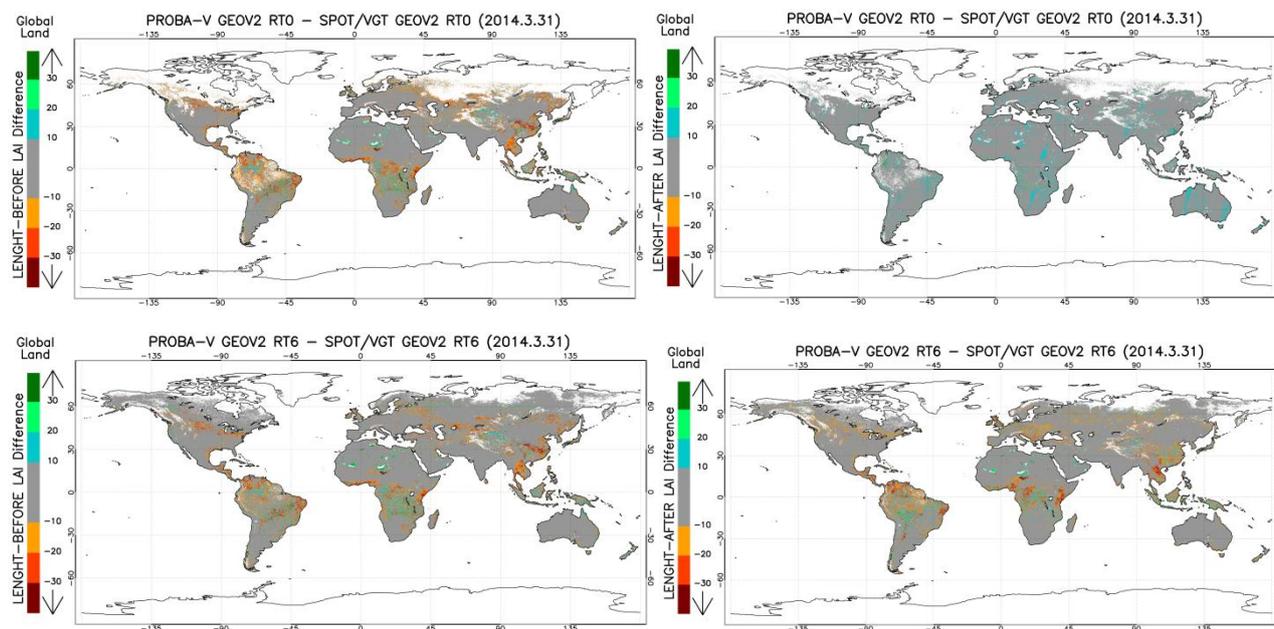


Figure 11: PROBA-V – SPOT/VGT LENGTH_BEFORE (left) and LENGTH_AFTER global maps (right) global maps for 31th March, 2014. Top: RT0 mode. Bottom: RT6 mode.

4.2 PRODUCT COMPLETENESS & QUALITY FLAG ANALYSIS

As observed for SPOT/VGT GEOV2 [GIOGL1_QAR_LAI1km-VGT-V2_I2.00]), GEOV2/PV shows almost complete coverage over land pixels, as a result of the temporal smoothing and gap filling techniques applied in Version 2 algorithm. Then, the spatio-temporal distribution of filled pixels was analysed by the activation of the bit3 of the QFLAG. The Bit 3 of the Quality Flag indicates if a pixel was filled. This Bit is set to 1 (filled) if the number of valid observations at (at least) one side (the left side in the NRT case) of the ± 60 -day period is lower than 6 and a gap filling procedure is applied.

Figure 12 displays the activation of bit 3 for a selected date in February of 2014 (typically example of large fraction of gap filling activation in winter time of north hemisphere) for PROBA-V GEOV2 RT0 (left) and RT6 (right) mode. The temporal evolution of the activation of the bit 3 of the QFLAG of PROBA-V GEOV2 is displayed in Figure 13 for RT0 and RT6 modes. Here, the temporal evolution of the activation of bit 3 was also compared to that of GEOV2/VGT RT6.

Figure 14 shows the percentage of filled pixels (activation of Bit 3) over the globe during one year period for PROBA-V GEOV2 LAI RT0 and RT6, showing the equator percentages up to 100% whereas northern latitudes shows around 50% of filled observations during the study period. The other variables show almost identical distribution and percentages of filled pixels. The annual and monthly maps of percentage of gap filled observations for LAI, FAPAR, FCOVER for RT0 and RT6 modes are available in the digital annex (see ANNEX XII. Digital Annex).

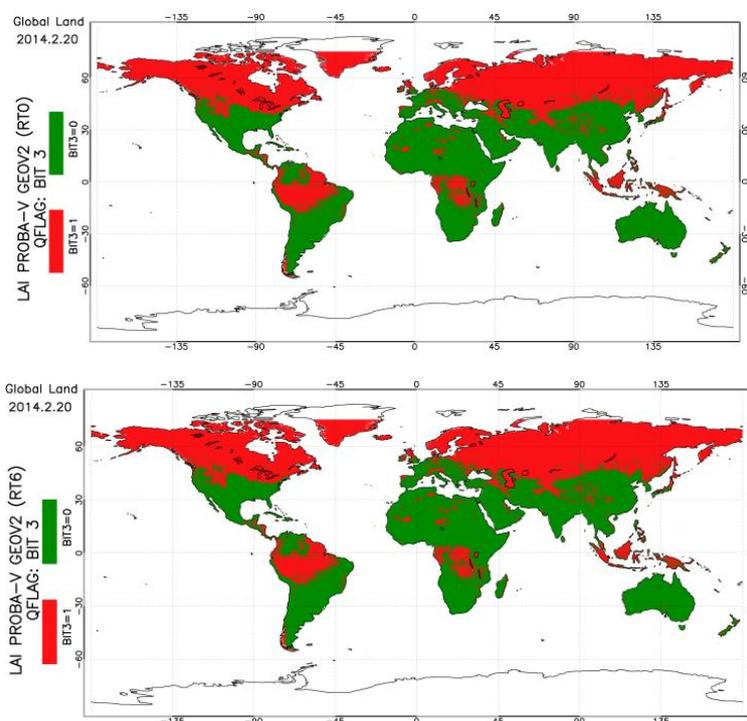


Figure 12: Map of the Quality Flag activation of Bit 3 (1=Filled, red / 0=No filled, green) of LAI GEOV2/PV for February20th, 2014. Left: RT0. Right: RT6.

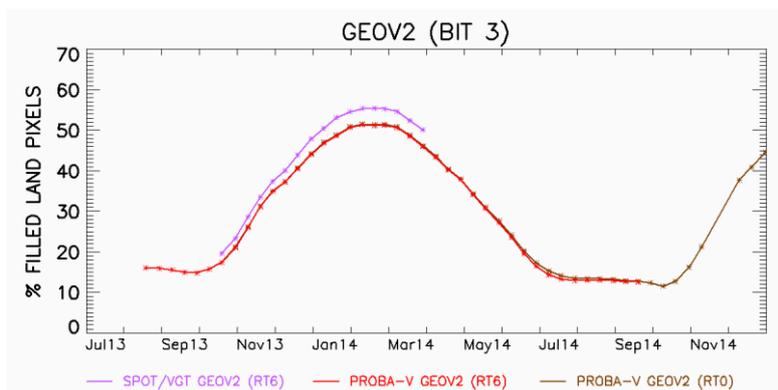


Figure 13: Temporal evolution of the activation of Bit 3 (Filled) during July 2013 to December 2014 for PROBA-V GEOV2 LAI (RT0 and RT6) and SPOT/VGT GEOV2 LAI (RT6). Percentages computed over Land pixels.

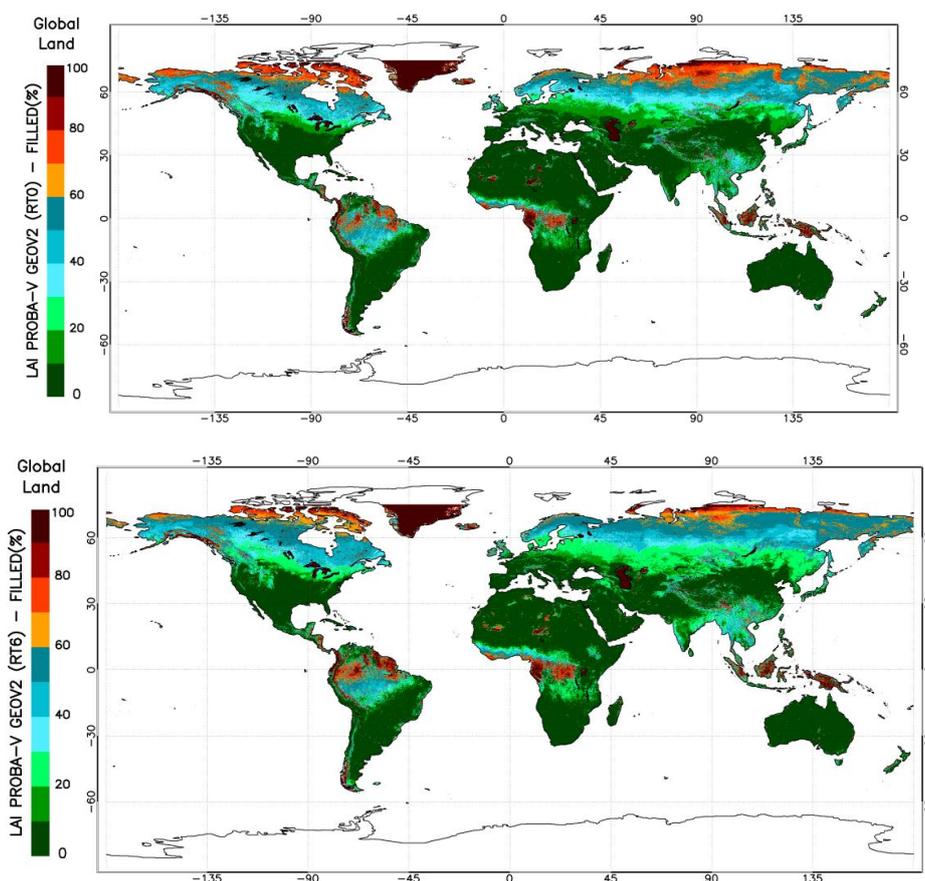


Figure 14: Percentage of gap filled pixels (activation of Bit 3) for PROBA-V GEOV2 LAI RT0 (Top) and RT6 over one year. This information is provided for LAI, FAPAR and FCOVER in the digital annex (see ANNEX XII. Digital Annex).

Figure 15 shows the temporal length of consecutive gap filled observations for the LAI products (almost identical results for the other two variables) over BELMANIP2.1 sites and one year period. The most frequent case is one consecutive filled observation with around 15% of cases. From 50 days to 200 days of consecutive gap filling, the frequency of cases ranges between 3% and 7% and then decreases to less than 1% for 270 days or longer periods.

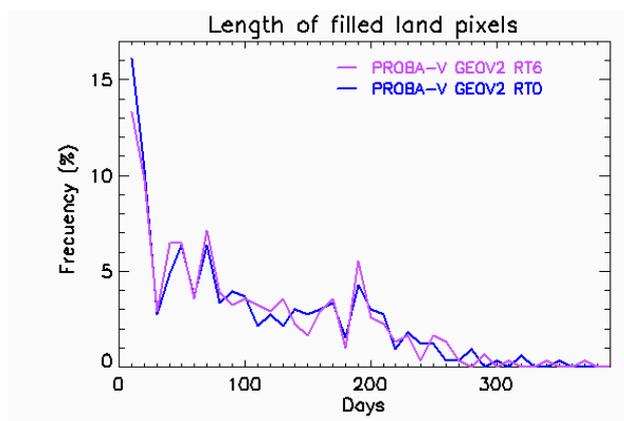


Figure 15: Temporal length of gap filled (activation of Bit 3) retrievals for PROBA-V GEOV2 LAI RT6 and RT0 over one year.

These results show:

- Almost identical global distributions of gap filled values were found for all modes (see Figure 12 and Figure 14 for RT0 and RT6). The activation of bit 3 is mainly located over the equatorial belt and northern latitudes.
- SPOT/VGT GEOV2 provides larger amount of filled pixels than PROBA-V GEOV2 (Figure 13), with differences up to 5% in winter time in northern hemisphere.
- The fraction of filled observation for PROBA-V GEOV2 over one year shows percentages up to 100% over equatorial areas, and around 50% for northern latitudes.
- The length of consecutive gap filled observations is quite variable, with significant number of cases (~3-7%) ranging between 10 and 200 days.

4.3 SPATIAL CONSISTENCY

4.3.1 Visual inspection of zooms

In addition to the visual inspection of global maps, zooms over sub-continental areas of PROBA-V GEOV2 products were displayed and analyzed at a full resolution. Figure 16 shows examples of full-resolution images for the PROBA-V GEOV2 FAPAR product for RT6 mode, and indicates:

- Smooth spatial distribution of the FAPAR was observed in all the regions, without observing any spatial artefact. Same conclusion applies for LAI and FCOVER.
- Consistent transitions were found over areas where GEOV2 algorithm uses specific treatment and corrects specific artefacts: see SOAM and AFRI where GEOV2 distinguishes

between EBF and other biomes, and ASIA where specific treatment is applied over northern latitudes (HLAT>50°).

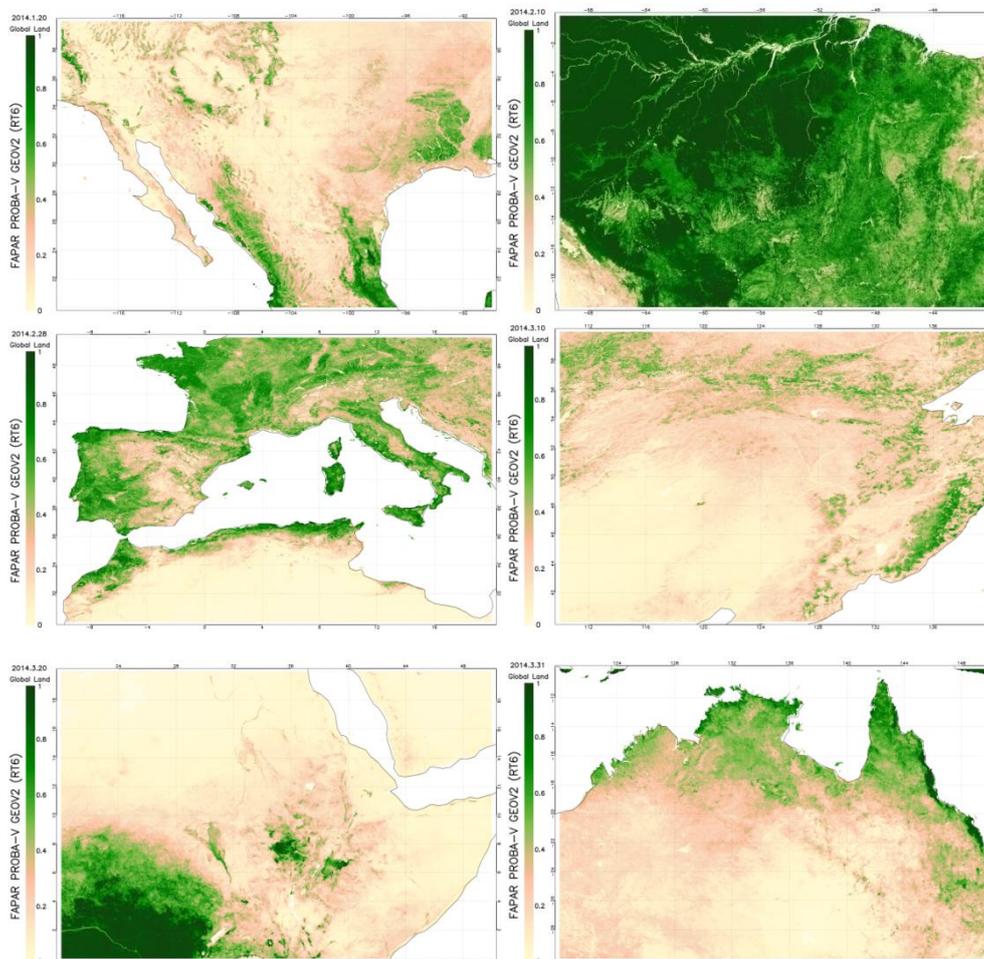


Figure 16: Maps of GEOV2 FAPAR (RT6) products at full resolution over regions of interest (20°x30°) located in NOAM, SOAM, EUR, AFRI, ASIA and OCE continental regions (see Figure 1). Different dates are shown for each zone.

4.3.2 Spatial Consistency between PROBA-V GEOV2 RT0 and RT6

- **Maps and histograms of Residuals**

Figure 17, Figure 18, Figure 19 show global maps of residuals between PROBA-V GEOV2 RT0 and RT6 modes for LAI, FAPAR and FCOVER respectively, and maps of the percentage of residuals beyond the optimal level of consistency (± 0.5 for LAI, ± 0.05 for FAPAR and FCOVER). Two different dates have been selected to illustrate differences during winter and summer time in north hemisphere. Additional maps of residuals (one per month) can be found in Annex III.

Both residual maps and percentage of values beyond optimal levels can be also found in the Digital Annex (see ANNEX XII. Digital Annex). Finally, the histograms of the residuals during one

year of data (from October 2013 to September 2014) between RT0 and RT6 modes at monthly base are also shown in Figure 20. Here two cases have been displayed: all land pixels are considered (top), and only non-filled values were considered (bottom).

These results indicate that:

- RT0 and RT6 are spatially consistent over large areas of the globe, with most of pixels lying in optimal levels (i.e., residuals between ± 0.5 for LAI and between ± 0.05 for FAPAR and FCOVER) over large areas.
- Spatial discrepancies larger than ± 0.5 LAI units or ± 0.05 FAPAR or FCOVER are however observed over some areas and periods (e.g., Northern latitudes, East Asia) without detecting systematic spatial patterns in the three variables. For LAI, however, RT0 tends to provide larger negative residuals (RT0<RT6) although the opposite trend (positive residuals) is also observed over some regions or periods. The percentage of residuals estimates lower than -0.05 is up 40% in vegetated areas around the world, whereas for positive residuals higher than 0.05, the number of cases is much lower. For FAPAR and FCOVER, the percentage of residuals beyond the optimal levels is more similar for positive and negative residuals.
- Histograms of residuals are centered at zero, with a slightly greater amount of pixels towards negative sign for LAI (RT0 < RT6).
- 94% of residuals over the globe are ranging between ± 0.5 for LAI, and 89% between ± 0.05 for FAPAR and FCOVER, considering one year of data. This percentage decrease only around 1% when "filled" pixels are removed.

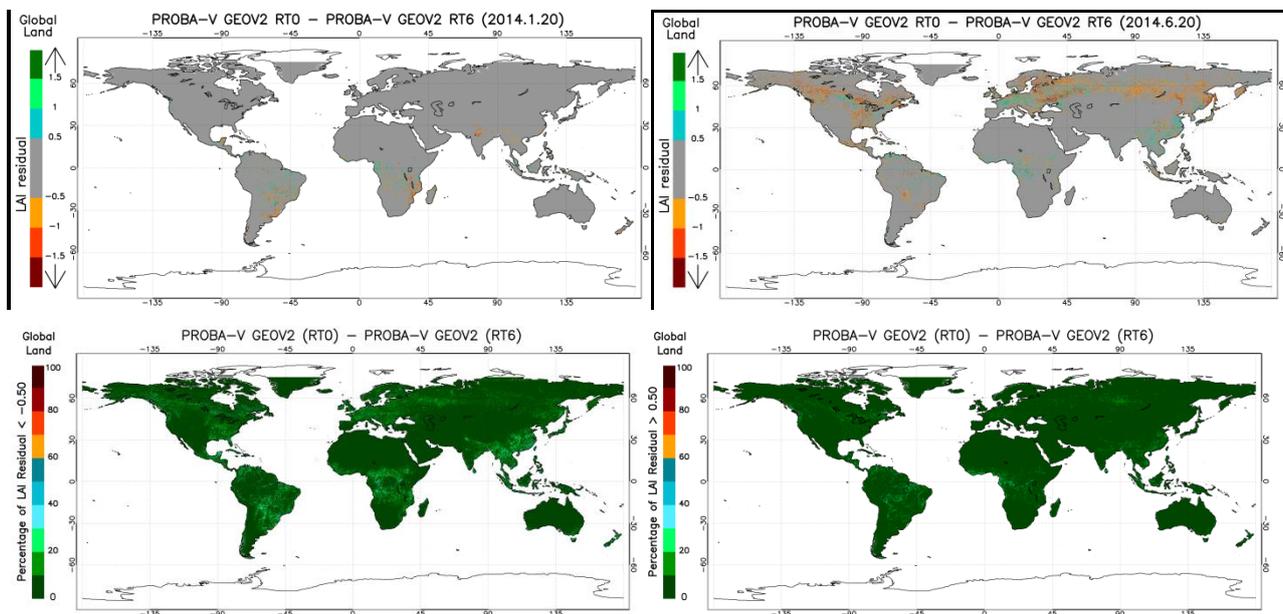


Figure 17: LAI residual map between PROBA-V GEOV2 RT0 and RT6 modes for 20th January, 2014 (top left) and 20th June, 2014 (top right). Percentage of residuals lower than -0.05 (bottom left) and higher than 0.05 (bottom right)

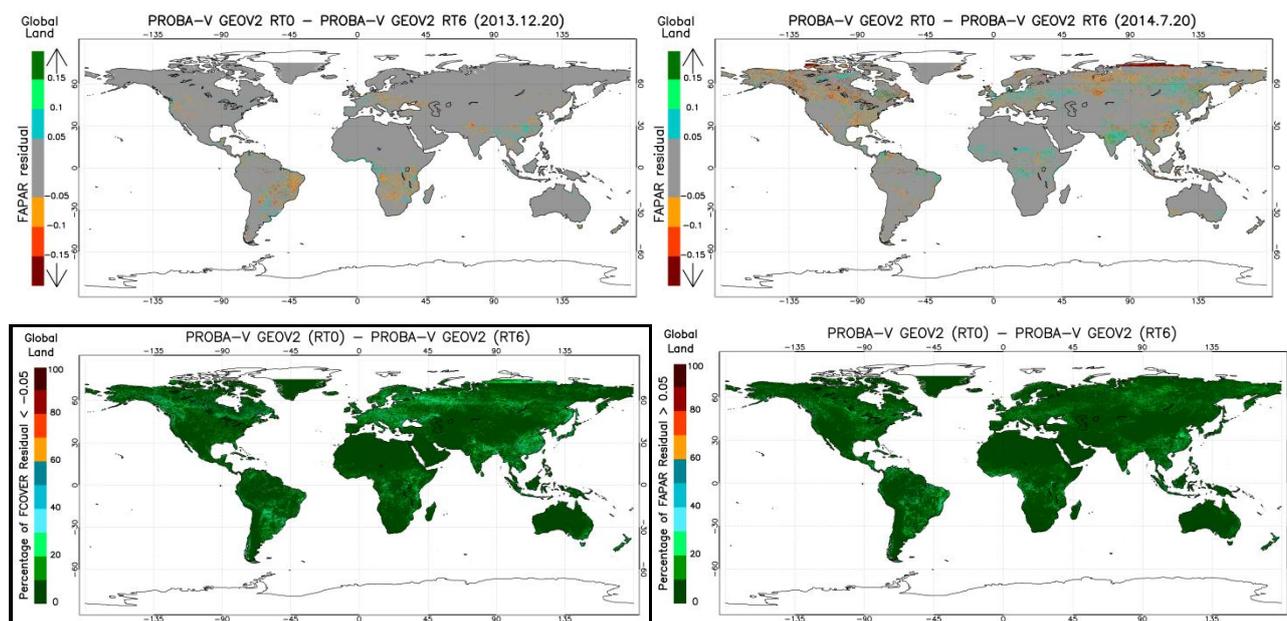


Figure 18: FAPAR residual map between PROBA-V GEOV2 RT0 and RT6 modes for 20th December, 2013 (top left) and 20th July, 2014 (top right). Percentage of residuals lower than -0.05 (bottom left) and higher than 0.05 (bottom right)

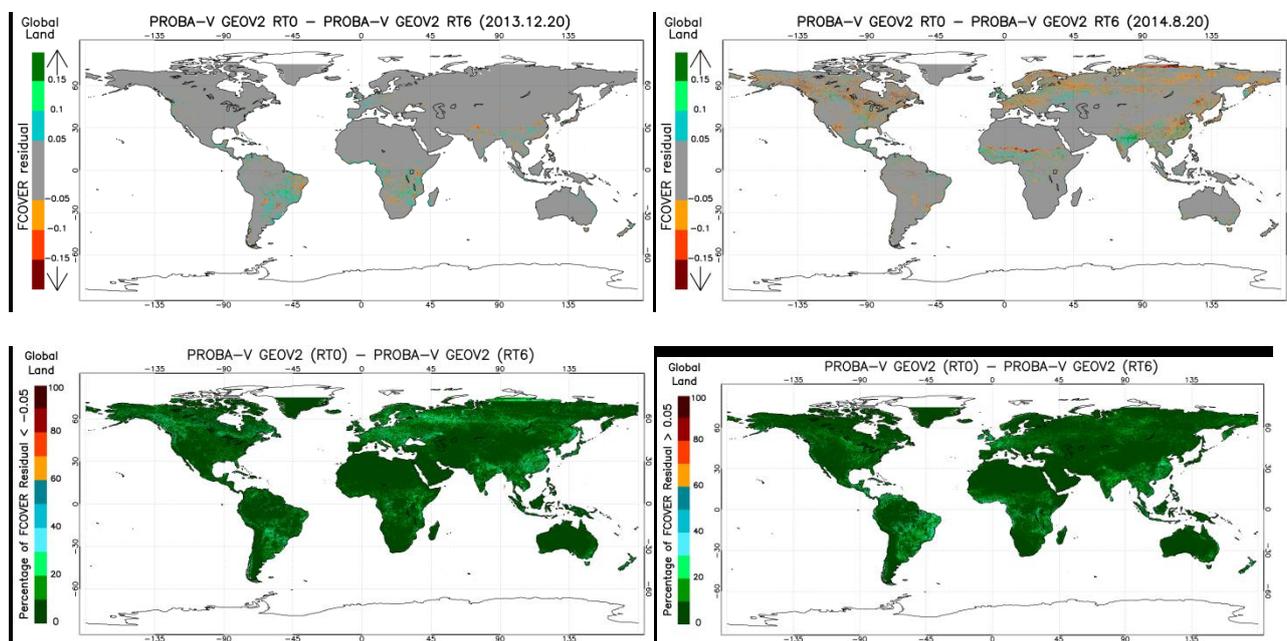


Figure 19: FCOVER residual map between PROBA-V GEOV2 RT0 and RT6 modes for 20th December, 2013 (top left) and 20th August, 2014 (top right). Percentage of residuals lower than -0.05 (bottom left) and higher than 0.05 (bottom right)

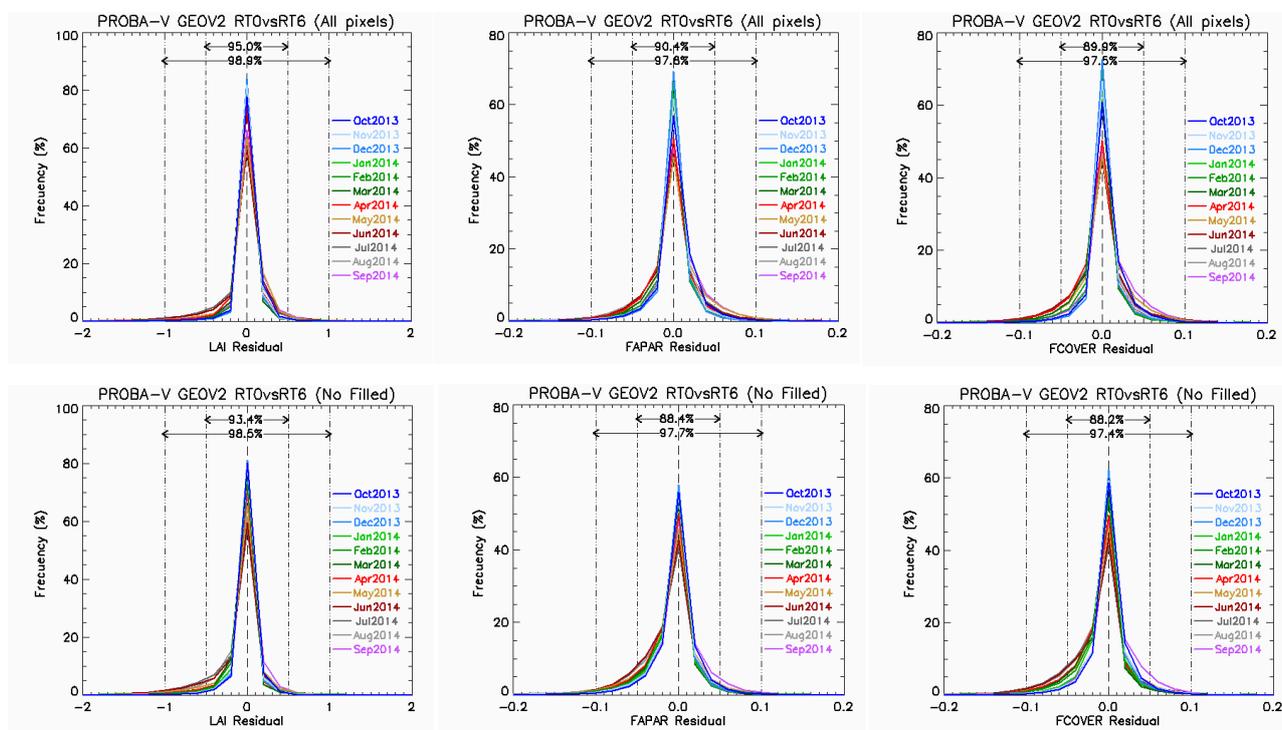


Figure 20: Histograms of residuals between RT0 and RT6 modes of PROBA-V GEOV2 LAI, FAPAR and FCOVER per month from October 2013 to September 2014. Top: All global land pixels are computed. Bottom: Non-Filled pixels (bit 3 of QGLAG removed).

4.3.3 Spatial Consistency between PROBA-V GEOV2 and SPOT/VGT GEOV2

- **Maps and histograms of Residuals**

The spatial consistency of PROBA-V GEOV2 (RT6) as compared to SPOT/VGT GEOV2 products during the overlap period (30thSeptember-March) was evaluated in order to analyze the impact in the GEOV2 output of the change of input data from SPOT/VGT to PROBA-V. This is a crucial aspect for the continuity of the time series. Figure 21, Figure 23 and Figure 25 show the residual maps and global distribution of residuals as a function of the predefined uncertainty levels for LAI, FAPAR and FCOVER during the three decades (one per product) of March (dates where higher discrepancies were found). In addition, maps with the percentage of cases lying within optimal level of consistency are displayed for each variable. ANNEX IV shows the residuals global maps (one example per month) between GEOV2/PV and GEOV2/VGT products for the overlap period. Residuals maps and percentage of residuals beyond and within optimal levels can be also found in the digital annex (see ANNEX XII. Digital Annex). Histograms of residuals at monthly basis period and the percentage of the residuals laying the uncertainty levels are displayed in Figure 22, Figure

24 and Figure 26. Finally, the percentage of residuals laying the uncertainty levels without considering "filled pixels" are displayed in Figure 27.

The main findings of this section over the overlap period (October-March) are:

- PROBA-V and SPOT/VGT GEOV2 LAI products are in overall spatially consistent, with histograms of residuals showing narrow distributions centered at zero with more than 95% of residuals ranging between ± 0.5 . More than 97% of residuals are matching the GCOS requirements, with very low values (~1%) showing poor consistency. However, the overlap period corresponds to the fall and winter period in the north hemisphere (low vegetation activity), and spatial inconsistencies were observed over regions of the south hemisphere. The percentage of cases within optimal consistency during the overlap period is typically 50-60% over south hemisphere regions, whereas in northern hemisphere is typically 100% (see below)
- For LAI, main spatial discrepancies were found over Africa (deciduous forest areas) and South of America (cultivated areas), with residuals ranging typically between 0.5 and 1.5 LAI units in large regions (see Regional Analysis in Section 4.7). These areas present the vegetation activity season during the period under study. This is further analysed in section 4.6.2.
- For FAPAR and FCOVER, PROBA-V and SPOT/VGT GEOV2 products were found also spatially consistent over most of regions and dates, with residuals typically ranging between ± 0.05 over large areas, and larger discrepancies are in many cases randomly distributed. Percentage of cases within optimal levels is ranging between 60% and 100% around the world. In overall, around 89% and 90% of FAPAR and FCOVER residuals fulfil optimal consistency according to GCOS accuracy requirements (max: 0.05, 10%) along the studied period.
- For FAPAR and FCOVER, however, over some regions of Africa, South America and East Asia (with larger values of FAPAR and FCOVER, except EBF where consistent values are provided), larger residuals up to ± 0.15 were found. Similar to the largest differences observed for GEOV1 FAPAR and FCOVER products.
- For FCOVER, better spatial consistency was found than in the comparison between GEOV1 PROBA-V and SPOT/VGT products, where a systematic positive bias for FCOVER was observed for high values.
- For non-filled values the percentage of residuals matching GCOS requirements levels are almost identical (~1% less).

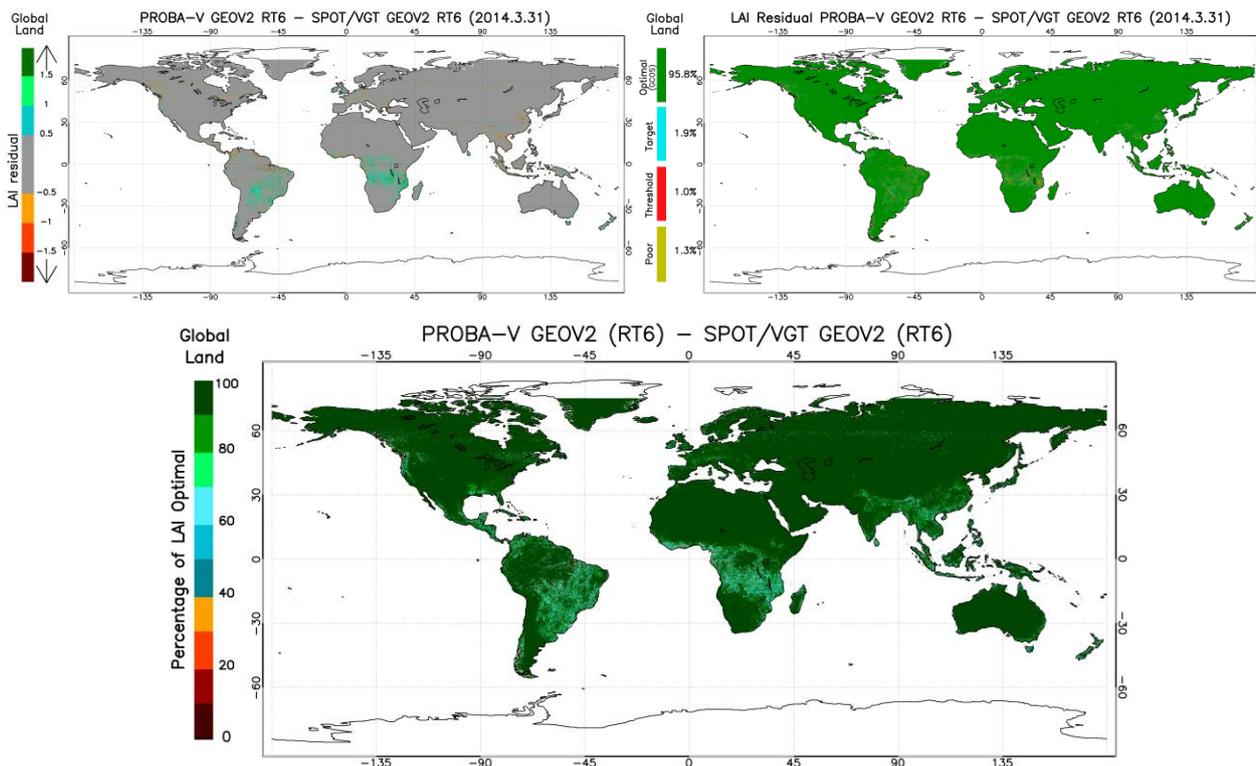


Figure 21: LAI residual map (top left) and global distribution of residuals laying the optimal (GCOS), target and threshold levels of consistency (top right) between PROBA-V GEOV2 and SPOT/VGT GEOV2 (RT6 mode) for 31th March, 2014. Bottom: Percentage of cases within optimal consistency levels during the overlap period (October 2013 to March 2014).

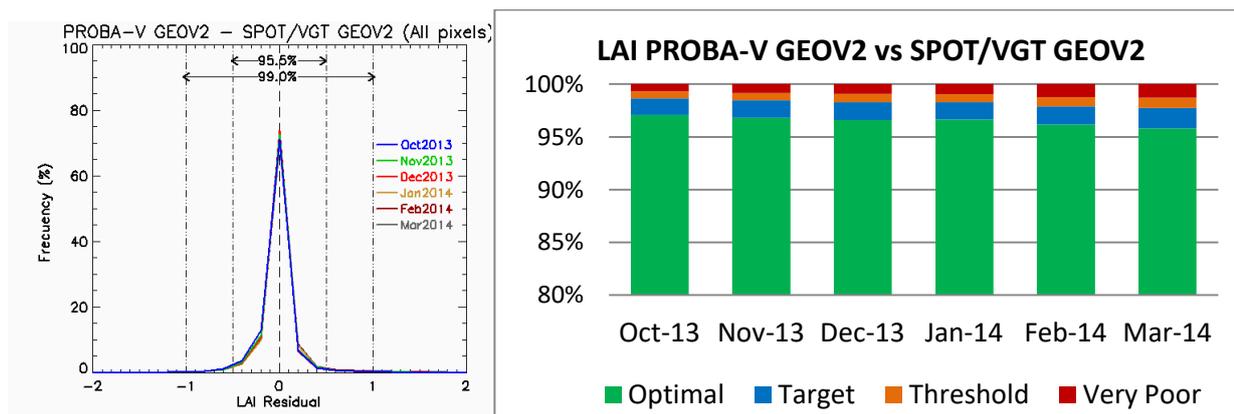


Figure 22: Histogram of residuals per month from October 2013 to March 2014 between LAI PROBA-V GEOV2 and SPOT/VGT GEOV2 products (mode RT6) (left side). Percentage of residuals laying the optimal (GCOS), target and threshold levels of consistency (right side).

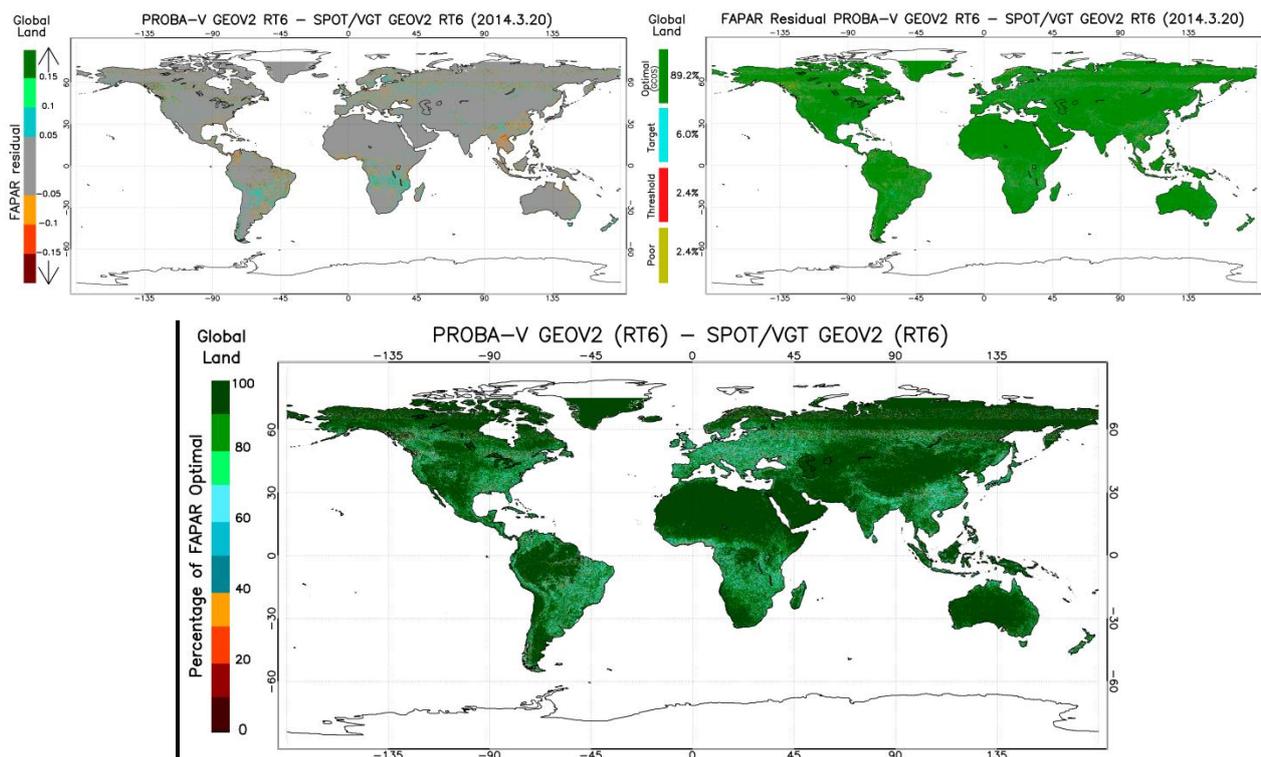


Figure 23: FAPAR residual map (top left) and global distribution of residuals lying the optimal (GCOS), target and threshold levels of consistency (top right) between PROBA-V GEOV2 and SPOT/VGT GEOV2 (RT6 mode) for 20th March, 2014. Bottom: Percentage of cases within optimal consistency levels during the overlap period (October 2013 to March 2014).

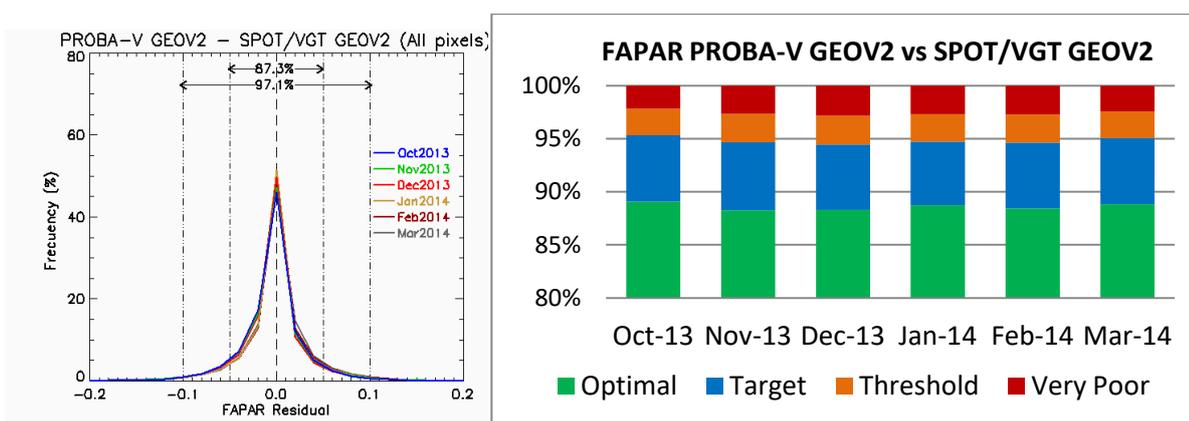


Figure 24: Histogram of residuals per month from October 2013 to March 2014 between FAPAR PROBA-V GEOV2 and SPOT/VGT GEOV2 products (mode RT6) (left side). Percentage of residuals laying the optimal (GCOS), target and threshold levels of consistency (right side).

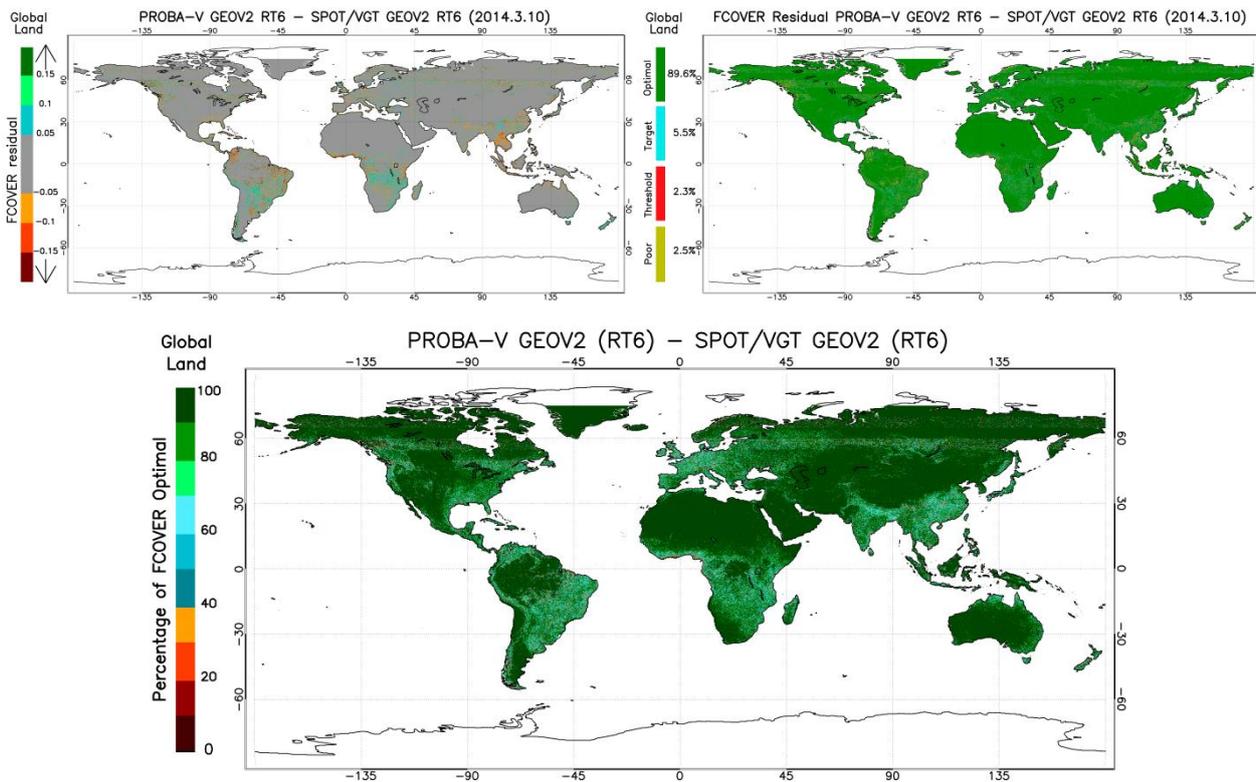


Figure 25: FCOVER residual map (top left) and global distribution of residuals laying the optimal, target and threshold levels of consistency (top right) between PROBA-V GEOV2 and SPOT/VGT GEOV2 (RT6 mode) for 10th March, 2014. Bottom: Percentage of cases within optimal consistency levels during the overlap period (October 2013 to March 2014).

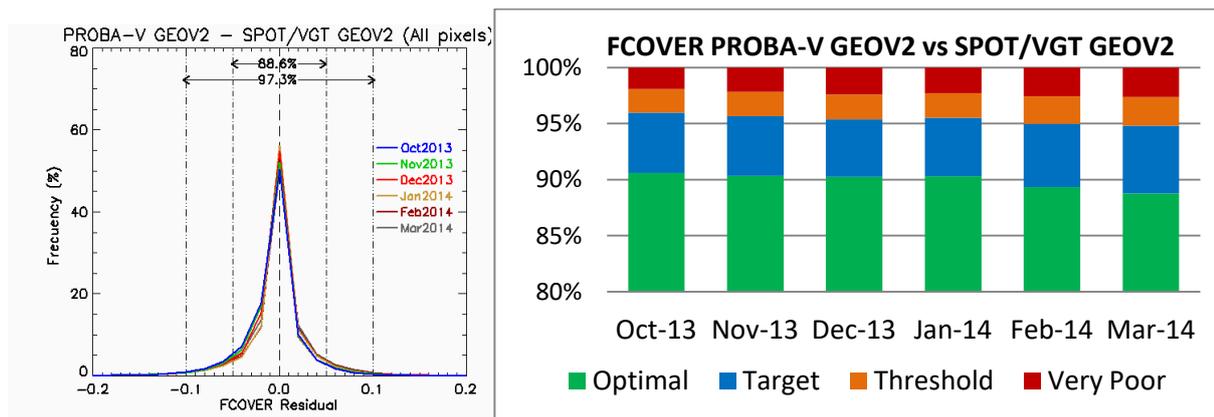


Figure 26: Histogram of residuals per month from October 2013 to March 2014 between FCOVER PROBA-V GEOV2 and SPOT/VGT GEOV2 products (mode RT6) (left side). Percentage of residuals laying the optimal, target and threshold levels of consistency (right side).



Figure 27: Percentage of residuals between PROBA-V GEOV2 and SPOT/VGT GEOV2 products (mode RT6) laying the optimal (LAI and FAPAR GCOS), target and threshold levels of consistency during the October'13-March'14 period for LAI (Top), FAPAR (Middle) and FCOVER (Bottom). Pixels flagged as "Filled value" have been removed of the computation.

- **Spatial Autocorrelation**

Table 12 shows the maps of LAI PROBA-V GEOV2 and SPOT/VGT GEOV2 products over the 15 selected BELMANIP2.1 sites (50kmx50km, see section 3.5), and their respective spatial indicators: Moran's Index (MI) corresponding to the spatial correlation and Coefficient of Variability (CV). The maps of the activation of the Bit 3 of the QFLAG are also displayed in order to identify possible dependency of the spatial variability with the activation of the gap filling method. The spatial correlation of FAPAR and FCOVER was also checked, providing very similar values of MI than the observed for LAI, for this reason only LAI is shown.

These results show:

- Positive spatial correlation (MI) was found in all cases for these homogeneous areas, with slightly higher results of SPOT/VGT than PROBA-V in most of cases. PROBA-V tends to provide generally higher spatial variability (CV) than SPOT/VGT, in agreement to that found between in previous validation exercises [GIOGL1_QAR_LAI1km-V1_I3.10].
- The lower spatial correlation was found for EBF, which are mainly filled retrievals. Very low spatial variability (CV) over these EBF homogeneous areas is obtained.
- In general, in the spatial autocorrelation, no difference between filled, non-filled or mixed (filled, non-filled) areas has been observed, which is a positive sign of the spatial consistency of the product.

Table 12: Maps of LAI and activation of "Gap Filling" method for GEOV2/PV and GEOV2/VGT over the 15 selected AOI of 50kmx50km in 2014.03.31 and the respective Spatial Indicators: Moran's Index (MI) and Coefficient of Variation (CV).

		LAI					
		B2.1#16	B2.1#18	B2.1#30	B2.1#46	B2.1#436	
EBF	GEOV2 /PV						 7 5 0 Filled (Red) No Filled (Green)
		MI= 0.31 CV=0.134	MI= 0.24 CV=0.092	MI= 0.16 CV=0.084	MI= 0.5 CV=0.121	MI= 0.61 CV=0.12	
	GEOV2 /VGT						
		MI= 0.33 CV=0.057	MI= 0.65 CV=0.09	MI= 0.11 CV=0.078	MI= 0.42 CV=0.07	MI= 0.54 CV=0.061	
DBF	GEOV2 /PV						 6 0 Filled (Red) No Filled (Green)
		MI= 0.75 CV=0.237	MI= 0.72 CV=0.693	MI= 0.63 CV=0.661	MI= 0.92 CV=0.293	MI= 0.86 CV=0.188	
	GEOV2 /VGT						
		MI= 0.84 CV=0.142	MI= 0.84 CV=0.447	MI= 0.73 CV=0.372	MI= 0.93 CV=0.315	MI= 0.89 CV=0.198	
Herb. /Shrub.	GEOV2 /PV						 3 0 Filled (Red) No Filled (Green)
		MI= 0.82 CV=0.153	MI= 0.75 CV=0.083	MI= 0.77 CV=0.205	MI= 0.37 CV=0.001	MI= 0.79 CV=0.144	
	GEOV2 /VGT						
		MI= 0.92 CV=0.173	MI= 0.88 CV=0.083	MI= 0.87 CV=0.198	MI= 0.54 CV=0.015	MI= 0.88 CV=0.146	

4.3.4 Spatial Consistency between PROBA-V GEOV2 and GEOV1/PV and MODIS reference products

- **PROBA-V GEOV2 vs PROBA-V GEOV1**

Figure 28, Figure 30 and Figure 32 show maps of residuals between PROBA-V GEOV2 and GEOV1 LAI, FAPAR and FCOVER products respectively. In addition, the percentage of cases within optimal levels for the studied period (one year) is also displayed. Two examples have been displayed for each variable: one for spring time in northern hemisphere and another at the end of summer time. The residual maps between both products can be found in Annex V during almost one year of data (November 2013- September 2014) as well as in the digital annex (see ANNEX XII. Digital Annex) along with the percentage of cases within or beyond optimal levels. The histograms of residuals at a monthly step as well as the percentage of residuals within the optimal, target and threshold uncertainty levels of consistency are also shown in Figure 29, Figure 31 and Figure 33 for LAI, FAPAR and FCOVER respectively.

- For LAI, PROBA-V GEOV2 and GEOV1 are over large areas spatially consistent, with differences lower than 0.05 for most of the pixels (85.3%). Larger spatial inconsistencies are observed over Equatorial Areas as expected, with GEOV2 showing higher values. In other regions (northern latitudes) as North America, Europe or East Asia negative residuals are observed (up to -2 LAI units) during the spring time (growing period), whereas slight positive residuals are observed at the maximum development (July, August), and important positive residuals (up to 2 LAI units) at the end of the season (September). In South America negative residuals are also observed during the growing season (December). The percentage of cases within optimal consistency levels on a pixel based is typically ranging between 50% and 100% (bare areas). Lower values are obtained only over few areas such as central Africa or northern latitudes.
- For LAI, typically more than 90% of residuals are lying within the GCOS accuracy requirements during winter time, with slightly lower percentages during spring and summer dates in northern hemisphere (~85%).
- For FAPAR, larger spatial inconsistencies were found with large negative and positive residuals up to ± 0.2 globally distributed, with larger areas showing negative residuals. As for LAI, the GEOV2/PV displays slight positive residuals mostly during the maximum development (Europe, Asia in July, August), and large positive residuals at the end of the season (September). The percentage of cases within optimal consistency levels shows between 50% and 100% (bare areas) but with some areas (e.g., Brazil, Canada, Siberia) showing lower than 30% of cases.
- Typically, between 70% and 80% of FAPAR residuals are matching the GCOS accuracy requirements.
- For the FCOVER, similar spatial discrepancies than for FAPAR are observed (ranging between -0.2 and +0.2) but more evenly distributed between positive and negative values.

The same seasonal pattern is observed. Spatial discrepancies observed over Sahara desert corresponds to a false seasonality depicted in GEOV1 FCOVER, which is corrected in GEOV2.

- Histograms of FCOVER residuals are wide and centred at zero and typically between 70% and 80% of them are within the optimal level of consistency.

In summary, discrepancies found between GEOV2/PV and GEOV1/PV are significant over large regions and shows a temporal dependency. These discrepancies may, in part, be attributed to the different input (daily TOC for GEOV2 vs normalized TOC for GEOV1) and the different compositing schemes. The seasonality observed in residuals deserves further investigation to determine which product provides more accurate results in each period.

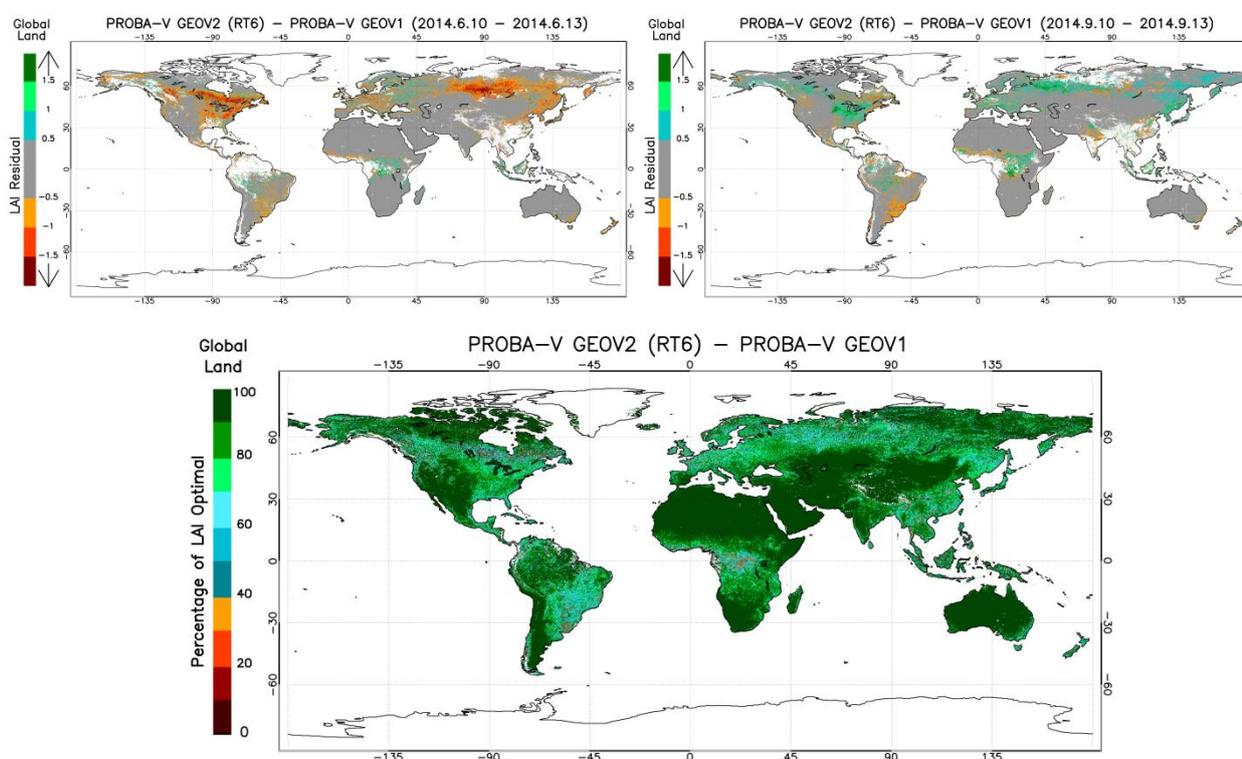


Figure 28: LAI residual map between PROBA-V GEOV2 and PROBA-V GEOV1 for 10th June, 2014 (top left) and for 10th September, 2014 (top right). Bottom: Percentage of cases within optimal consistency levels during the study period (October 2013 to September 2014).

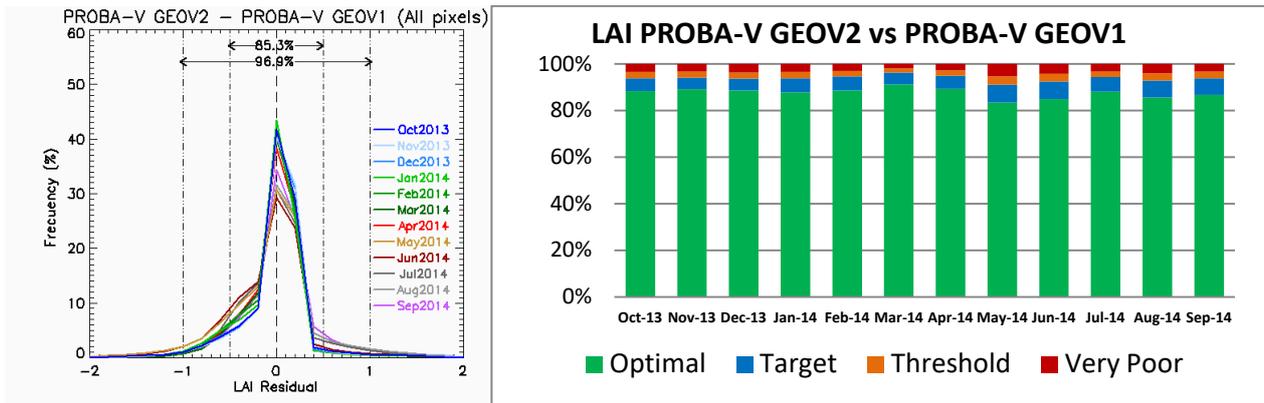


Figure 29: Histogram of residuals per month from October 2013 to September 2014 between LAI PROBA-V GEOV2 and PROBA-V GEOV1 products (left side). Percentage of residuals laying the optimal (GCOS), target and threshold levels of consistency (right side).

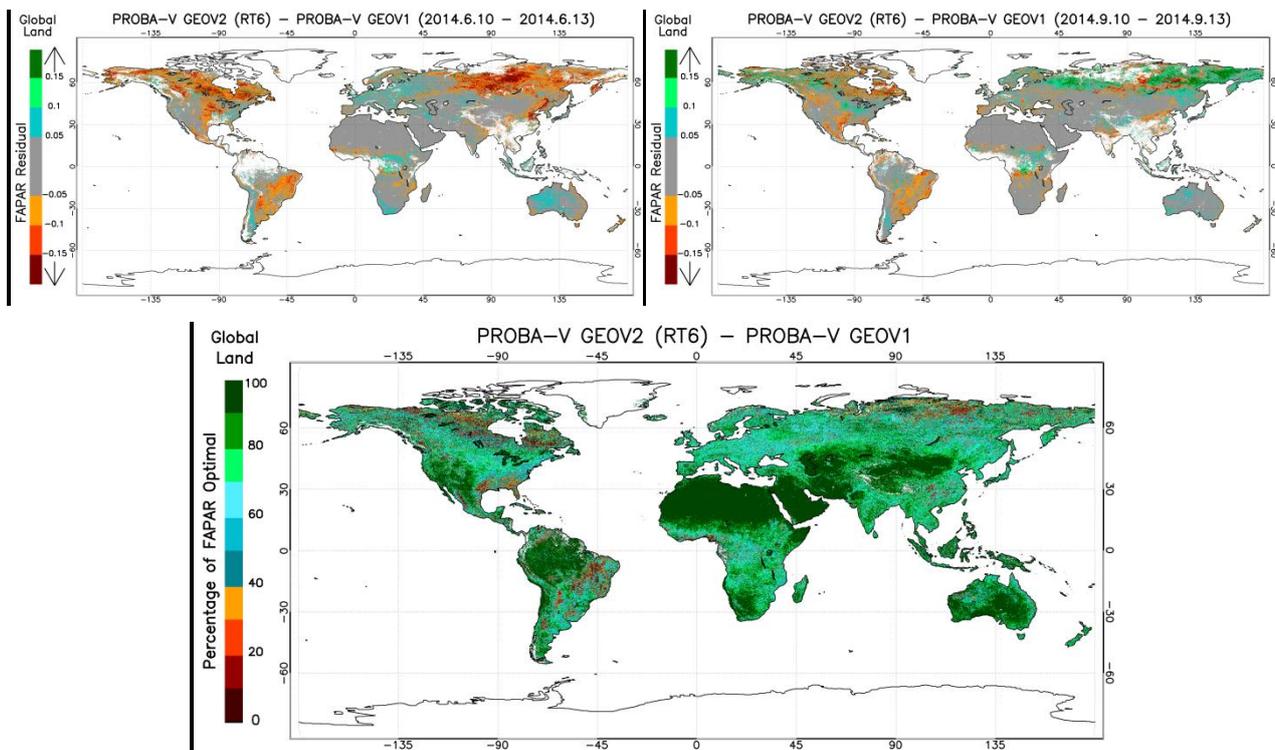


Figure 30: FAPAR residual map between PROBA-V GEOV2 and PROBA-V GEOV1 for 10th June, 2014 (top left) and for 10th September, 2014 (top right). Bottom: Percentage of cases within optimal consistency levels during the study period (October 2013 to September 2014).

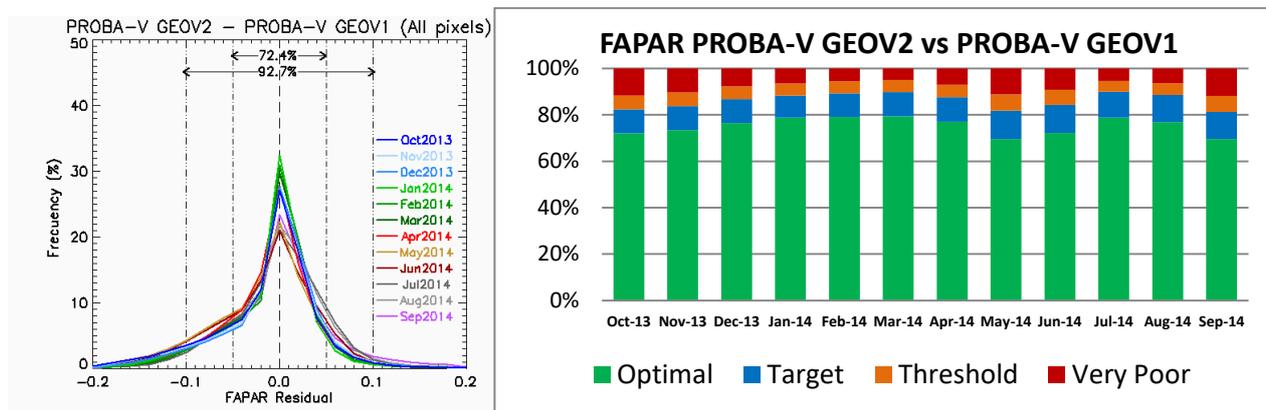


Figure 31: Histogram of residuals per month from October 2013 to September 2014 between FAPAR PROBA-V GEOV2 and PROBA-V GEOV1 products (left side). Percentage of residuals laying the optimal (GCOS), target and threshold levels of consistency (right side).

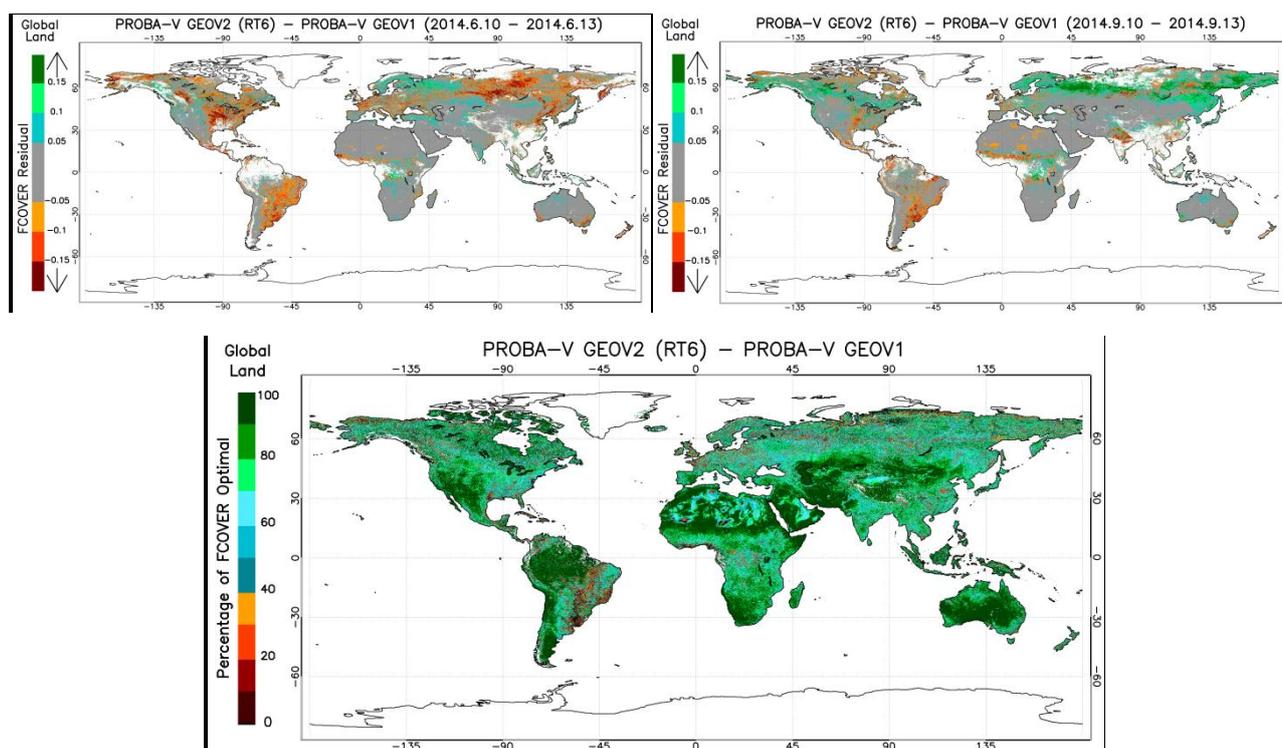


Figure 32: FCOVER residual map between PROBA-V GEOV2 and PROBA-V GEOV1 for 10th June, 2014 (top left) and for 10th September, 2014 (top right). Bottom: Percentage of cases within optimal consistency levels during the study period (October 2013 to September 2014).

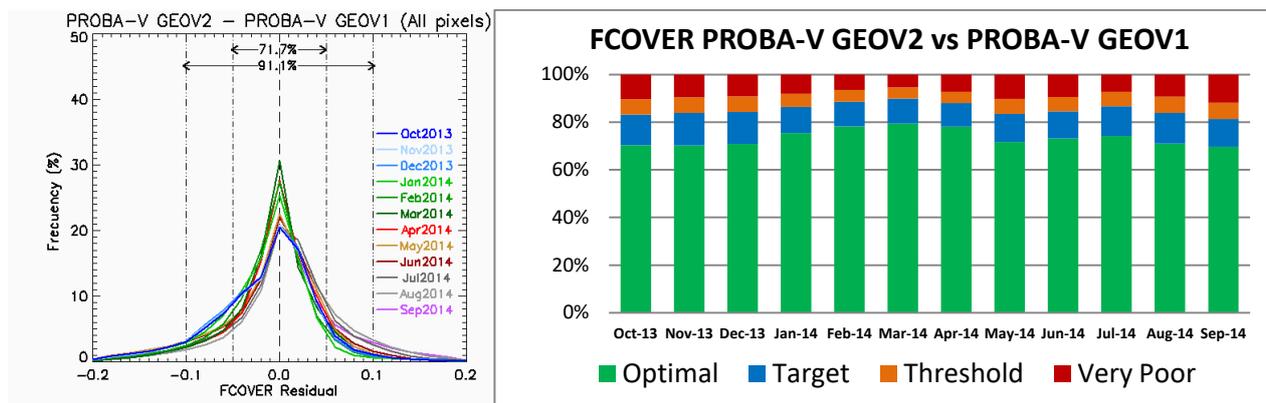


Figure 33: Histogram of residuals per month from October 2013 to September 2014 between FCOVER PROBA-V GEOV2 and PROBA-V GEOV1 products (left side). Percentage of residuals laying the optimal, target and threshold levels of consistency (right side).

• **PROBA-V GEOV2 vs MODIS C5**

This section presents the results of the spatial consistency between PROBA-V GEOV2 (RT6 mode) and TERRA MODIS C5 (MOD15A2) LAI and FAPAR products during one year of data (from October 2013 to September 2014). Maps of residuals for two selected dates are shown in Figure 34 for LAI and Figure 36 for FAPAR (additional residual maps can be found in ANNEX VI and in the digital Annex along with the percentage of cases within optimal consistency levels (see ANNEX XII. Digital Annex). Histograms of residuals and percentage of pixels within the uncertainty levels are displayed in Figure 35 and Figure 37 for LAI and FAPAR, respectively.

- For LAI, very large spatial discrepancies between GEOV2 and MODISC5 are found worldwide. Larger discrepancies are observed over equatorial forest and densest evergreen forest (Central America, East Asia) where MODIS provides larger LAI values. Over the north hemisphere, large areas in North of America (East Coast), Europe and Asia shows spatial discrepancies of different sign. GEOV2 tends to provide higher values in areas of Europe and North America (East Coast), whereas for Needle-leaf and Mixed leaf forest areas (Siberia, Canada), negative residuals are observed at the start of the season (May, June), which turns in positive in summer-time (July, August), with better consistency in September. Different sign of residuals are also observed at the start and end of the season over deciduous forest areas in Africa. Similar results were observed in the comparison of GEOV2/VGT and MODISC5 products [GIOGL1_QAR_LAI1km-VGT-V2_I2.00].
- The percentage of retrievals within optimal levels is around 50% in vegetated areas and goes up to 100% in arid regions. On the contrary, some regions such as Western Africa, Central America or East Asia displayed very low fractions (<20%) of cases matching optimal consistency.
- The histograms of LAI residuals per month are slightly biased towards negative values (around -0.25). This overall tendency was however not observed between SPOT/VGT GEOV2 and MODIS for the year 2004 [GIOGL1_QAR_LAI1km-VGT-V2_I2.00].

- Typically between 70% and 80% of LAI residuals are within the GCOS accuracy requirements (optimal level of consistency defined here). Between 12% and 18% of valid pixels (here excluding bare areas as MODIS does not provides values) shows poor consistency, with larger percentage in July and August. Very similar results were obtained in the comparison of GEOV2/VGT with MODIS for the year 2004 [GIOGL1_QAR_LAI1km-VGT-V2_I2.00]
- For FAPAR, PROBA-V GEOV2 and MODIS C5 products show very important discrepancies around the world, with wide histograms of residuals centered around -0.05 and spanning between -0.2 and 0.2. As for LAI, a seasonal tendency can be observed in the north hemisphere over NLF areas (see Figure 36) (negative residuals at the start of the season which turns positive at the maximum development), and in the south hemisphere over BDF areas (Africa). A tendency to provide negative residuals over sparsely vegetated areas is also observed, which is positive due to the well-known tendency of FAPAR MODIS to overestimate sparsely vegetated targets (Camacho et al. 2013, D'Odorico et al., 2014).
- For FAPAR, large areas displayed very low fraction (<20%) of cases within optimal level of consistency including northern latitudes, South-Est Asia or Western Africa, on the contrary only few areas reached large percentage (<80%) of cases with optimal consistency (e.g., Amazonia).
- For FAPAR, typically around 50% of pixels are matching the optimal level of consistency (GCOS requirements on accuracy), and between 20% to 25% of valid land pixels (excluding bare areas) show very poor consistency. Very similar results were obtained in the comparison of GEOV2/VGT with MODIS for the year 2004 [GIOGL1_QAR_LAI1km-VGT-V2_I2.00].

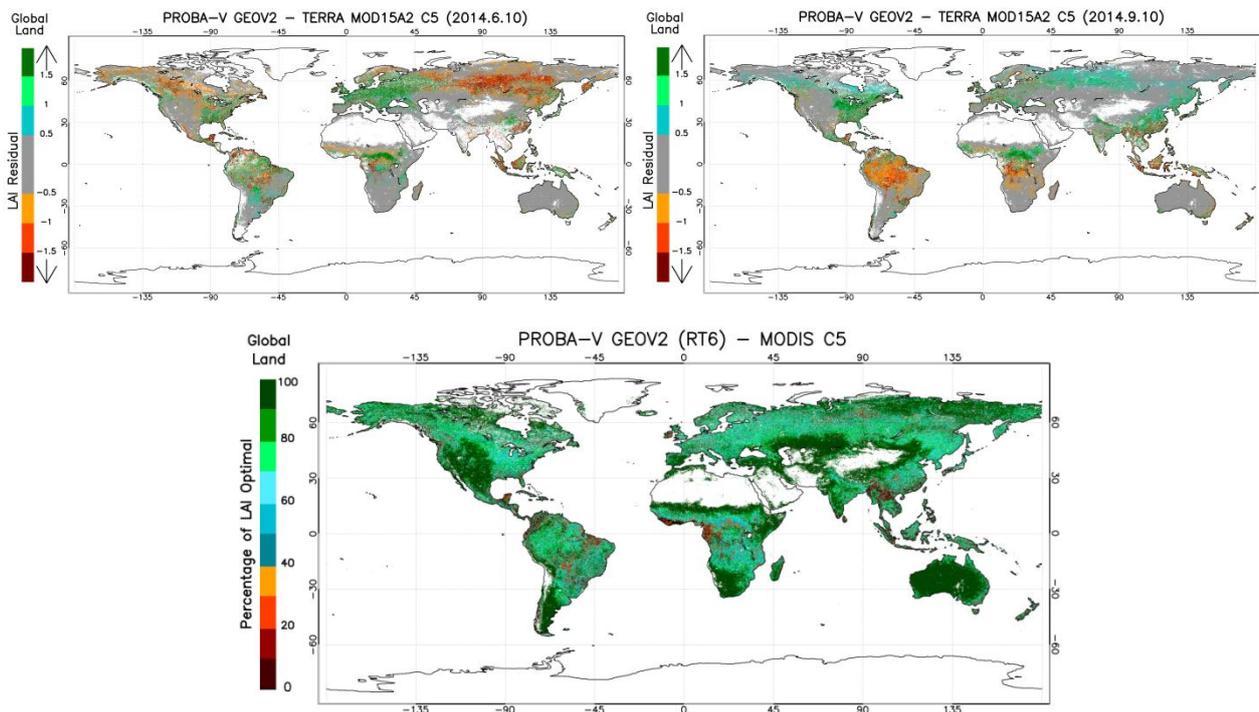


Figure 34: LAI residual map between PROBA-V GEOV2 and MODIS C5 for 10th June, 2014 (top left) and for 10th September, 2014 (top right). Bottom: Percentage of cases within optimal consistency levels during the study period (October 2013 to September 2014).

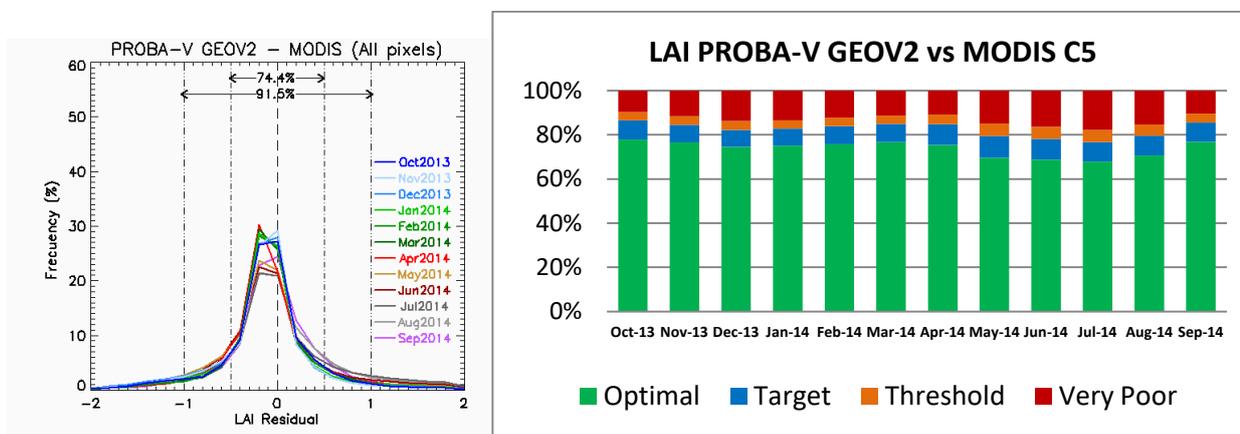


Figure 35: Histogram of residuals per month *f* from October 2013 to September 2014 between LAI PROBA-V GEOV2 and MODIS C5 products (left side). Percentage of residuals laying the optimal (GCOS), target and threshold levels of consistency (right side).

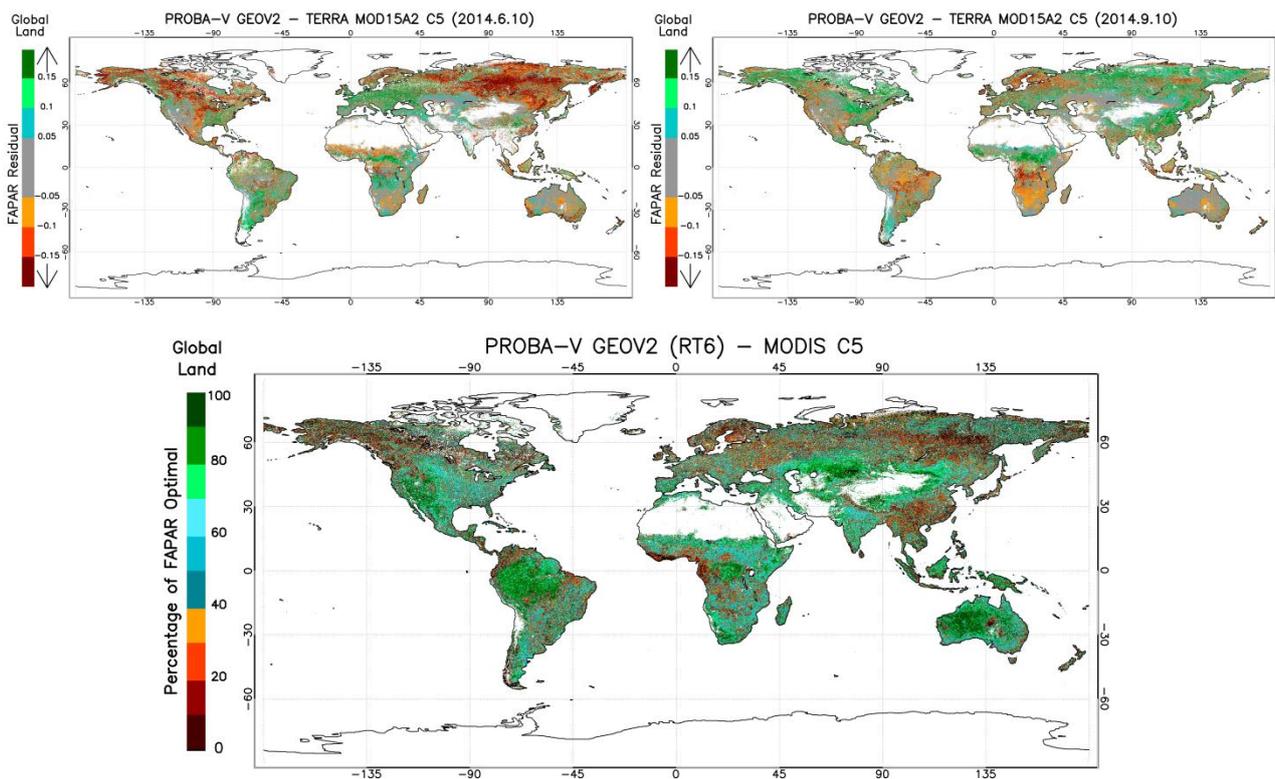


Figure 36: FAPAR residual map between PROBA-V GEOV2 and MODIS C5 for 10th June, 2014 (top left) and for 10th September, 2014 (top right). Bottom: Percentage of cases within optimal consistency levels during the study period (October 2013 to September 2014).

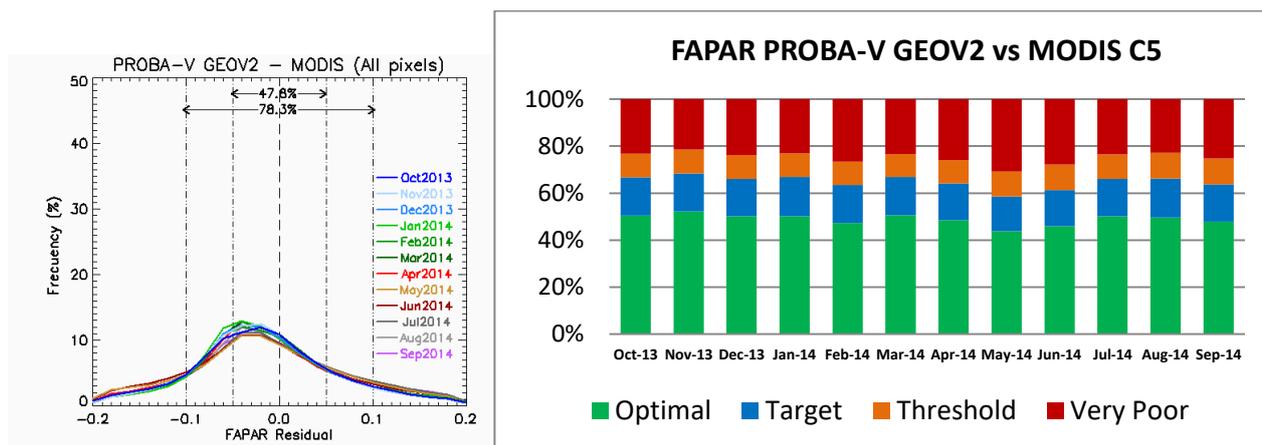


Figure 37: Histogram of residuals per month from October 2013 to September 2014 between FAPAR PROBA-V GEOV2 and MODIS C5 products (left side). Percentage of residuals laying the optimal (GCOS), target and threshold levels of consistency (right side).

- **Distribution of retrievals and residuals per Biome Type and Continental Region**

The distribution of values and histograms of residuals for the three products under study (GEOV2/PV, GEOV1/PV and MODIS C5) were computed over BELMANIP2.1 sites during the period from October 2013 to September 2014 and analyzed per biome type and continental region. These results show that:

For LAI (Figure 38 and Figure 39):

- PROBA-V GEOV2 and GEOV1 show similar distributions for all biome type except for EBF, and NLF where some differences can be observed. Per continental region, with GEOV2 and GEOV1 providing similar distribution of retrievals except in SOAM (area with high fraction of EBF sites) where larger differences are found. Some discrepancies are observed also in Europe and North America..
- Histograms of LAI residuals between GEOV2 and GEOV1 are centered around zero for DBF, around -0.25 for NLF, and around 0.25 for Cultivated, Herbaceous and SBA. For EBF, wider distributions were found. Per continental region, slight positive LAI residuals between GEOV2 and GEOV1 are found in all regions, with more than 87% of LAI residuals laying between ± 0.05 for all regions except for SOAM (72%).
- Between PROBA-V GEOV2 and MODIS C5, the main discrepancies were observed for EBF. MODIS C5 provides slightly higher LAI values than PROBA-V GEOV2 for non-forest sites.
- Over BELMANIP2.1, histograms of residuals between GEOV2/PV and MODIS C5 show slightly better agreement than between GEOV1/PV and MODIS C5 for all biome type except for EBF and SBA.

For FAPAR (Figure 40 and Figure 41):

- The main discrepancies on the distribution of FAPAR retrievals between GEOV2/PV and GEOV1/PV were found for EBF and NLF. For the rest of biomes slight discrepancies were found. Per continental region, the main discrepancies were found in SOAM, NOAM and Europe.
- Histograms of FAPAR residuals between PROBA-V GEOV2 and GEOV1 are generally centered around zero for all biome type except for EBF and Herbaceous (around 0.05). Per continental region, more than 75% of FAPAR residuals (GEOV2 vs GEOV1) are between ± 0.05 except for SOAM (62%) and OCEA (66.6%).
- As compared to MODIS C5, different distributions are observed in almost all biome types, mainly on NLF, H and SBA. Note also that MODIS provides lower frequencies for low FAPAR values in BDF and NLF, as well as in Cropland, Herbaceous and SBA where the positive bias for MODIS is observed.
- Over BELMANIP2.1, histograms of residuals between GEOV2/PV and MODIS C5 FAPAR show slightly better agreement than between GEOV1/PV and MODIS C5 for all biome type except for NLF that are almost identical.

Finally, for FCOVER (Figure 42 and Figure 43):

- Similar distributions of PROBA-V GEOV2 and GEOV1 retrievals were observed for non-forest types and DBF. Large discrepancies observed for NLF and EBF, mainly located over areas where GEOV2 uses particular gap filling methods (equatorial areas and northern latitudes).
- Histograms of FCOVER residuals between PROBA-V GEOV2 and GEOV1 are centered at zero for all biome type except for EBF (around -0.05). Per continental region, more than 70% of residuals are within the ± 0.05 threshold except for SOAM (51.7%).

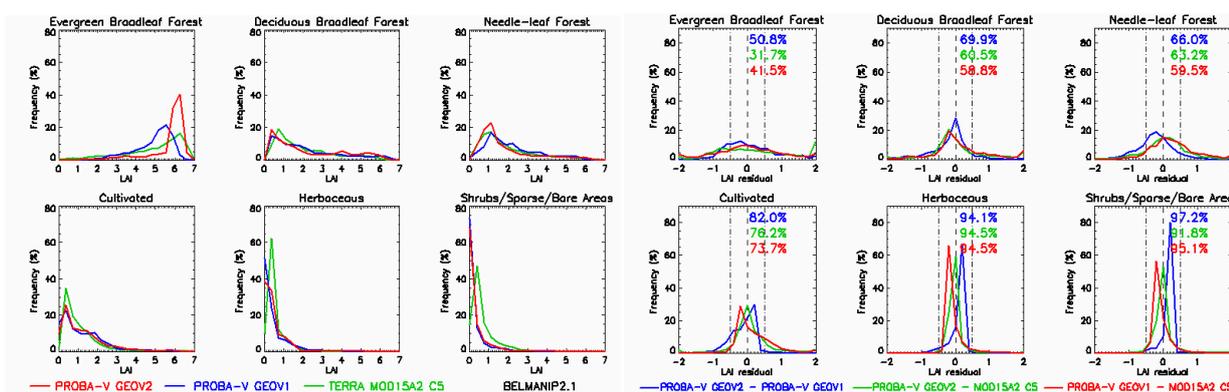


Figure 38: Distribution of LAI values (left panel) and residuals (right panel) for the BELMANIP2.1 sites during the Oct.2013-Nov.2014 period for each biome type.

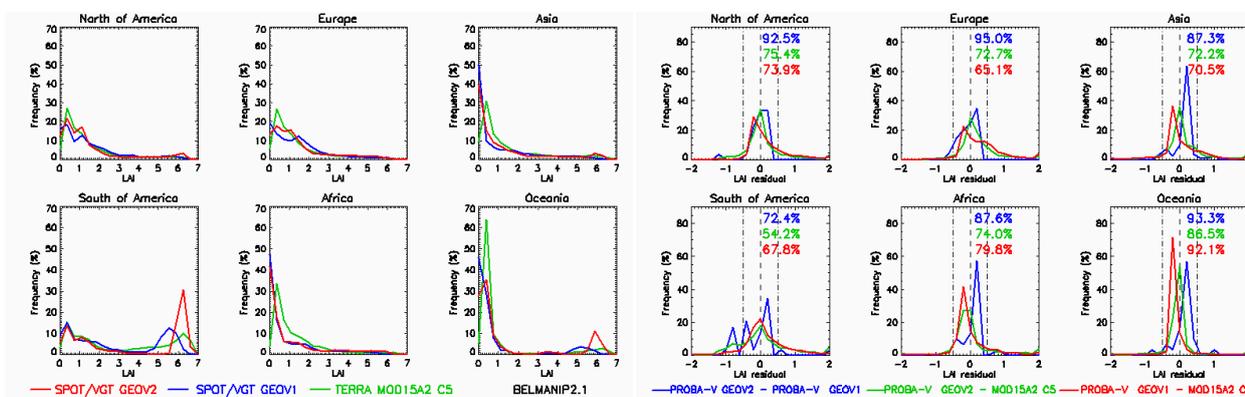


Figure 39: Distribution of LAI values (left panel) and residuals (right panel) for the BELMANIP2.1 sites during the Oct.2013-Nov.2014 period for each continental region.

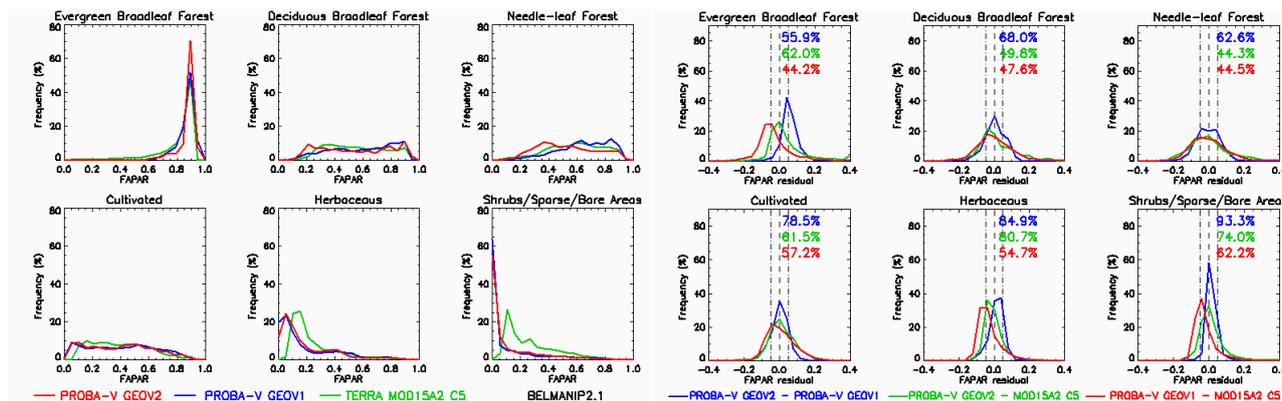


Figure 40: Distribution of FAPAR values (left panel) and residuals (right panel) for the BELMANIP-2.1 sites during the Oct.2013-Nov.2014 period for each biome type.

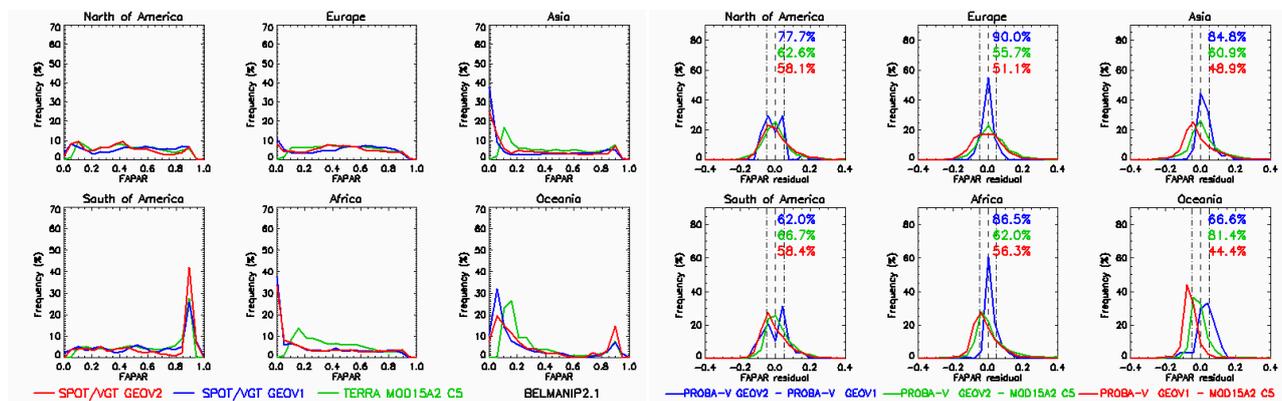


Figure 41: Distribution of FAPAR values (left panel) and residuals (right panel) for the BELMANIP-2.1 sites during the Oct.2013-Nov.2014 period for each continental region.

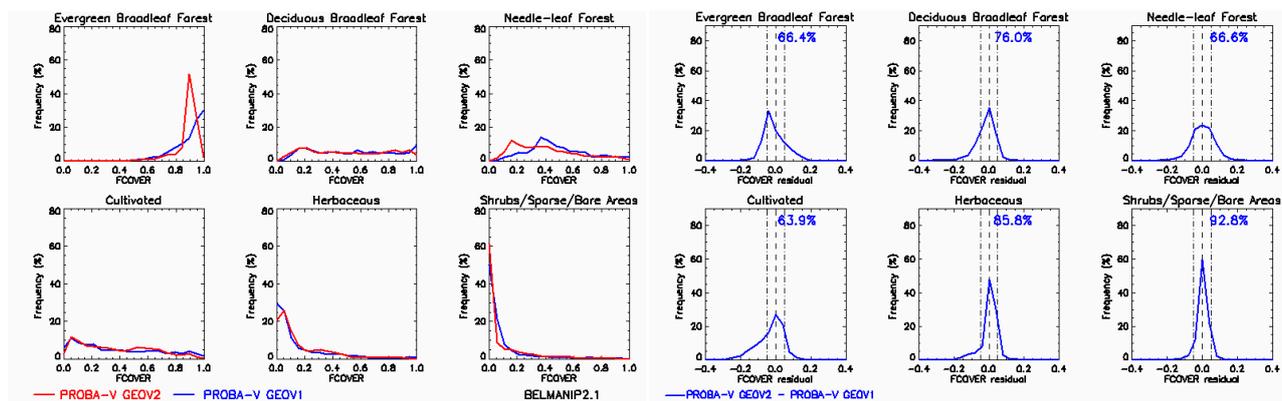


Figure 42: Distribution of FCOVER values (left panel) and residuals (right panel) for the BELMANIP-2.1 sites during the Oct.2013-Nov.2014 period for each biome type.

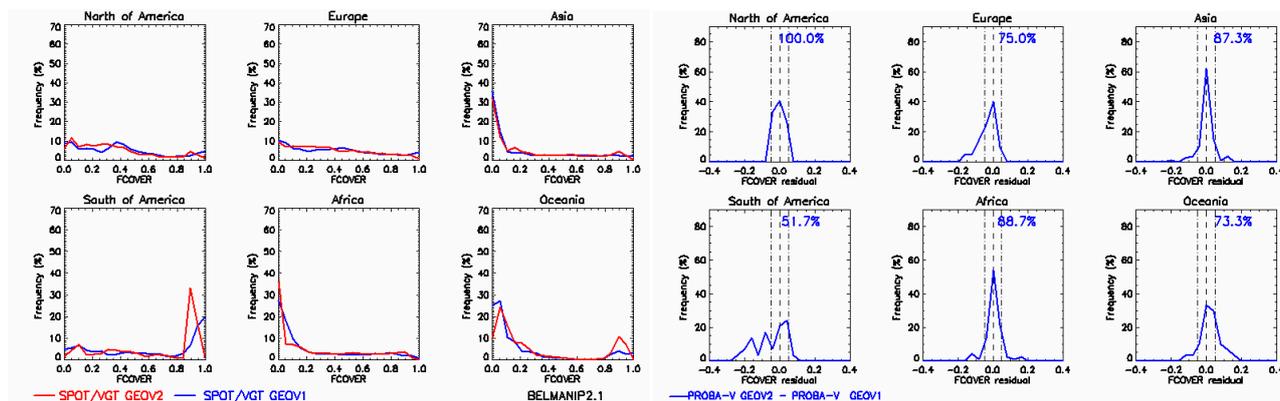


Figure 43: Distribution of FCOVER values (left panel) and residuals (right panel) for the BELMANIP-2.1 sites during the Oct.2013-Nov.2014 period for each continental region.

4.4 TEMPORAL CONSISTENCY ANALYSIS

4.4.1 Temporal consistency among PROBA-V GEOV2 modes

The consistency of the temporal variations for the several GEOV2 RT modes is investigated here. Figure 44 shows the temporal profiles of all PROBA-V GEOV2 modes (RT0 to RT6) over a selection of BELMANIP2.1 sites for different biomes. All the temporal profiles are provided as a complementary material in a digital annex (see ANNEX XII. Digital Annex for details). Table 13 shows the cross-correlation values of the temporal profiles (Figure 44).

In summary:

- Very consistent temporal trajectories have been found for the several RT modes. Only RT0 (NRT mode) provided slight discrepancies with the other consolidated modes. In some cases, RT0 shows lower slopes during the growing period, lower maximum values, and slightly shifted temporal course than the other RT modes (e.g., B2.1#157 BDF and B2.1#65 NLF sites, B2.1#332 Cultivated site). This deserves further investigation to know if these cases corresponds with larger RMSE or lower NOBS where the RT0 product is less reliable.
- The differences in the temporal variations between the different modes and the RT6 mode are almost negligible from the first consolidated period (RT1) onwards.
- The cross-correlation between RT0 and RT6 is typically higher than 0.95.

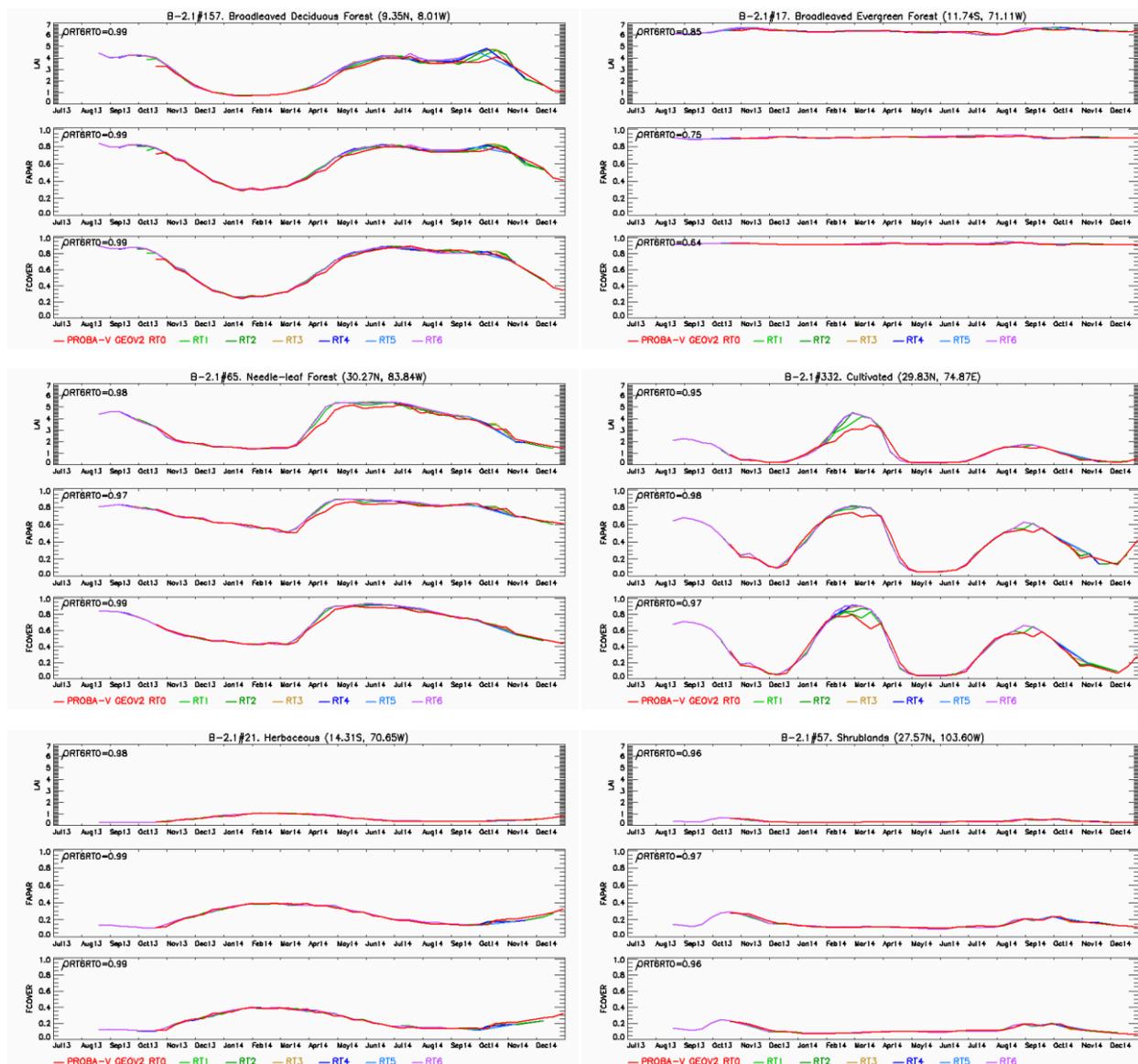


Figure 44: Temporal profiles of PROBA-V GEOV2 products (all modes) for different biomes. LAI (top) FAPAR (middle) and FCOVER (bottom). Cross-correlation estimates pRT6RT0 (RT6 versus RT0) are shown.

Table 13: Summary of the cross-correlation ρ_{RT6RT0} (RT6 versus RT0) for the temporal profiles shown in Figure 441.

	ρ_{RT6RT0}		
	LAI	FAPAR	FCOVER
BDF (B-2.1#157)	0.99	0.99	0.99
BEF (B-2.1#17)	0.85	0.75	0.64
NLF(B-2.1#65)	0.98	0.97	0.99
Cultivated (B-2.1#332)	0.95	0.98	0.97
Herbaceous (B-2.1#21)	0.98	0.99	0.99
Shrublands (B-2.1#57)	0.96	0.97	0.96

4.4.2 Temporal consistency of PROBA-V GEOV2 with reference products

In this section, the temporal consistency of PROBA-V GEOV2 is examined as compared to SPOT/VGT GEOV2 and reference PROBA-V GEOV1 and MODIS C5 products. From Figure 45 to Figure 50, two examples for each biome type are displayed. Table 15 shows the cross-correlation values for the examples displayed (Figure 45-507). Several additional temporal profiles can be found in ANNEX VII. Additional Temporal Profiles, and all the temporal profiles analyzed are provided as a complementary material in a digital annex (see ANNEX XII. Digital Annex for details). The quantitative assessment (histograms of cross-correlation) per biome type is presented below.

The main findings of this section are:

- For Broadleaved Evergreen Forest (Figure 45), the temporal trajectories of GEOV2 are very smooth and present very low seasonality as expected after application of the temporal smoothing and gap filling methods over equatorial and northern areas (bit 3 corresponding to gap filling method is activated in most cases).
- For Needle-leaf Forest (Figure 46), GEOV2/PV tends to provide lower values at the start of the season and then higher values during the maximum development and at the end of the season (e.g. see B2.1#392). This partly explains the observed seasonality of the residuals over northern latitudes. The false growth observed in GEOV1 around November (see ANNEX VII. Additional Temporal Profiles, B2.1#391) is solved in GEOV2.
- For Broadleaved Deciduous Forest (Figure 47), GEOV2/PV shows similar temporal variations than other products but higher values of up to 2 LAI units or about 0.1 for FAPAR/FCOVER as compared to SPOT/VGT GEOV2 are observed over some sites (e.g., B2.1#144, ANNEX VII. Additional Temporal Profiles B2.1#130). These differences in magnitude confirm the spatial discrepancies observed over large BDF areas in Africa (see Section 4.7, Regional Analysis). Differences with GEOV1 at the start and the end of the season can be observed over some sites (e.g., ANNEX VII. Additional Temporal Profiles,

- B2.1#74). For LAI, the GEOV2 profile at the end of the season is more consistent with other variables (FAPAR) than in GEOV1 where an anticipated decrease is observed (e.g., B2.1#243, ANNEX VII. Additional Temporal Profiles B2.1#74).
- Over Cropland sites, two examples of sites located in South America were selected due to the vegetation cycle can be observed during the overlap period between PROBA-V and SPOT/VGT (Figure 48). Similar temporal courses are observed among the several products. A slight positive bias of GEOV2/PV as compared to GEOV2/VGT can be observed in some sites (e.g., Environet Pandeiros site). These differences in magnitude confirm the spatial discrepancies observed over large cultivated areas of South America (section 4.7). Over some sites GEOV2 shows narrower bell-shape than reference products (e.g., ANNEX VII. Additional Temporal Profiles, B2.1#7), in particular than GEOV1.
 - For Shrublands (Figure 49) and Herbaceous (Figure 50), a good temporal agreement was found in most of the sites. However, for Shrublands, discrepancies in magnitude with GEOV1 and MODIS was detected of more than 2 LAI units (e.g. B2.1#149), larger than between GEOV2/VGT and GEOV1 or MODIS. The unrealistic seasonal behaviour of FCOVER detected in GEOV1 over some desertic sites is not shown in GEOV2 (e.g., ANNEX VII. Additional Temporal Profiles, 206).

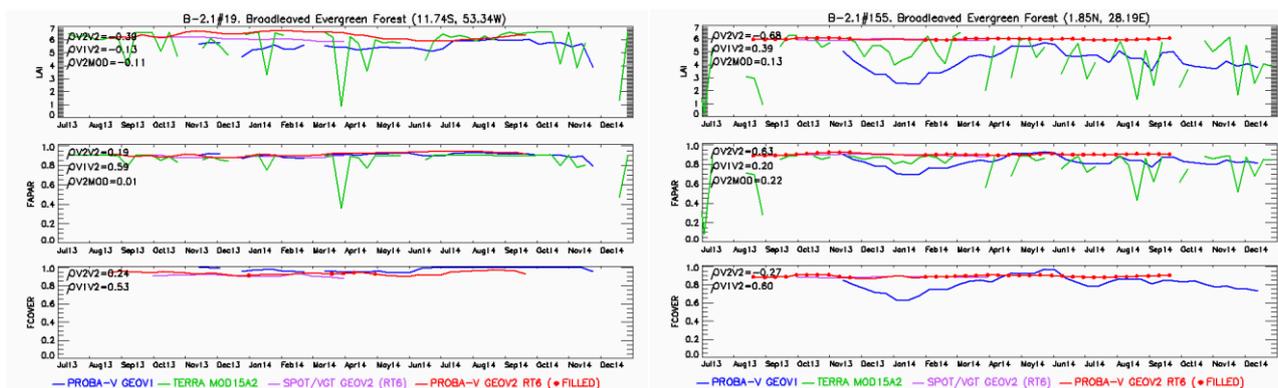


Figure 45: Temporal profiles of PROBA-V GEOV2 (RT6) and reference products SPOT/VGT GEOV2 (RT6), PROBA-V GEOV1 and TERRA MODIS C5 over two selected Evergreen Broadleaved Forests. Dots represent filled data according to PROBA-V GEOV2 QF bit 3, and vertical bars represent PROBA-V GEOV2 RMSE estimations. Cross-correlation estimates of PROBA-V GEOV2 and SPOT/VGT GEOV2 (ρ_{V2V2}), PROBA-V GEOV1 (ρ_{V2V1}) and MODIS C5 (ρ_{V2MOD}) are shown in the graphs.

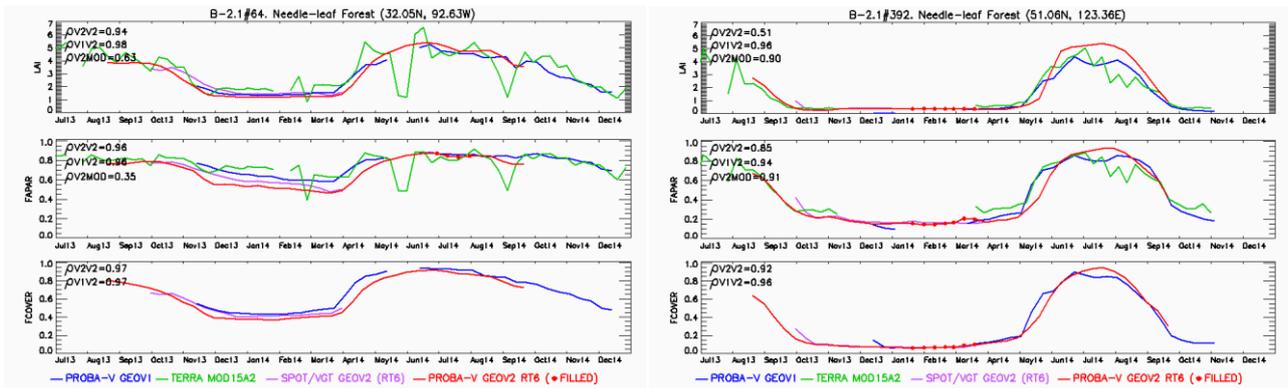


Figure 46: As in Figure 45 for Needle-leaf Forest.

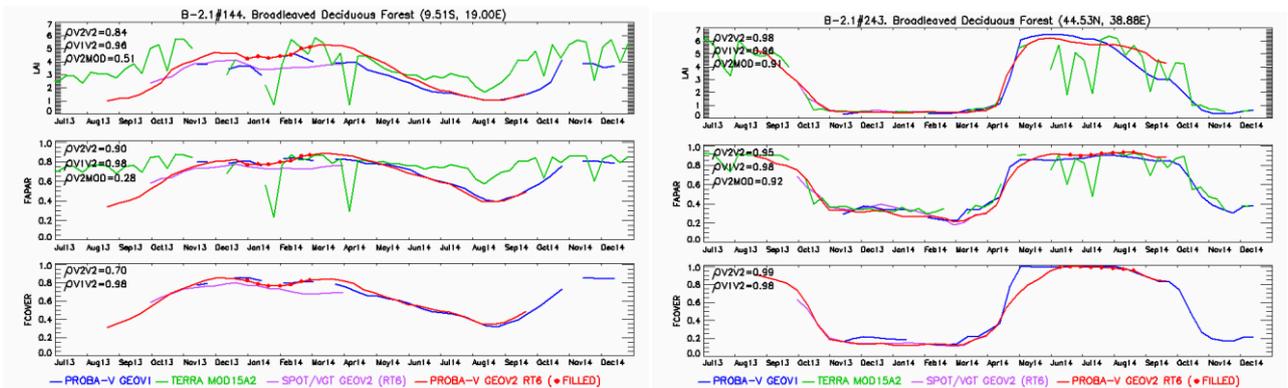


Figure 47: As in Figure 45 for Broadleaved Deciduous Forests.

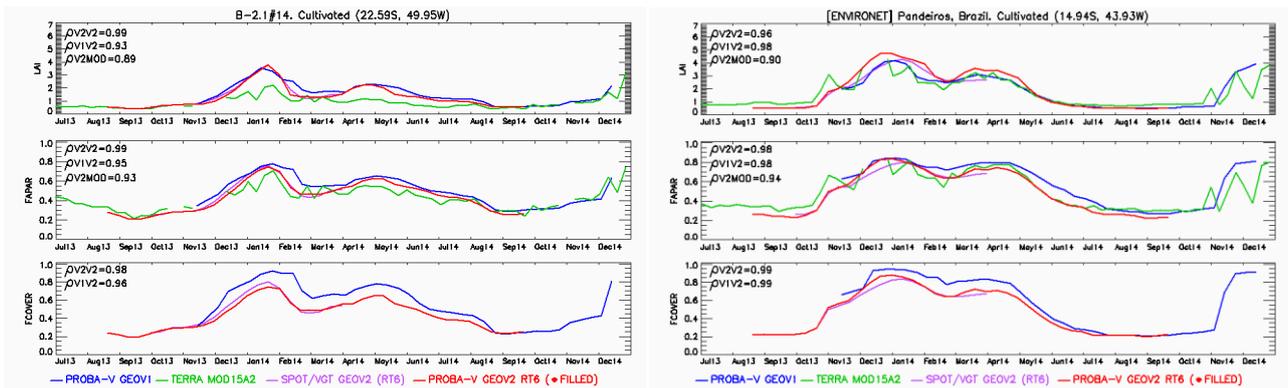


Figure 48: As in Figure 45 for Cultivated.

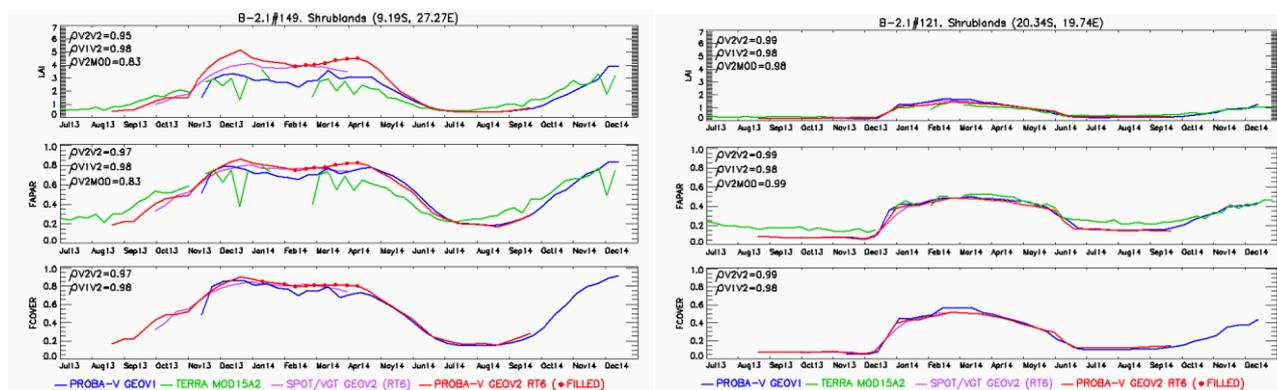


Figure 49: As in Figure 45 for Shrublands.

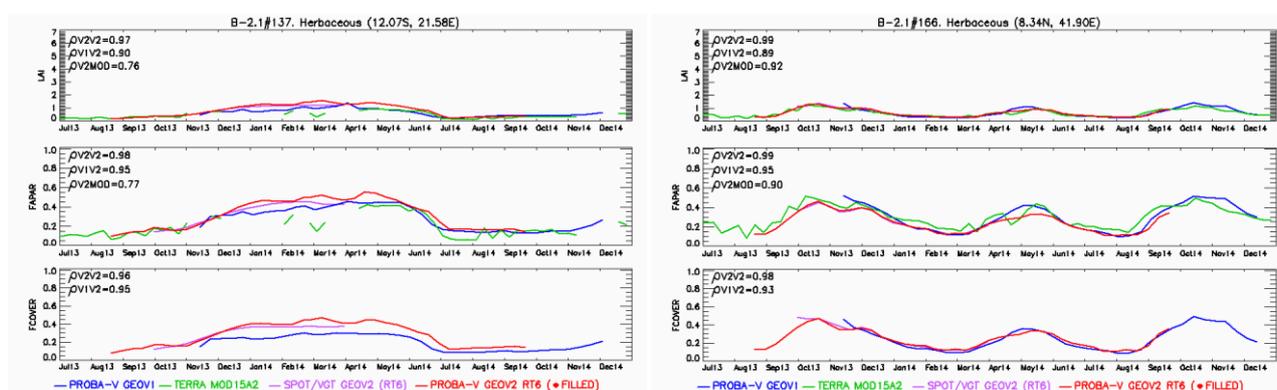


Figure 50: As in Figure 45 for Herbaceous.

Table 14: Summary of the cross-correlation of PROBA-V GEOV2 with SPOT/VGT GEOV2 ($\rho V2V2$), PROBA-V GEOV1 ($\rho V2V1$) and MODIS C5 ($\rho V2MOD$) shown in Figure 45 to Figure 50.

		$\rho V2V2$			$\rho V2V1$			$\rho V2MOD$	
		LAI	FAPAR	FCOVER	LAI	FAPAR	FCOVER	LAI	FAPAR
BEF	#19	-0.39	0.19	0.24	-0.13	0.59	0.53	-0.11	0.01
	#155	-0.98	0.63	-0.27	0.39	0.2	0.6	0.13	0.22
NLF	#64	0.94	0.96	0.97	0.98	0.96	0.97	0.63	0.35
	#392	0.51	0.85	0.92	0.96	0.94	0.96	0.9	0.91
BDF	#144	0.84	0.9	0.7	0.96	0.98	0.98	0.51	0.28
	#243	0.98	0.95	0.99	0.96	0.98	0.98	0.91	0.92
Cultivated	#14	0.99	0.99	0.98	0.93	0.95	0.96	0.89	0.93
	Pandeiros	0.96	0.98	0.99	0.98	0.98	0.99	0.9	0.94
Shrublands	#149	0.95	0.97	0.97	0.98	0.98	0.98	0.83	0.83
	121	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.99
Herbaceous	#137	0.97	0.98	0.96	0.9	0.92	0.91	0.76	0.77
	#166	0.99	0.99	0.98	0.95	0.96	0.95	0.92	0.9

- **Cross-Correlation distributions**

The cross-correlation of the temporal variations between GEOV2/PV and GEOV2/VGT (Figure 51) was assessed per biome type over BELMANIP2.1 sites during the overlap period.

- For LAI, cross-correlation between PROBA-V and SPOT/VGT was higher than 0.8 in more than 70% of samples except for Herbaceous (68%) and SBA (52%) explained in the almost constant and very low values observed over some sites in these biomes. The uncertainties attached to GEOV2 products have strong impact in the correlations over these particular conditions. Poor correlations were also observed over EBF, which indicates that the small intra-annual variability displayed by the GEOV2 in this biome is not consistent when changing the sensor.
- For FAPAR and FCOVER cross-correlation was higher than 0.8 in typically more than 80% of cases for all biome type except for SBA and EBF, as explained above. Note the very high percentage (>97%) for DBF.
- The cross-correlation between GEOV2 PROBA-V and SPOT/VGT improves the figures obtained for GEOV1 for a similar period, except for SBA [GIOGL1_QAR_LAI1km-V1_I3.10].

The cross-correlation of the temporal variations between PROBA-V GEOV2 and references GEOV1/PV and MODIS C5 (Figure 52) was assessed per biome type over BELMANIP2.1 sites considering one year of overlap period.

For LAI:

- Very good agreement between PROBA-V GEOV2 and GEOV1 for all biome type except for EBF (which can be partly explained due to the impact of cloud contamination), with cross-correlation higher than 0.8 in more than 70% of cases and up to 99.9% of the samples for DBF and 97% for Cultivated.
- The comparison between GEOV2 and MODIS shows very similar results than the comparison between GEOV1 and MODIS. Good agreement for all biome type except for EBF.

For FAPAR and FCOVER:

- Good temporal consistency between PROBA-V GEOV2 and GEOV1 for all biome type except for EBF (noisier profiles) and SBA (typically low FAPAR and FCOVER seasonality), with cross-correlation values higher than 0.8 in more than 80% of cases, and close to 100% of samples in BDF and Croplands
- Similar results, as observed for LAI, in the comparison between GEOV2/PV and MODIS than in the comparison between GEOV1/PV and MODIS for all biome type.

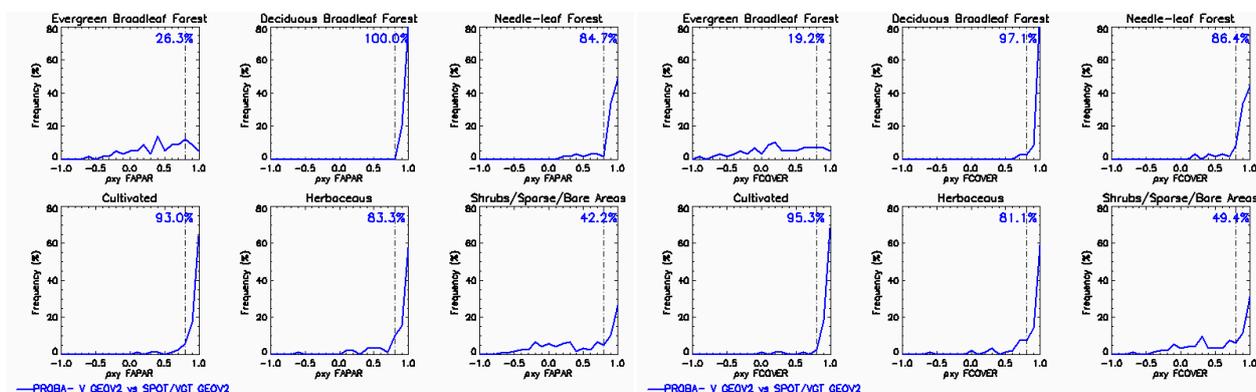
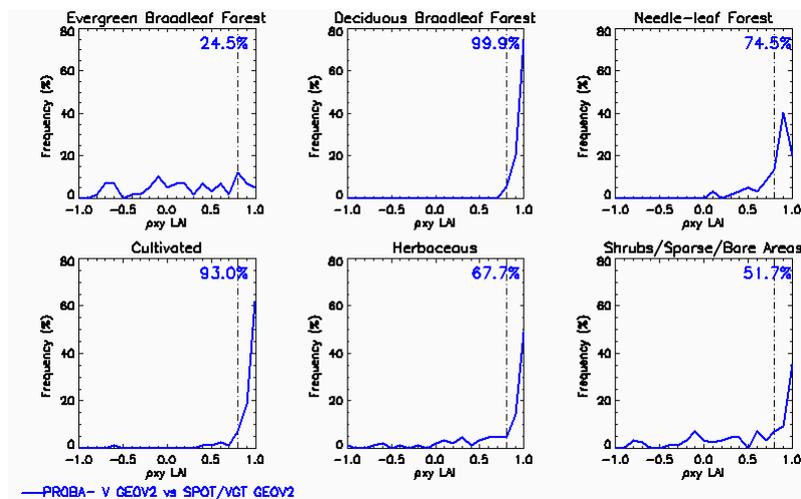


Figure 51: Cross-correlation distributions (ρ_{xy}) between PROBA-V GEOV2 and SPOT/VGT GEOV2 (RT6 mode) temporal profiles for BELMANIP-2.1 sites during Oct.2013-Mar.2014 period for each biome type for LAI (top), FAPAR (bottom-left) and FCOVER (bottom-right). The values in the plot shows the percentage of cases with correlations higher than 0.8.

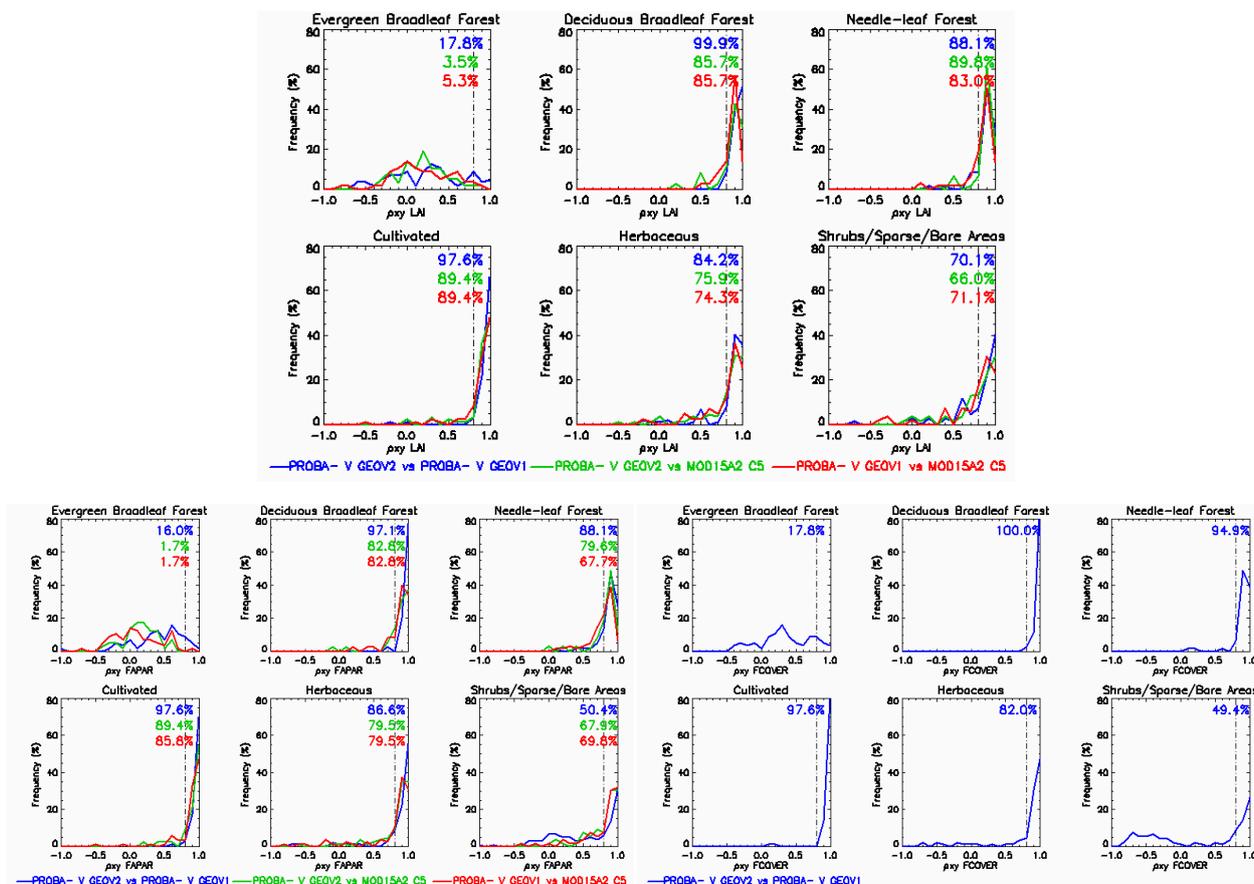


Figure 52: Cross-correlation distributions (ρ_{xy}) between PROBA-V GEOV2, PROBA-V GEOV1 and MODIS C5 temporal profiles for BELMANIP-2.1 sites during Oct.2013-Sep.2014 period for each biome type for LAI (top), FAPAR (bottom-left) and FCOVER (bottom-right). The values in the plot shows the percentage of cases with correlations higher than 0.8.

4.5 INTRA-ANNUAL PRECISION

Figure 53 and Figure 54 shows the histograms of the smoothness, defined by Weiss et al., (2007), and used here as indicator of the intra-annual precision as proposed by Fernandes et al., (2014). The cumulative histograms of the δ LAI, δ FAPAR and δ FCOVER for the different PROBA-V GEOV2 modes (Figure 53) and for the different reference products (Figure 54) have been computed to quantify the variability of the retrieval over very short-time periods.). These results indicate:

- High stability at short time scale was found for PROBA-V GEOV2 products, as expected for a smoothed product.
- Almost identical results for all modes. The cumulative histograms fit a negative exponential function, with almost identical lower decay constant (τ) for all the modes (from RT0 to RT6).The decay constant is considered here a typical value of the short-time variability of

the delivered dekadal product, but does not provide information on the precision of GEOV2 algorithm on daily estimates.

- No improvement in the smoothness of the product is observed when new observations are considered (i.e., from RT1 to RT6).
- GEOV2 shows, as expected, lower delta values as compared to GEOV1 and MODIS C5.

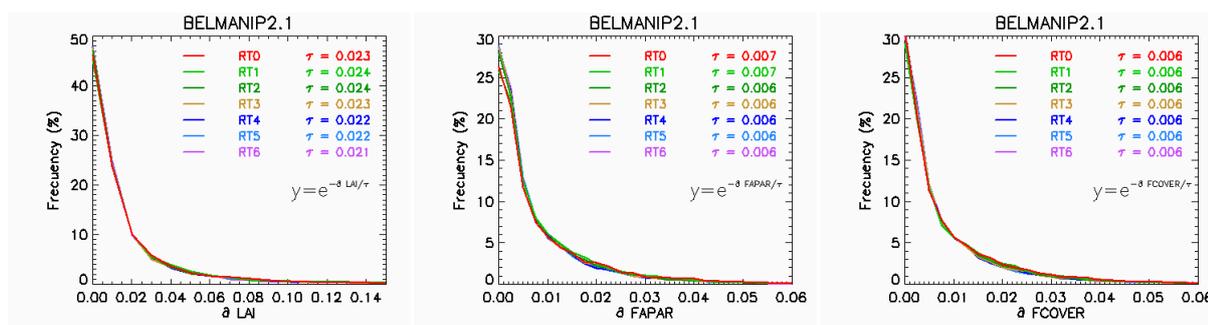


Figure 53: Histograms of the delta function (smoothness) for LAI, FAPAR and FCOVER PROBA-V GEOV2 products (modes from RT0 to RT6) for BELMANIP-2.1. The curves are adjusted to an exponential function and the exponential decay constant (τ) is presented in the figure.

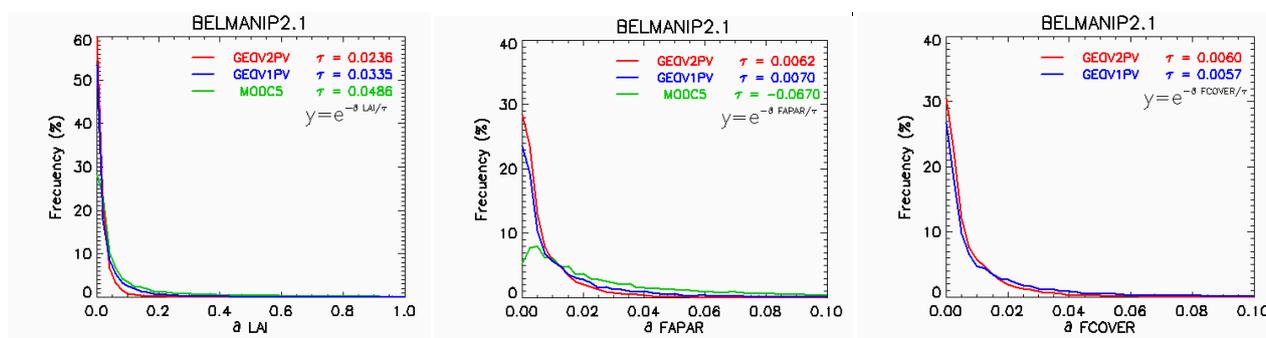


Figure 54: Histograms of the delta function (smoothness) for LAI, FAPAR and FCOVER PROBA-V GEOV2 RT6, PROBA-V GEOV1 and MODIS C5 products over BELMANIP-2.1 for the Oct. 2013-Sep. 2014 period. The curves are adjusted to an exponential function and the exponential decay constant (τ) is presented in the figure.

4.6 OVERALL STATISTICAL CONSISTENCY

4.6.1 Consistency between PROBA-V GEOV2 modes

For analyzing the consistency of the several PROBA-V GEOV2 modes (from RT0 to RT5) with the RT6, scatter-plots of GEOV2 modes vs GEOV2 RT6 and corresponding performance metrics were computed over BELMANIP2.1 network of sites. Table 15 shows the R^2 , RMSE and Bias metrics, whereas the scatter-plots of the different combinations can be found in Annex VIII.

In terms of correlation, there is no improvement of the successive consolidated estimates. The bias and RMSE improves notably after one decade (i.e., first consolidated estimate, RT1), improves slightly in the second consolidation (RT2), and then the metrics remains almost constant for the successive modes with only marginal improvements for the LAI. Note also, that for the three variables, the consistency of RT0 with RT6 is already very good.

This result over BELMANIP2.1 shows the very good consistency between modes and suggests that one or two decades of observations in the future (RT1, RT2 mode) seems to be enough to consolidate the GEOV2 estimates as compared to RT6. This could however not be the case over some situations with low number of observations, cloud contamination or high RMSE of the estimate (see GIOGL1_ATBD_LAI1km-V2).

Table 15: Performance metrics of PROBA-V GEOV2 RT6 vs RT0 to RT5 modes.

LAI						
RT6 vs	RT0	RT1	RT2	RT3	RT4	RT5
R^2	0.98	0.99	0.99	0.99	0.99	0.99
RMSE	0.21	0.12	0.08	0.06	0.06	0.05
BIAS	-0.05	-0.02	-0.009	-0.002	-0.001	<0.001
FAPAR						
RT6 vs	RT0	RT1	RT2	RT3	RT4	RT5
R^2	0.99	0.99	0.99	0.99	0.99	0.99
RMSE	0.02	0.01	0.01	0.01	0.01	0.01
BIAS	-0.004	-0.001	<0.001	<0.001	<0.001	<0.001
FCOVER						
RT6 vs	RT0	RT1	RT2	RT3	RT4	RT5
R^2	0.99	0.99	0.99	0.99	0.99	0.99
RMSE	0.02	0.01	0.01	0.01	<0.01	<0.01
BIAS	-0.005	-0.002	-0.001	<0.001	<0.001	<0.001

4.6.2 Consistency between PROBA-V GEOV2 and reference products

- Overall assessment over BELMANIP2.1 (GEOV2/PV vs GEOV2/VGT)**

The overall consistency between GEOV2/PV and GEOV2/VGT products was assessed over the BELMANIP2.1 network of sites during the overlap period available (October 2013-March 2014). Note that in the considered period most of the vegetation located in the north hemisphere is inactive (fall and winter period), and the results have to be interpreted accordingly. A regional analysis focused over a region and period with active vegetation is considered hereafter.

Figure 55 shows the scatter-plots between both products for LAI, FAPAR and FCOVER. Here, two different cases have been considered: 1) All pixels have been used (Top of the Figure 55), and 2) "filled values" have been discarded (Bottom of the Figure 55). The relevant statistics are shown in Table 16 (all pixels) and Table 17 (discarding "filled values").

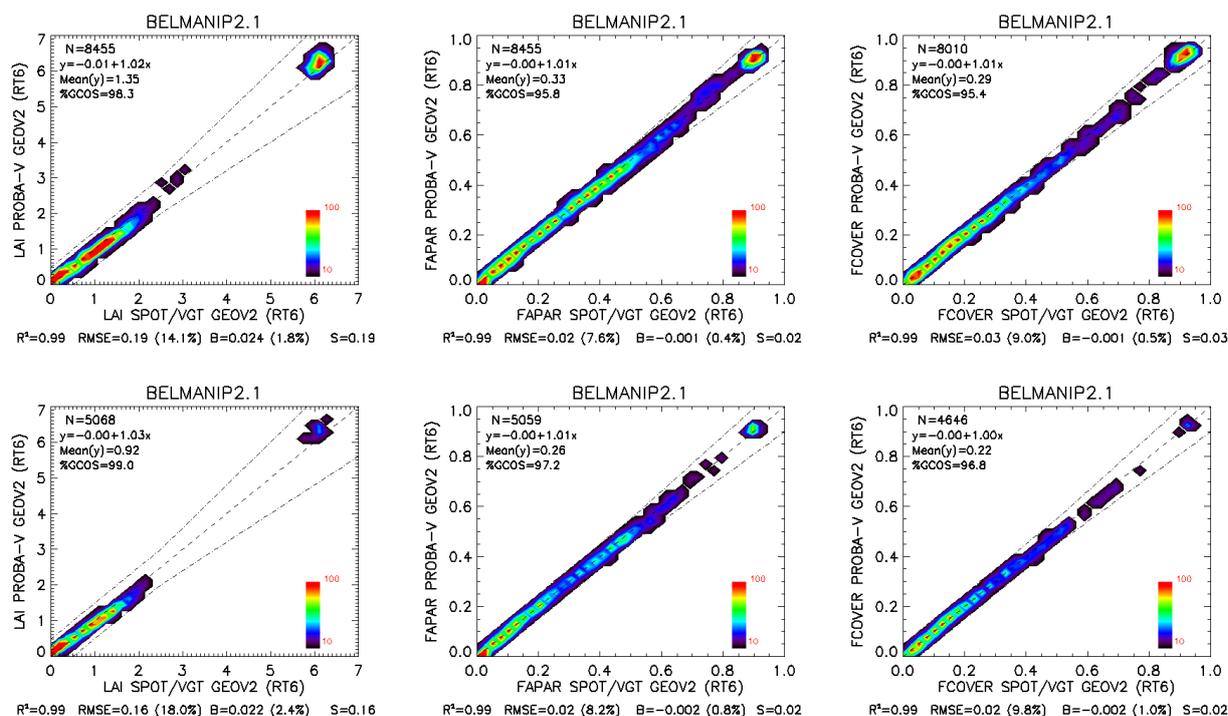


Figure 55: PROBA-V GEOV2 LAI, FAPAR and FCOVER products (RT6 mode) versus SPOT/VGT GEOV2 similar product scatter-plots over all BELMANIP-2.1 sites for the Oct.2013-Mar.2014 period. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels. Top: All pixels are considered. Bottom: Pixels flagged as "Filled" have been removed.

Table 16: Relevant statistics between PROBA-V GEOV2 RT6 LAI/FAPAR/FCOVER products versus SPOT/VGT GEOV2RT6 over all BELMANIP-2.1 sites for the Oct.2013-Mar.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1. All pixels are considered.

	PROBA-V GEOV2 vs SPOT/VGT GEOV2 (All pixels)		
	LAI	FAPAR	FCOVER
Correlation (R^2)	0.99	0.99	0.99
Bias	0.02	-0.001	-0.001
RMSE	0.19	0.02	0.03
Offset (MAR)	-0.01	0.00	0.00
Slope (MAR)	1.02	1.01	1.01
p-value	0.001	0.001	0.001
%optimal (LAI, FAPAR GCOS)	98.3	95.8	95.4

Table 17: Relevant statistics between PROBA-V GEOV2 RT6 LAI/FAPAR/FCOVER products versus SPOT/VGT GEOV2RT6 over all BELMANIP-2.1 sites for the Oct.2013-Mar.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1. Pixels flagged as "Filled" have been removed.

	PROBA-V GEOV2 vs SPOT/VGT GEOV2 (No "filled" pixels)		
	LAI	FAPAR	FCOVER
Correlation (R^2)	0.99	0.99	0.99
Bias	0.02	-0.002	-0.002
RMSE	0.16	0.02	0.02
Offset (MAR)	0.00	0.00	0.00
Slope (MAR)	1.03	1.01	1.00
p-value	0.001	0.001	0.076
%optimal (LAI, FAPAR GCOS)	99.0	97.2	96.8

The following are the main findings:

- For all the three variables, a very good agreement is obtained over BELMANIP2.1 sites and the period under study. More than 95% of the samples are within GCOS level on accuracy, and no bias is detected, with correlations larger than 0.99 and very low RMSE values. These results in terms of RMSE and bias are better than those obtained for GEOV1 PV vs GEOV1 VGT [see GIOGL1_QAR_LAI1km-V1_I3.10].
- The statistics are almost identical for all pixels than removing filled values.
- As the other metrics, the MAR linear fit between GEOV2/PV and GEOV2/VGT products provides very good results, with no offset, and slope very close to 1 (albeit significantly different to 1 in most cases). These results showed the good performance of GEOV2/PV as compared to GEOV2/VGT achieved over the learning database for which the re-scaling of

the NNT output (PV to VGT) was trained (see ATBD). However, this is not the case for other regions where large discrepancies are observed (see section 4.7).

4.6.3 Consistency between PROBA-V GEOV2 and reference products (one year of data)

To evaluate the overall consistency of the PROBA-V GEOV2 with reference products (PROBA-V GEOV1 and MODIS C5), scatter-plots and relevant statistics were computed over BELMANIP2.1 network of sites during one complete year of data (from October 2013 to September 2014). This analysis has been complemented per biome type (hereafter) and continental region (ANNEX IX. Analysis per Continental Region).

- **Global scatter-plots**

The comparison between PROBA-V GEOV2 and PROBA-V GEOV1 (Figure 56 and Table 18) shows:

- For LAI, the overall consistency between GEOV2/PV and GEOV1/PV over BELMANIP2.1 is good with RMSE of 0.47, showing GEOV2>GEOV1 for high LAI values. Most of the samples (90%) are within GCOS level.
- For the FAPAR, an overall consistency of RMSE=0.05 was found, but with systematic lower retrievals for medium FAPAR values (between 0.3 to 0.8 approximately) and 80% of pixels within the GCOS uncertainty level.
- For the FCOVER, overall discrepancies (RMSE) of 0.06 are found (more scattering) with 77% within the optimal level of consistency.
- Very similar results between PROBA-V GEOV2 and GEOV1 were found than in the comparison between SPOT/VGT GEOV2 and GEOV1 during the 2004-2005 period [GIOGL1_QAR_LAI1km-VGT-V2_I2.00] for the three variables under study.

On the other hand, the overall statistical consistency between GEOV2/PV and MODIS C5 LAI and FAPAR (Figure 57 and Table 19) products show:

- For LAI, large scattering was found showing GEOV2 higher retrievals than MODIS. The largest discrepancies are observed for very high values, explained by the GEOV2 method used over tropical forests. The overall discrepancies are RMSE=0.94 with 77.1% of point within the GCOS requirements and mean positive bias of 0.3.
- For the FAPAR, overall discrepancies of 0.11 were found with only 47% of points within the GCOS uncertainty requirements. Some scattering was found for the whole range of FAPAR values. For low FAPAR values, MODIS provides higher values than GEOV2, whereas the opposite trend (GEOV2 > MODIS) is observed for high FAPAR values.
- These results between PROBA-V GEOV2 and MODIS C5 are very similar to that reported for GEOV2/VGT [GIOGL1_QAR_LAI1km-VGT-V2_I2.00], with RMSE of 0.85 and 0.11 for LAI and FAPAR.

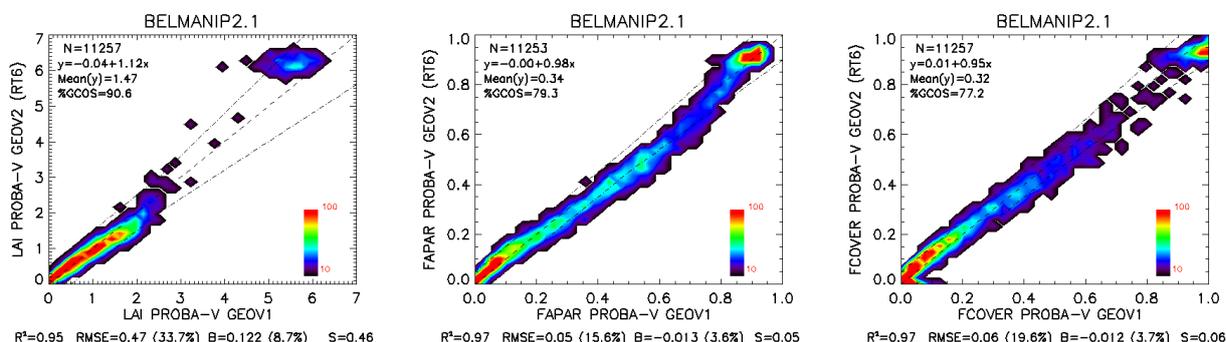


Figure 56: PROBA-V GEOV2 LAI, FAPAR and FCOVER products (RT6 mode) versus PROBA-V GEOV1 similar product scatter-plots over all BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

Table 18: Relevant statistics between PROBA-V GEOV2 RT6 LAI/FAPAR/FCOVER products versus PROBA-V GEOV1 over all BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1.

	PROBA-V GEOV2 vs PROBA-V GEOV1		
	LAI	FAPAR	FCOVER
Correlation (R^2)	0.95	0.97	0.97
Bias	0.12	-0.013	-0.012
RMSE	0.47	0.05	0.06
Offset (M.A.R)	-0.04	0.00	0.01
Slope (M.A.R)	1.12	0.98	0.95
p-value	0.001	0.001	0.001
%optimal (GCOS)	90.6	79.3	77.2

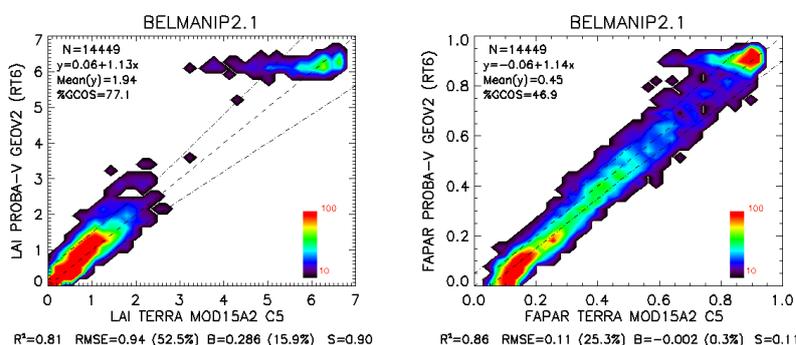


Figure 57: PROBA-V GEOV2 LAI and FAPAR products (RT6 mode) versus MODIS C5 similar product scatter-plots over all BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

Table 19: Relevant statistics between PROBA-V GEOV2 RT6 LAI/FAPAR/FCOVER products versus MODIS C5 over all BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1.

	PROBA-V GEOV2 vs MODIS C5	
	LAI	FAPAR
Correlation (R^2)	0.81	0.86
Bias	0.286	-0.002
RMSE	0.94	0.11
Offset (M.A.R)	0.06	-0.06
Slope (M.A.R)	1.13	1.14
p-value	0.001	0.001
%optimal (GCOS)	77.1	46.9

- **Analysis per biome type**

This section presents the statistical analysis between PROBA-V GEOV2 and references PROBA-V GEOV1 and MODIS C5 products per land cover type over the BELMANIP2.1 network of sites during one year of data (from October 2013 to September 2014). The scatter-plots per continental region can be found in ANNEX IX. Analysis per Continental Region.

For LAI:

- A good agreement between PROBA-V GEOV2 and GEOV1 was found for all biome type (Figure 58), with correlation better than 0.89 and RMSE lower than 0.6 except for EBF where the "gap filling" algorithm introduces stable high GEOV2 values, as observed in the temporal analysis (section 4.4.2).
- The percentage of pixels within the GCOS uncertainty levels in the comparison between PROBA-V GEOV2 and GEOV1 is greater than 90% for non-forest sites and 70.3%, 84.3% and 79.6% for EBF, DBF and NLF respectively.
- Larger discrepancies were found in the comparison between PROBA-V GEOV2 and MODIS C5 for all biome type (Figure 59), mainly for EBF due to the noisy retrievals observed in MODIS C5 LAI as compared with the filled values of GEOV2. For the rest of biomes, overall discrepancies are lower than 1 except for DBF (RMSE=1.11) (Table 21). Higher GEOV2 LAI values than MODIS LAI values over croplands where MODIS tends to underestimate LAI over crops (see section 4.7).

For the FAPAR:

- The scatter plots between PROBA-V GEOV2 and GEOV1 (Figure 60) show good agreement (RMSE<0.1) for all biome type. GEOV2 tends to provide lower FAPAR retrievals than GEOV1 for all biome type except for EBF, with larger negative bias for BDF and NLF.

- The percentage within the GCOS uncertainty requirement between GEOV2 and GEOV1 is very good (>90%) for EBF and SBA and satisfactory good (between 68% and 80%) for DBF, Cultivated and Herbaceous, whereas it is poor for NLF (55.1%) (Table 22).
- The comparison between GEOV2/PV and MODIS C5 (Figure 61) shows generally lower bias than the comparison between GEOV2 and GEOV1 but large scattering, and larger overall discrepancies (RMSE) with lower percentages of pixels within the GCOS uncertainty level (Table 23).

Finally, for the FCOVER (Figure 62 and Table 24):

- Overall good consistency between GEOV2 and GEOV1, but GEOV2 tends to provide lower values mainly observed for medium to high FCOVER retrievals in Cultivated, Herbaceous and DBF sites.

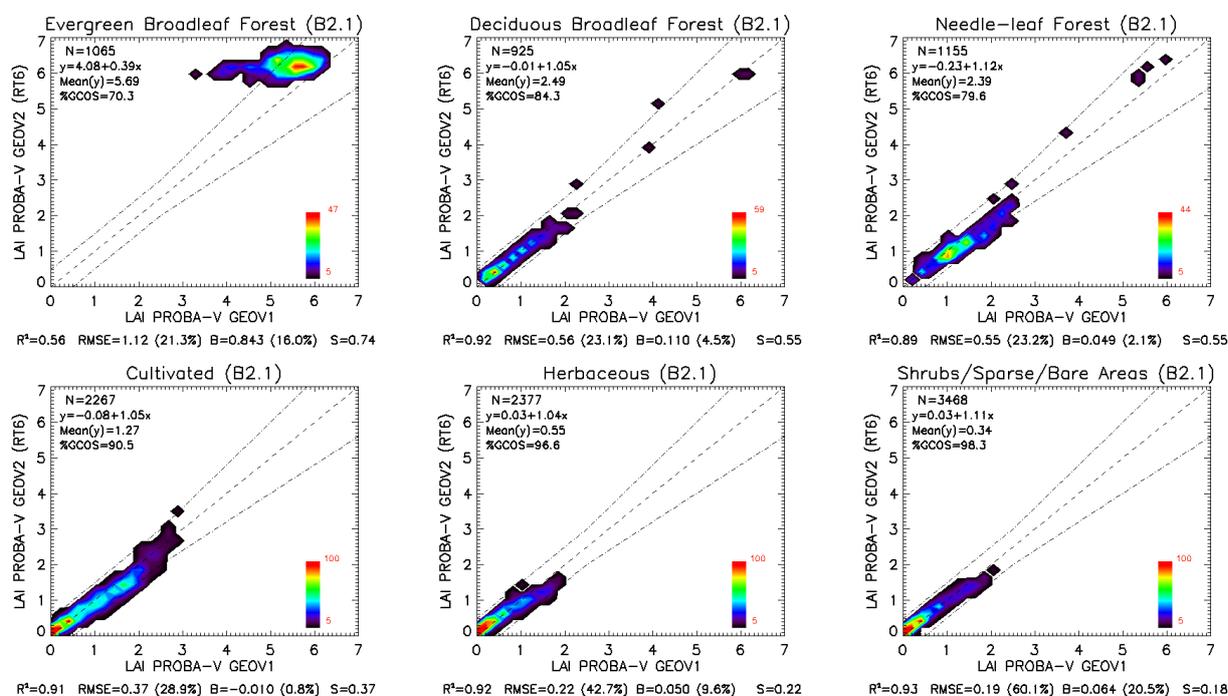


Figure 58: PROBA-V GEOV2 LAI product versus PROBA-V GEOV1 product scatter-plots over BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period for each land cover type. The terms Band S represent the mean and the standard deviation of the difference. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

Table 20: Relevant statistics between PROBA-V GEOV2 LAI products versus PROBA-V GEOV1 over all BELMANIP-2.1 sites per main biome type for the Oct.2013-Sep.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1. Numbers in brackets indicate statistics resulting from excluding filled pixels.

LAI: PROBA-V GEOV2 vs PROBA-V GEOV1						
	EBF	DBF	NLF	Cult.	Herb.	SBA
Correlation	0.56 (0.66)	0.92 (0.92)	0.89 (0.89)	0.91 (0.91)	0.92 (0.92)	0.93 (0.93)
Bias	0.84 (0.779)	0.11 (0.109)	0.049 (0.079)	-0.01 (-0.016)	0.050 (0.048)	0.064 (0.068)
RMSE	1.12 (1.06)	0.56 (0.56)	0.55 (0.55)	0.37 (0.34)	0.22 (0.22)	0.19 (1.17)
Offset	4.08 (3.93)	-0.01 (0)	-0.23 (-0.23)	-0.08 (-0.08)	0.03 (0.03)	0.03 (0.04)
Slope	0.39 (0.42)	1.05 (1.05)	1.12 (1.13)	1.05 (1.05)	1.04 (1.04)	1.11 (1.09)
p-value	0.027 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.014 (0.045)	0.001 (0.001)
%optimal(GCOS)	70.3 (73.3)	84.3 (84.6)	79.6 (79.4)	90.5 (91.1)	96.6 (96.8)	98.3 (98.6)

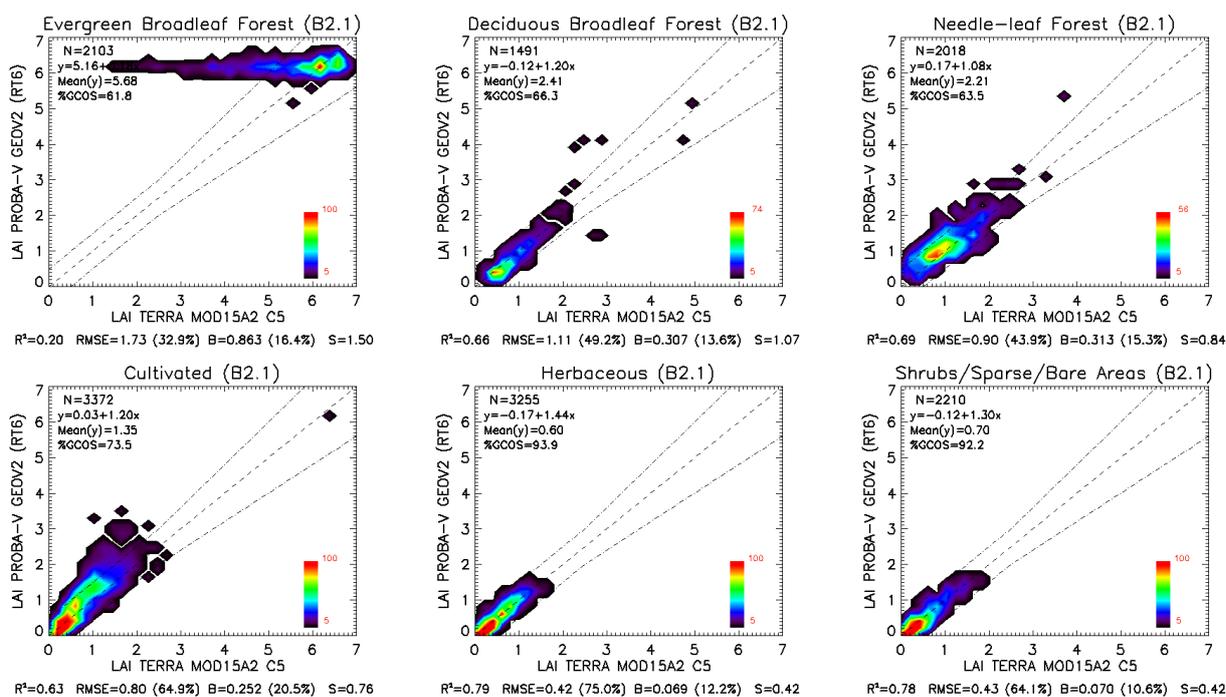


Figure 59: PROBA-V GEOV2 LAI product versus MODIS C5 product scatter-plots over BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period for each land cover type. The terms Band S represent the mean and the standard deviation of the difference. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

Table 21: Relevant statistics between PROBA-V GEOV2 LAI products versus MODIS C5 over all BELMANIP-2.1 sites per main biome type for the Oct.2013-Sep.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1. Numbers in brackets indicate statistics resulting from excluding filled pixels.

LAI: PROBA-V GEOV2 vs MODIS C5						
	EBF	DBF	NLF	Cult.	Herb.	SBA
Correlation	0.20 (0.46)	0.66 (0.75)	0.69 (0.74)	0.63 (0.63)	0.79 (0.83)	0.78 (0.84)
Bias	0.86 (0.51)	0.31 (0.25)	0.31(0.31)	0.25 (0.23)	0.069 (0.05)	0.07 (0.04)
RMSE	1.73 (1.14)	1.11 (0.96)	0.90 (0.85)	0.80 (0.76)	0.42 (0.37)	0.43 (0.33)
Offset	5.16 (4.52)	-0.12 (- 0.29)	0.17 (-0.05)	0.03 (-0.09)	-0.17 (- 0.18)	-0.1 (-0.12)
Slope	0.18 (0.29)	1.20 (1.26)	1.08 (1.17)	1.20 (1.31)	1.44 (1.44)	1.30 (1.27)
p-value	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
%optimal (GCOS)	61.8 (72.7)	66.3 (65.4)	63.5 (63.2)	73.5 (75.5)	93.9 (94.7)	92.2 (94.5)

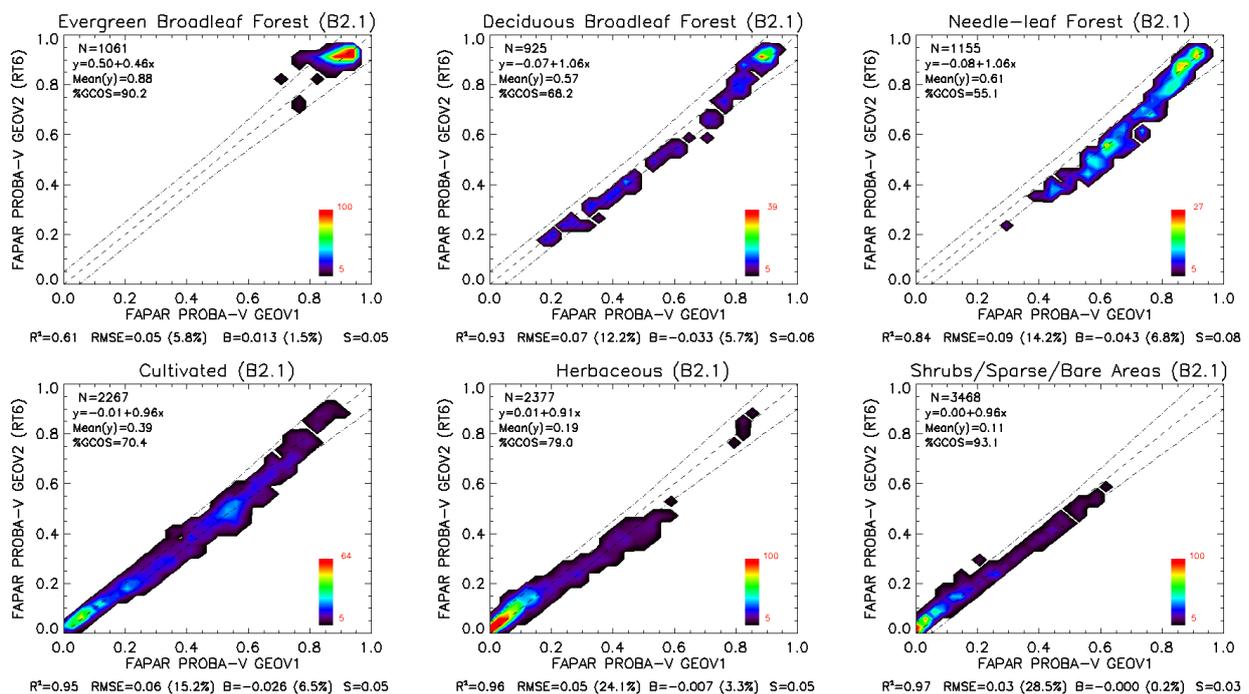


Figure 60: PROBA-V GEOV2 FAPAR product versus PROBA-V GEOV1 product scatter-plots over BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period for each land cover type. The terms Band S represent the mean and the standard deviation of the difference. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

Table 22: Relevant statistics between PROBA-V GEOV2 FAPAR products versus PROBA-V GEOV1 over all BELMANIP-2.1 sites per main biome type for the Oct.2013-Sep.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1. Numbers in brackets indicate statistics resulting from excluding filled pixels.

FAPAR: PROBA-V GEOV2 vs PROBA-V GEOV1						
	EBF	DBF	NLF	Cult.	Herb.	SBA
Correlation	0.61 (0.76)	0.93 (0.93)	0.84 (0.84)	0.95 (0.95)	0.96 (0.96)	0.97 (0.97)
Bias	0.013(0.01)	-0.033 (-0.036)	-0.043 (-0.041)	-0.026 (-0.027)	-0.007 (-0.006)	0 (0.003)
RMSE	0.05(0.05)	0.07 (0.07)	0.09 (0.09)	0.06 (0.06)	0.05 (0.05)	0.03 (0.03)
Offset	0.5 (0.44)	-0.07 (-0.07)	-0.08 (-0.08)	-0.01 (-0.01)	0.01 (0.01)	0 (0.01)
Slope	0.46 (0.52)	1.06 (1.06)	1.06 (1.06)	0.96 (0.96)	0.91 (0.9)	0.96 (0.96)
p-value	0.041 (0.001)	0.001 (0.001)	0.001(0.001)	0.001(0.001)	0.001 (0.001)	0.001 (0.001)
%optimal(GCOS)	90.2(91.2)	68.2 (66.6)	55.1 (54.4)	70.4 (70.3)	79.0 (78.9)	93.1 (92.4)

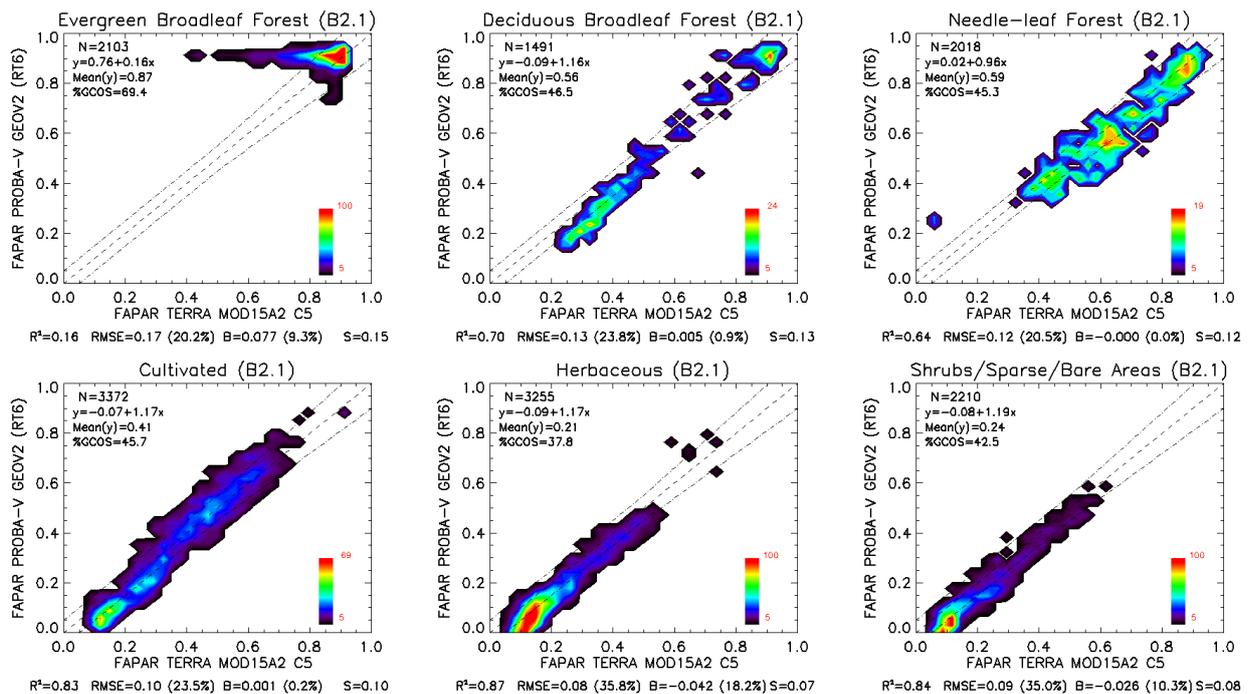


Figure 61: PROBA-V GEOV2 FAPAR product versus MODIS C5 product scatter-plots over BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period for each land cover type. The terms Band S represent the mean and the standard deviation of the difference. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

Table 23: Relevant statistics between PROBA-V GEOV2 FAPAR products versus MODIS C5 over all BELMANIP-2.1 sites per main biome type for the Oct.2013-Sep.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1. Numbers in brackets indicate statistics resulting from excluding filled pixels.

FAPAR: PROBA-V GEOV2 vs MODIS C5						
	EBF	DBF	NLF	Cult.	Herb.	SBA
Correlation	0.16 (0.37)	0.7 (0.78)	0.64 (0.71)	0.86 (0.86)	0.87 (0.9)	0.84 (0.89)
Bias	0.077 (0.049)	0.005 (-0.007)	0 (-0.006)	0.001 (-0.005)	-0.042 (-0.044)	-0.026 (-0.032)
RMSE	0.17 (0.11)	0.13 (0.11)	0.12 (0.1)	0.1 (0.09)	0.08 (0.08)	0.09 (0.08)
Offset	0.76 (0.67)	-0.09 (-0.11)	0.02 (-0.05)	-0.07 (-0.08)	-0.09 (-0.09)	-0.08 (-0.07)
Slope	0.16 (0.27)	1.16 (1.19)	0.96 (1.07)	1.17 (1.2)	1.17 (1.19)	1.19 (1.16)
p-value	0.001 (0.001)	0.001 (0.001)	0.002 (0.001)	0.001 (0.001)	0.001 (0.001)	0.001 (0.001)
%optimal(GCOS)	69.4 (75)	46.5 (46.4)	45.3 (54)	45.7 (45.9)	37.8 (38.4)	42.5 (42.5)

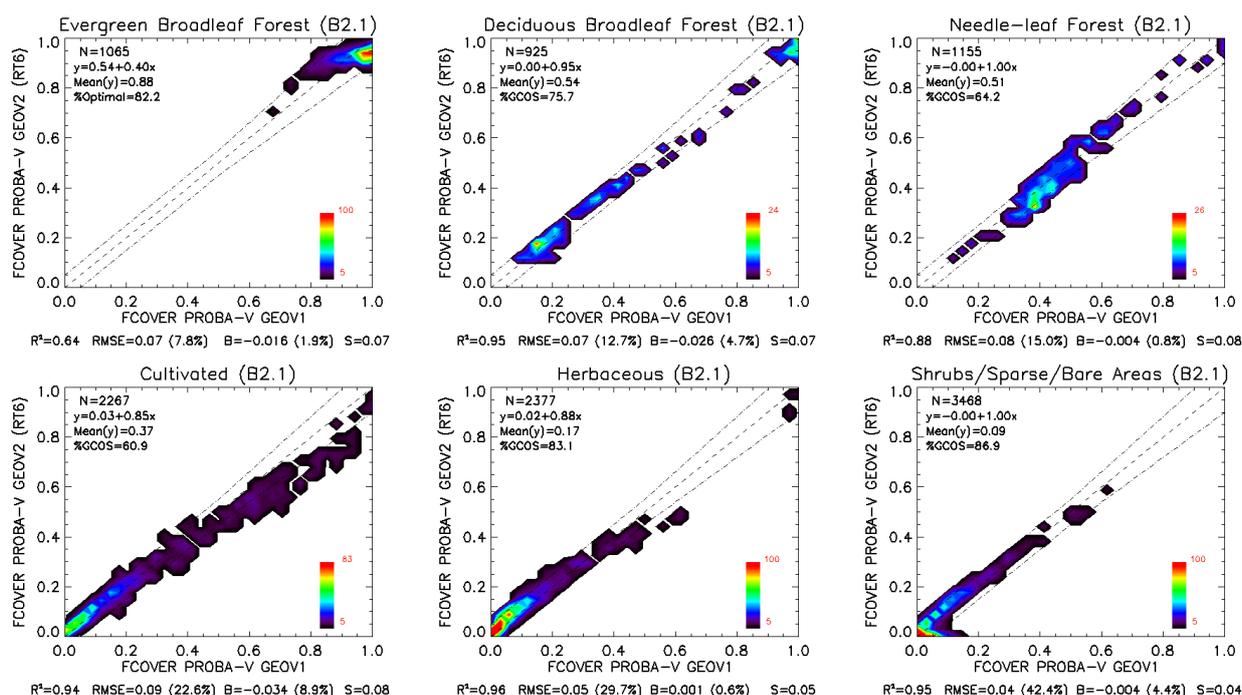


Figure 62: PROBA-V GEOV2 FCOVER product versus PROBA-V GEOV1 product scatter-plots over BELMANIP-2.1 sites for the Oct.2013-Sep.2014 period for each land cover type. The terms Band S represent the mean and the standard deviation of the difference. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

Table 24: Relevant statistics between PROBA-V GEOV2 FCOVER products versus PROBA-V GEOV1 over all BELMANIP-2.1 sites per main biome type for the Oct.2013-Sep.2014 period. p-value corresponds to the test on whether the slope is significantly different to 1. Numbers in brackets indicate statistics resulting from excluding filled pixels.

	FCOVER: PROBA-V GEOV2 vs PROBA-V GEOV1					
	EBF	DBF	NLF	Cult.	Herb.	SBA
Correlation	0.64 (0.69)	0.95 (0.94)	0.88 (0.88)	0.94 (0.94)	0.96 (0.95)	0.95 (0.96)
Bias	-0.016 (-0.018)	-0.026 (-0.027)	-0.004 (-0.002)	-0.034 (-0.034)	0.001 (0.001)	-0.004 (0.003)
RMSE	0.07 (0.07)	0.07 (0.07)	0.08 (0.07)	0.09 (0.09)	0.05 (0.05)	0.04 (0.03)
Offset	0.54 (0.52)	0.00 (0.01)	0 (0)	0.03 (0.03)	0.02 (0.02)	0 (0)
Slope	0.4 (0.42)	0.95 (0.93)	1.00 (0.99)	0.85 (0.84)	0.88 (0.87)	1.00 (0.98)
p-value	0.001 (0.001)	0.001 (0.001)	0.725 (0.361)	0.001 (0.001)	0.001 (0.001)	0.593 (0.002)
%optimal	82.2 (79.1)	75.7 (72.5)	64.2 (65.1)	60.9 (61)	83.1 (82.9)	86.9 (90.3)

4.7 REGIONAL ANALYSIS

Due to the limited overlap period between PROBA-V and SPOT/VGT (winter time in northern hemisphere), the statistical analysis results over BELMANIP2.1 network of sites may not be representative of global conditions. Most of the B2.1 samples are located in the north hemisphere and have low vegetation activity during this period. Moreover, B2.1 sites were used for re-scaling the GEOV2/PV daily outputs to GEOV2/VGT. To analyse better the existing discrepancies observed in the spatial consistency analysis, a regional analysis over a window (20°x35°) in Africa (from 5°S-10°E to 25°S-45°E), where vegetation displays the growing cycle during the overlap period, has been performed. Figure 63 displays the LAI, FAPAR and FCOVER maps of PROBA-V GEOV2 over the selected area in Africa on 31th of March, 2014, as well as the difference maps between PROBA-V GEOV2 and SPOT/VGT GEOV2. Scatter-plots between PROBA-V GEOV2 and SPOT/VGT GEOV2 and relevant statistics are shown in Figure 64.

Benchmarking with MODIS C5 and GEOV1 products (difference maps and scatter-plots) are presented for the same date in Figure 65 to Figure 72.

Finally, the temporal evolution of the slope of the linear fit between PROBA-V and SPOT/VGT during the overlap period is compared for both GEOV1 and GEOV2 products in Figure 73.

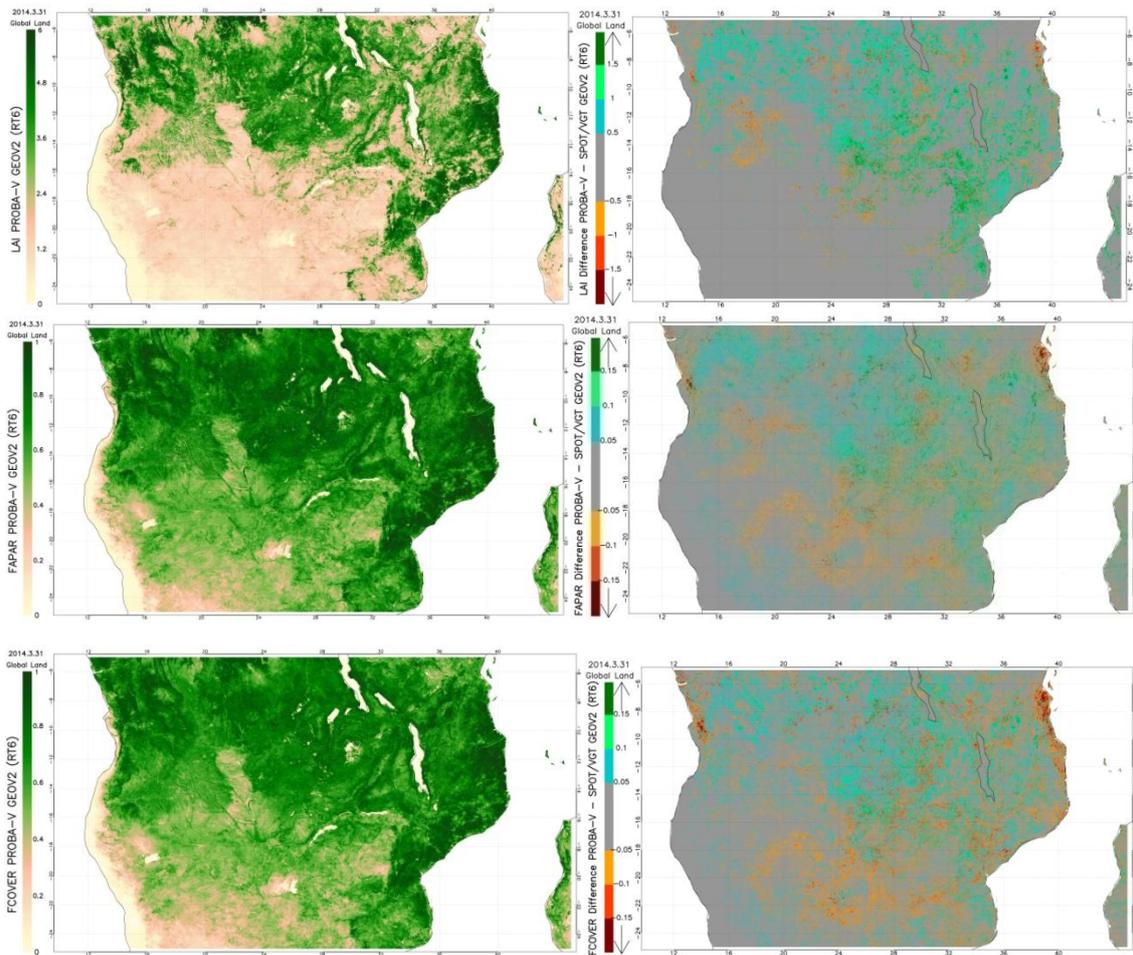


Figure 63: PROBA-V GEOV2 LAI (Top), FAPAR (Middle) and FCOVER (Bottom) maps (Left) and maps of differences (Right) between PROBA-V GEOV2 and SPOT/VGT GEOV2 over a selected area in Africa on 31th of March, 2014.

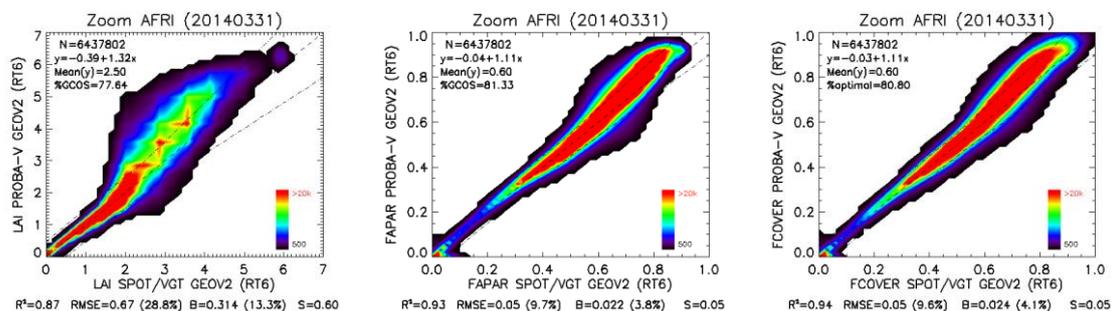


Figure 64: PROBA-V GEOV2 LAI, FAPAR and FCOVER products (RT6 mode) versus SPOT/VGT GEOV2 similar product scatter-plots over a selected area in Africa on 31th of March, 2014. Relevant statistics are displayed in the figure. Dashed lines correspond to the 1:1 line and GCOS uncertainty levels.

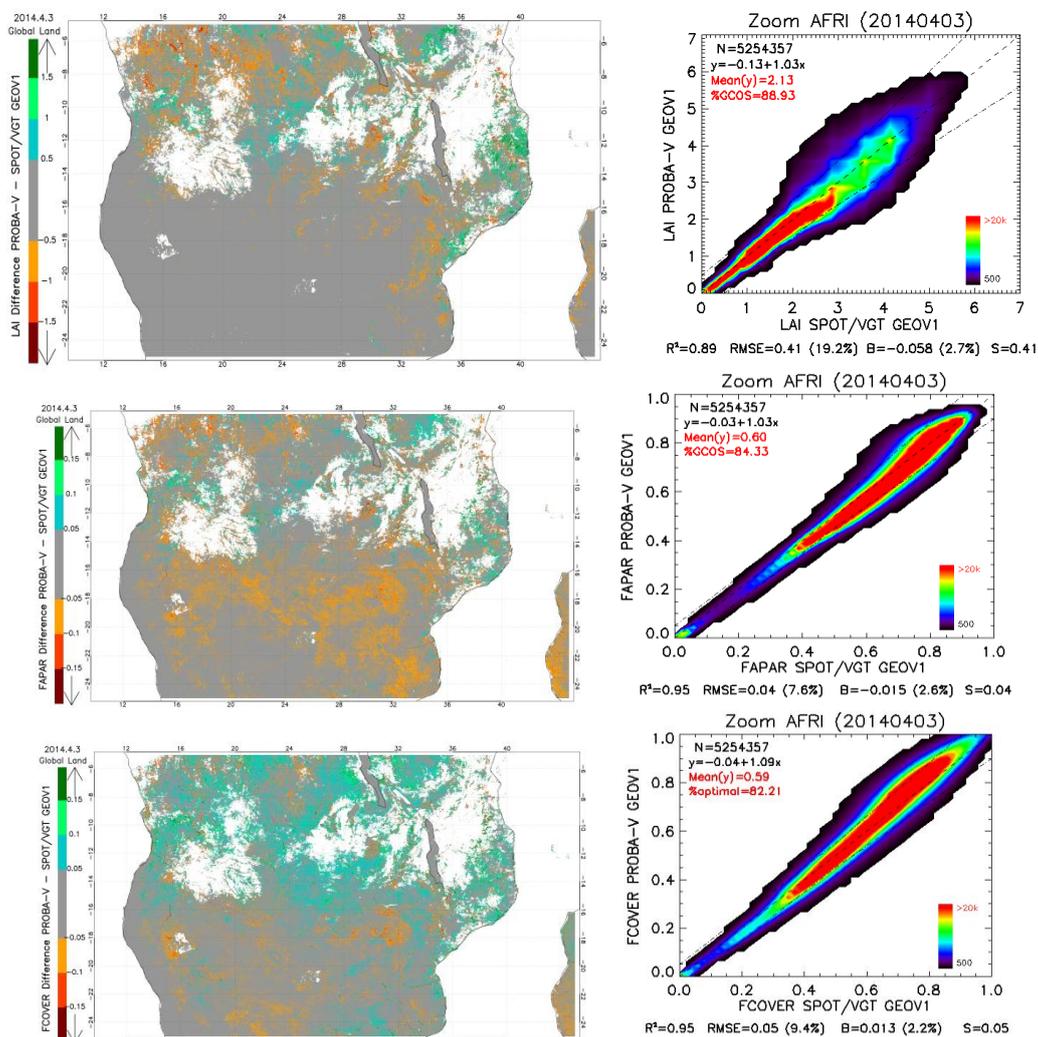


Figure 65: GEOV1/PV vs GEOV1/VGT LAI (top), FAPAR (middle) and FCOVER (bottom) over a selected area in Africa on 03rd of April, 2014.

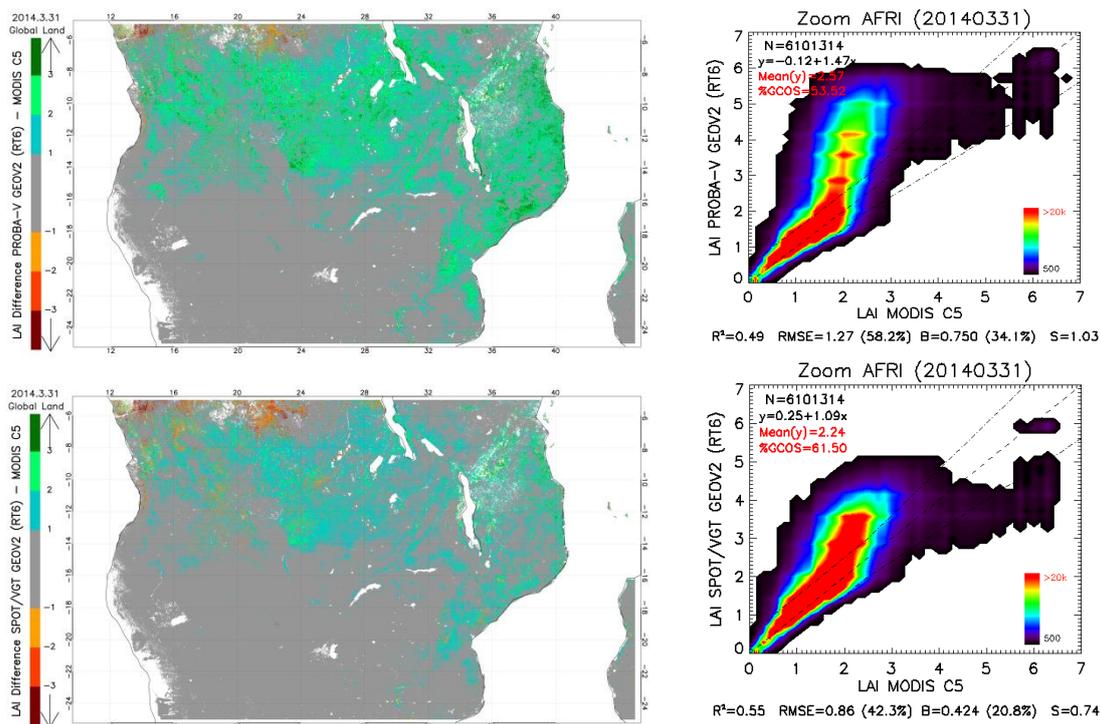


Figure 66: GEOV2 LAI versus MODIS C5 LAI over a selected area in Africa on 31th of March, 2014. Top: PROBA-V GEOV2. Bottom: SPOT/VGT GEOV2. Note the range of the legend in difference maps ranges here between -4 and 4.

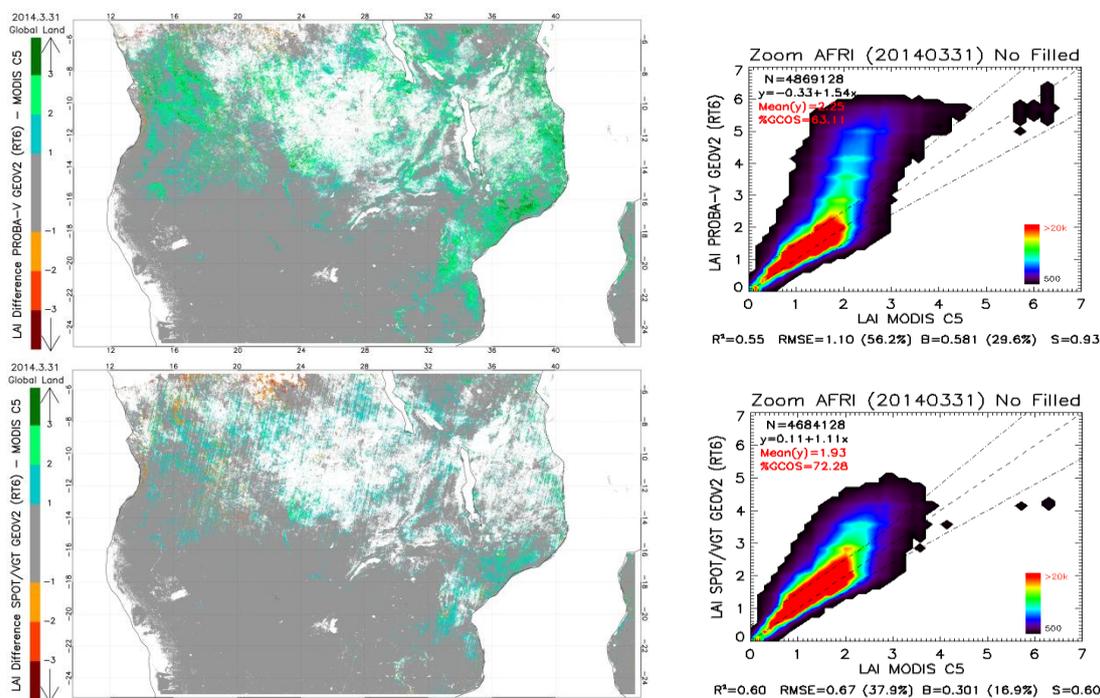


Figure 67: As in Figure 66 excluding GEOV2 filled values (QF bit 3).

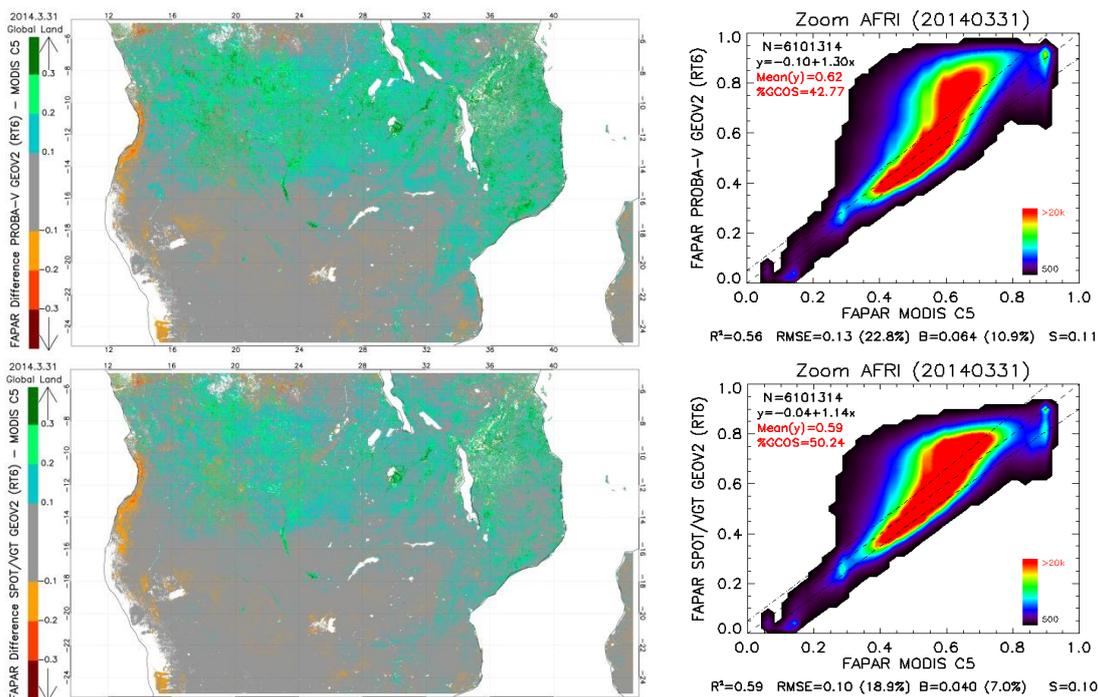


Figure 68: GEOV2 FAPAR versus MODIS C5 FAPAR over a selected area in Africa on 31th of March, 2014. Top: PROBA-V GEOV2. Bottom: SPOT/VGT GEOV2. Note the range of the legend in difference maps ranges here between -0.4 and 0.4

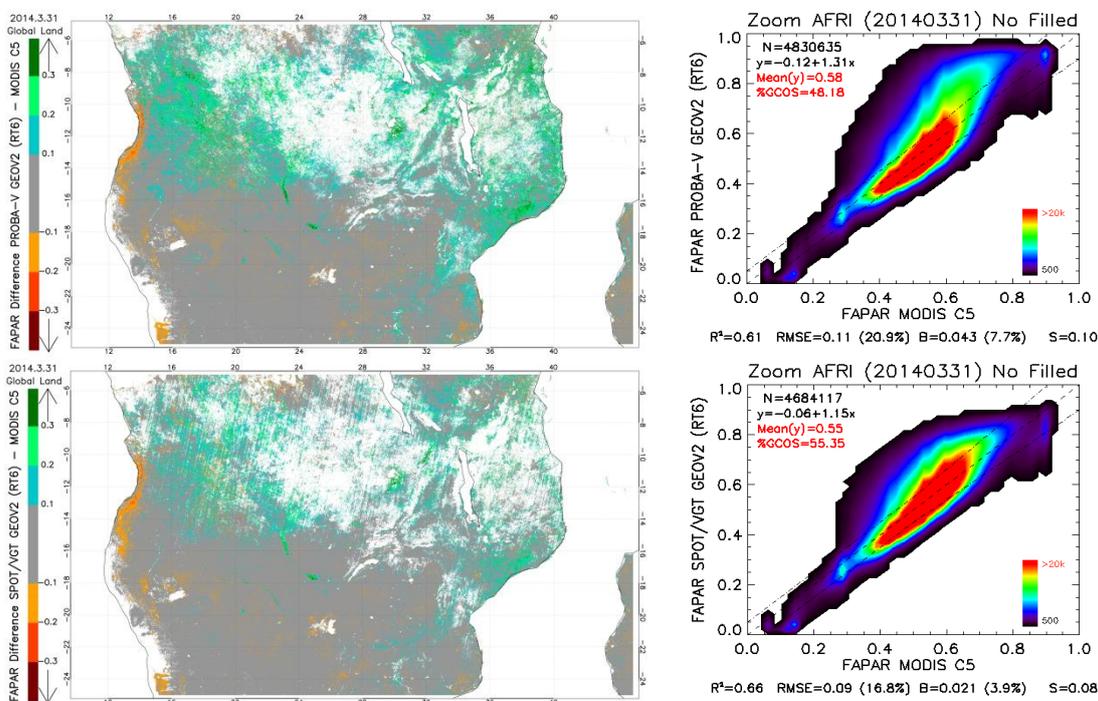


Figure 69: As in Figure 68 excluding GEOV2 filled values (QF bit 3).

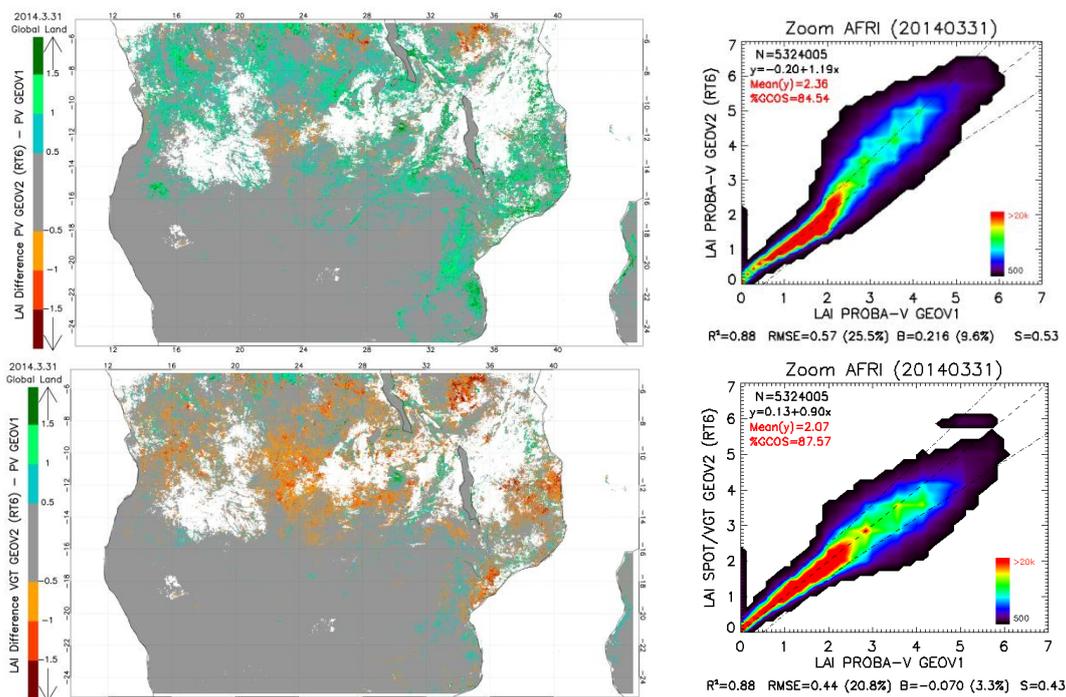


Figure 70: GEOV2 LAI versus GEOV1/PV LAI over a selected area in Africa on 31th of March, 2014.
 Top: PROBA-V GEOV2. Bottom: SPOT/VGT GEOV2.

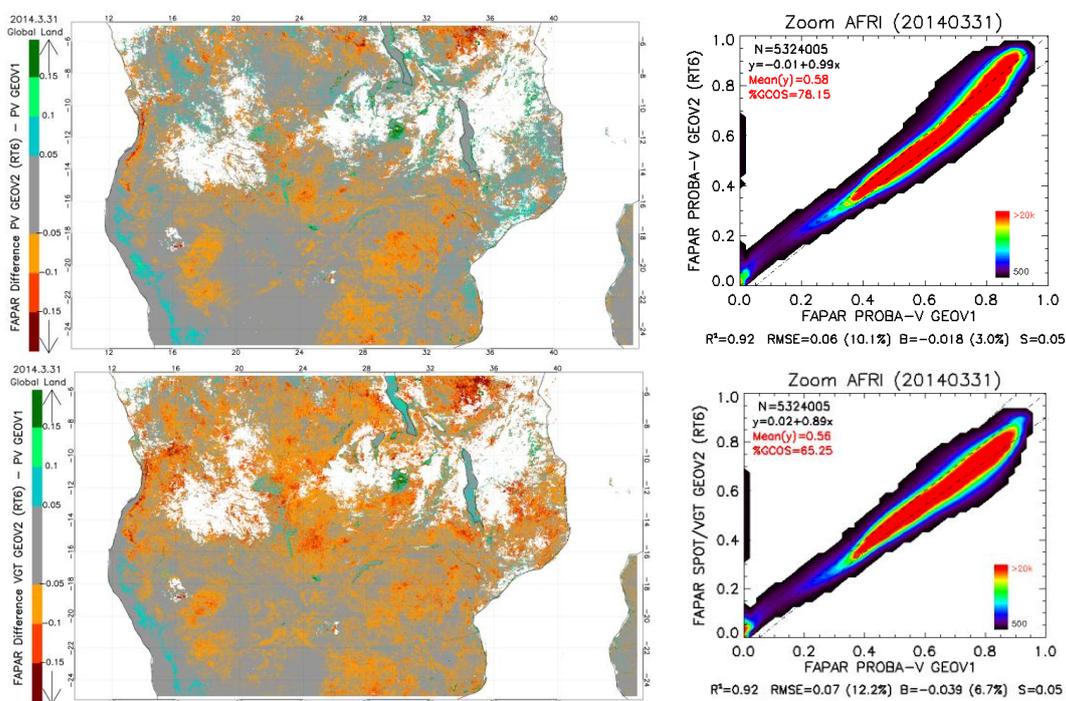


Figure 71: GEOV2 FAPAR versus GEOV1/PV FAPAR over a selected area in Africa on 31th of March, 2014. Top: PROBA-V GEOV2. Bottom: SPOT/VGT GEOV2.

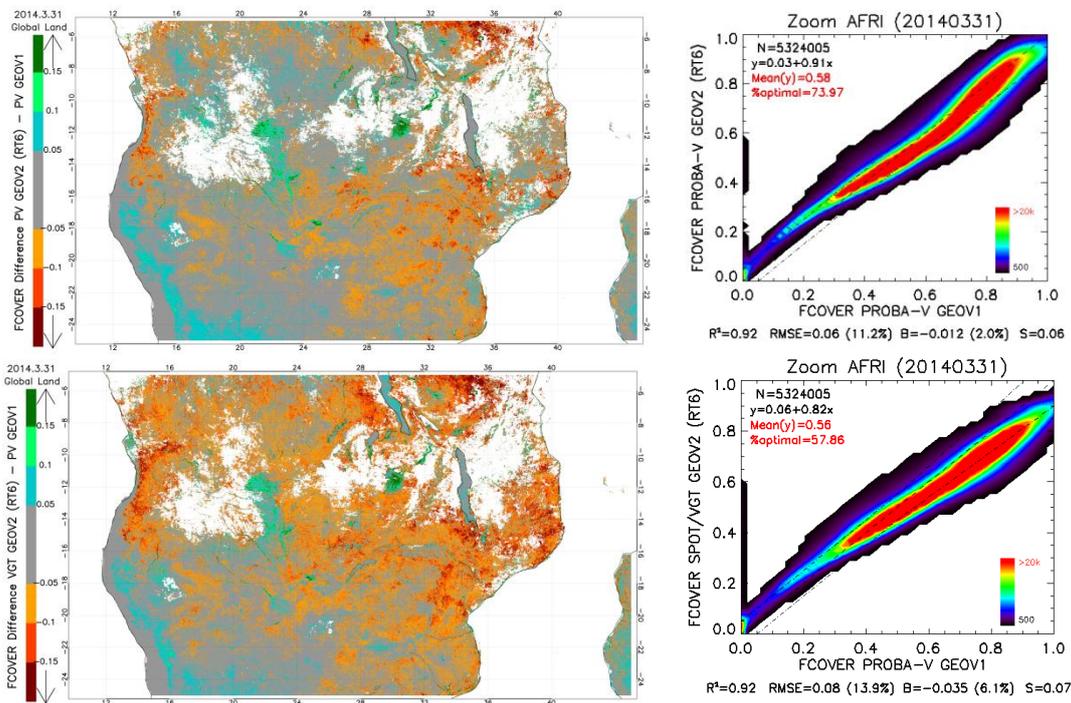


Figure 72: GEOV2 FCOVER versus GEOV1/PV FCOVER over a selected area in Africa on 31th of March, 2014. Top: PROBA-V GEOV2. Bottom: SPOT/VGT GEOV2.

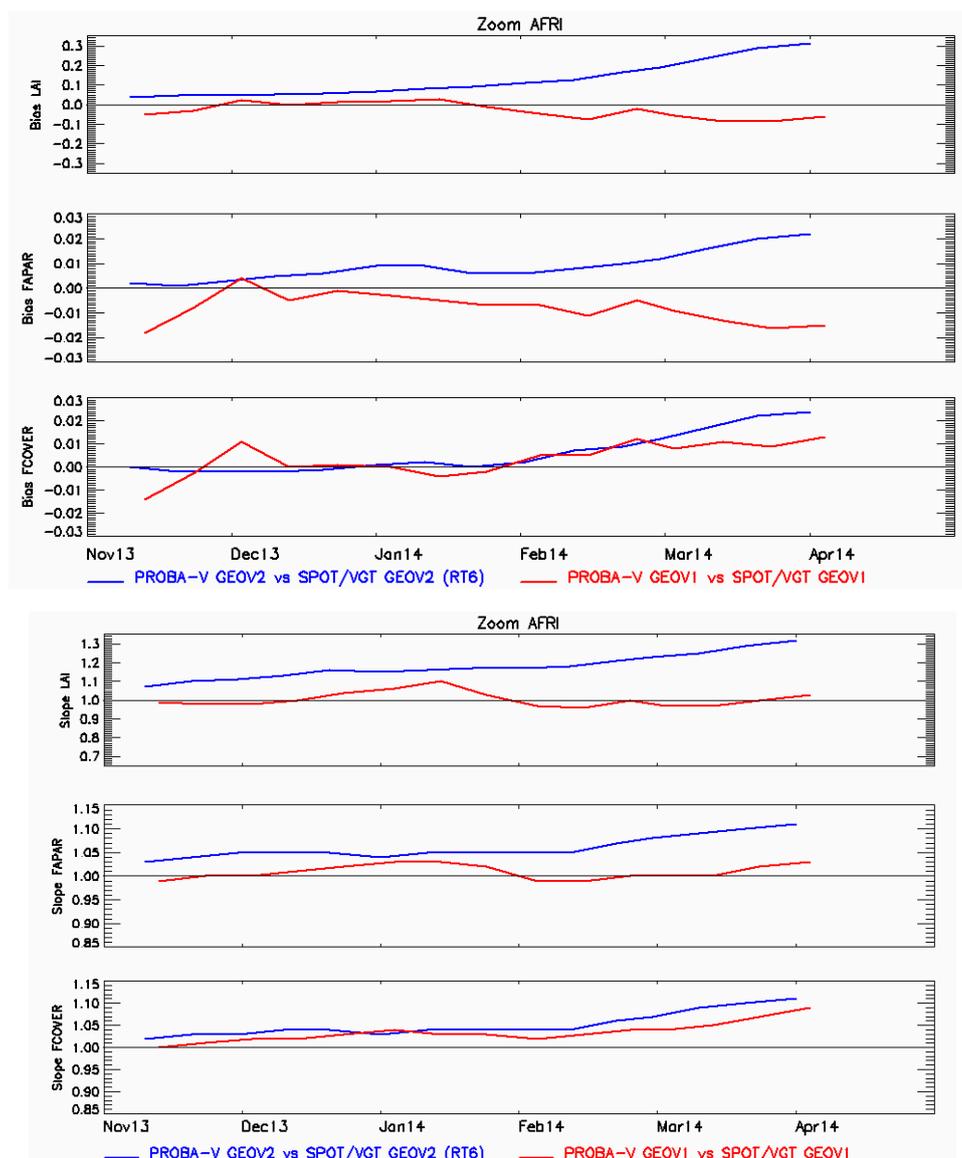


Figure 73: Temporal evolution of the mean bias (top) and the slope of the linear fit (bottom) between PROBA-V and SPOT/VGT GEOV1 and GEOV2 LAI (top), FAPAR (middle) and FCOVER (bottom) products over a selected region in Africa.

These results show that:

- GEOV2 PROBA-V provides higher values than GEOV2 SPOT/VGT during the maximum development of vegetation, over the region of Africa. This positive bias is mainly observed for LAI, with differences higher than 1.5 units over some areas. For LAI the mean bias and the slope of the linear fit increases as the vegetation increases (relative mean bias from 4% in November to 12% in March, slope of the linear fit changes from 1.1 to 1.3 in the same period, see Figure 73 and ANNEX XI. Monthly Scatter-plots over Africa Region (20°x35°)). The bias mostly affects to LAI values larger than 2. For FAPAR and FCOVER, differences

are spatially randomly distributed ranging typically between ± 0.15 . However, a slight systematic tendency is observed as the vegetation increases (Figure 73), with mean relative bias from 0.5% in November to about 3.5% in March for both products. The slope of the linear fit also increase for FAPAR and FCOVER as the vegetation increases, with variations ranging typically between 1.02 and 1.10.

- These GEOV2 PV vs VGT systematic discrepancies observed for LAI are not observed for the GEOV1 PV vs VGT products, where random discrepancies (similar magnitude than for GEOV2) are mainly observed (mean bias between 0.2% and 3.7%, slope of the fit around 0.96-1.1, higher in January). For FAPAR and FCOVER, similar results are obtained for GEOV1, with mostly random discrepancies and low mean bias mainly affecting to FCOVER (see ANNEX XI. Monthly Scatter-plots over Africa Region (20°x35°))
- GEOV2/PV LAI provides large bias as compared to MODIS LAI over large areas (typically ranging between 2 and 3), larger than the discrepancies between GEOV2/VGT and MODIS LAI (typically ranging between 1 and 2). For the FAPAR, GEOV2/PV shows also higher discrepancies (ranging between 0.2 and 0.3) with MODIS FAPAR than GEOV2/VGT (ranging between 0.1 and 0.2) over this region/date.
- Similar discrepancies are obtained when filled retrievals are removed from the analysis, which suggest that the filling method does not introduce additional discrepancies.
- GEOV2/PV LAI provides positive bias (around 10%) as compared to GEOV1/PV LAI, whereas GEOV2/VGT shows slightly negative bias (around 3%) with GEOV1/PV and slightly lower overall discrepancies (RMSE). For FAPAR and FCOVER, similar distributions are observed, with improved consistency for GEOV2/PV with GEOV1/PV compared to GEOV2/VGT.

4.8 ACCURACY ASSESSMENT

Figure 74, Figure 75, Figure 76 show the scatter-plots between PROBA-V GEOV2, PROBA-V GEOV1 and MODIS C5 satellite products and ground-based reference maps generated according CEOS LPV guidelines. The relevant statistics are summarized in Table 25 considering two cases: concomitant dataset over ImagineS cropland sites during the 2014 year, and considering also forest and grassland OLIVE Direct sites over non-concomitant years (same date of a different year). The Accuracy Assessment for GEOV2/PV RT0 mode is presented in ANNEX X. Accuracy Assessment PROBA-V Version 2 RT0 and validation statistics in Table 27.

The accuracy assessment shows:

- For LAI, GEOV2 shows an accuracy of 1.06 (all data) or 0.79 (concomitant croplands) with a tendency to overestimate (mean positive bias of about 0.5 in both cases, slope of the MAR regression about 0.2), and 65% of the samples within GCOS requirements. GEOV1 provides slightly better accuracy than GEOV2 and similar to MODISC5 over this limited dataset with RMSE of 0.8 and mean positive bias of 0.25 (all data) or 0.4 (concomitant croplands), with 67% of samples within GCOS accuracy levels. MODIS accuracy is of 0.79

for all data, and 0.88 for concomitant croplands, displaying a negative bias for concomitant croplands (with almost all croplands shows negative bias, mean bias -0.12 and offset of the linear fit -0.5). MODIS LAI shows 60% of the data points within the GCOS accuracy levels.

- Large overestimation for all LAI products is observed over La Albufera rice site in June and July, at points #11, where GEOV2 provides closer estimation, and #12, where GEOV1 provides closer estimation, which is a particular case of vegetation under flooded conditions. In this particular condition, the three satellite products overestimate which can be interpreted due to the lack of representation of flooded (very dark) backgrounds in the canopy radiative transfer models used for deriving CYCLOPES (Baret et al., 2007) and MODIS (Knyazikhin et al., 1999) products. Thus, larger values of vegetation are needed, to compensate the strong absorption of water surfaces.
- For the FAPAR, GEOV2 and GEOV1 shows very similar results, with an accuracy of 0.1 and a mean positive bias of about 0.05 (all data) that increase up to 0.1 when only concomitant values (cropland) are considered. MODIS FAPAR displays similar overall accuracy (RMSE=0.1), but showing lower accuracy for very low values (positive bias) and better accuracy for concomitant values (croplands) with a slight mean bias of 0.05 mainly due to the points #11 and #12 (La Albufera rice site, flooded conditions). The other concomitant cropland points fit well within the GCOS accuracy levels.
- For the FCOVER, both GEOV2 and GEOV1 display similar performances with ground truth. Low accuracy with RMSE values of 0.17 (0.12 for concomitant data) and mean positive bias of 0.1 in both cases.
- For GEOV2 RT0 (NRT estimates) very similar accuracy are obtained for FAPAR and FCOVER, but improved accuracy as compared to GEOV2 RT6 is obtained for LAI with RMSE of 0.83 (0.74) for all (concomitant cropland) data and a slightly lower positive bias of about 0.3.

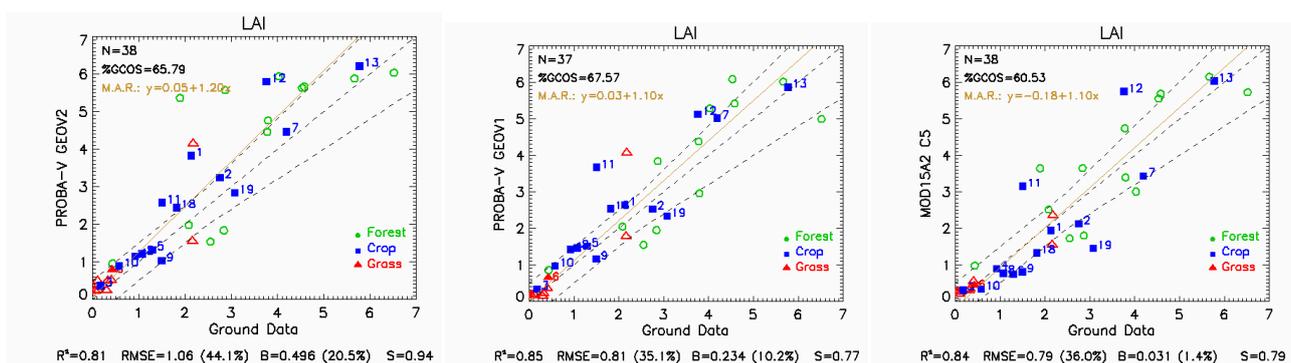


Figure 74: Comparison of satellite LAI products (PROBA-V GEOV2, PROBA-V GEOV1 and MODIS C5) with the ground-based maps. Filled (unfilled) symbols correspond to concomitant (non-concomitant) values. Forest stands for Broadleaf Evergreen, Broadleaf Deciduous and Needle-leaf Forests, Crops stands for Cultivated and Grass refers to Herbaceous, Shrubs, Sparse and Bare Areas sites.

Numbers identify the ground data (Table 11). Dashed lines correspond to the 1:1 line and GCOS uncertainty levels, and continuous yellow line to the linear fit using Major Axis Regression (M.A.R.).

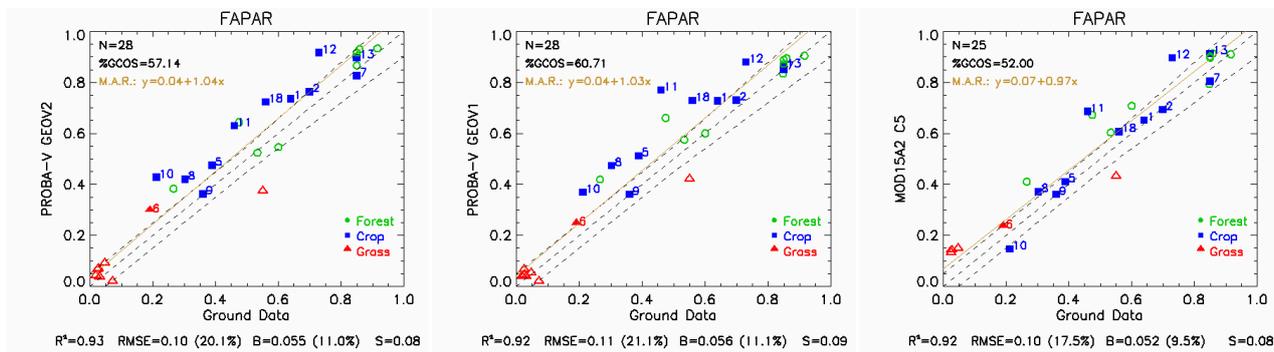


Figure 75: As in Figure 74 for FAPAR.

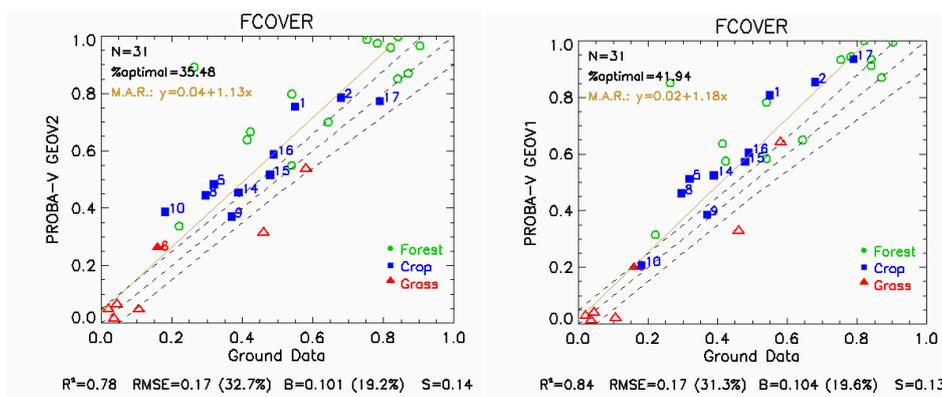


Figure 76: As in Figure 74 for FCOVER.

Table 25: Performance of PROBA-V GEOV2 RT6 (RT0 in italics), PROBA-V GEOV1 and MOD15A2 C5 products against reference ground based maps.

		Concomitant data			All data		
		LAI	FAPAR	FCOVER	LAI	FAPAR	FCOVER
PROBA-V GEOV2 vs Ground Data	N	15	12	11	38	28	31
	Correlation	0.88 <i>0.86</i>	0.9 <i>0.89</i>	0.85 <i>0.85</i>	0.81 <i>0.86</i>	0.93 <i>0.92</i>	0.78 <i>0.77</i>
	Bias	0.46 <i>0.38</i>	0.10 <i>0.09</i>	0.10 <i>0.08</i>	0.49 <i>0.32</i>	0.06 <i>0.05</i>	0.10 <i>0.09</i>
	RMSE	0.79 <i>0.74</i>	0.12 <i>0.12</i>	0.12 <i>0.11</i>	1.06 <i>0.83</i>	0.1 <i>0.1</i>	0.17 <i>0.17</i>
	Offset	0.09 <i>0.16</i>	0.14 <i>0.12</i>	0.14 <i>0.15</i>	0.05 <i>0.06</i>	0.04 <i>0.06</i>	0.04 <i>0.04</i>
	Slope	1.18 <i>1.11</i>	0.93 <i>0.95</i>	0.91 <i>0.85</i>	1.2 <i>1.12</i>	1.04 <i>0.97</i>	1.13 <i>1.09</i>
	p-value	0.356 <i>0.51</i>	0.595 <i>0.62</i>	0.024 <i>0.221</i>	0.194 <i>0.127</i>	0.418 <i>0.55</i>	0.002 <i>0.203</i>
	%optimal (LAI, FAPAR GCOS)	73.3 <i>66.7</i>	33.3 <i>41.7</i>	27.3 <i>21.3</i>	65.8 <i>65.8</i>	57.1 <i>43.4</i>	35.5 <i>35.5</i>
PROBA-V GEOV1 vs Ground Data	N	15	12	11	37	28	31
	Correlation	0.84	0.84	0.93	0.85	0.92	0.84
	Bias	0.40	0.10	0.12	0.23	0.06	0.10
	RMSE	0.78	0.14	0.14	0.81	0.11	0.17
	Offset	0.2	0.13	0.02	0.03	0.04	0.02
	Slope	1.1	0.95	1.25	1.1	1.03	1.18
	p-value	0.189	0.449	0.450	0.036	0.268	0.057
%optimal (LAI, FAPAR GCOS)	73.3	41.7	27.3	67.6	60.7	71.9	
MOD15A2C5 vs Ground Data	N	15	12	N/A	38	25	N/A
	Correlation	0.77	0.9	N/A	0.87	0.92	N/A
	Bias	-0.12	0.04	N/A	0.03	0.05	N/A
	RMSE	0.88	0.09	N/A	0.79	0.1	N/A
	Offset	-0.49	0	N/A	-0.18	0.07	N/A
	Slope	1.18	1.09	N/A	1.1	0.97	N/A
	p-value	0.294	0.351	N/A	0.185	0.490	N/A
%optimal (LAI, FAPAR GCOS)	53.3	66.7	N/A	60.5	52	N/A	

5 SUMMARY AND CONCLUSIONS

The quality assessment of PROBA-V Collection 1km LAI, FAPAR and FCOVER Version 2 GEOV2 (GEOV2/PV) products was conducted following validation procedure described in the Copernicus Global Land Service Validation Plan 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, smoothness, statistical assessment of discrepancies among similar products per biome type, continental region, or specific regions, and the accuracy as compared to ground data collected and processed according to CEOS LPV guidelines. Three main inter-comparison exercises were conducted to assess: 1) consistency of GEOV2 near-real time estimate (RT0) with regard to the consolidated (RT6) estimate, 2) consistency between PROBA-V and SPOT/VGT GEOV2 variables, and 3) consistency with reference products (PROBA-V Version1 and MODIS C5). To assess the consistency between PROBA-V and SPOT/VGT GEOV2 consolidated products only 6 months overlap period was available (from October 2013 to March 2014). For the other analysis, one year of data was available (October 2013 - September 2014). The summary of results and main conclusions are given below.

Product completeness

- PROBA-V Version 2 products shows complete coverage over land pixels as a result of the gap filling method. This is a main improvement as compared to Version 1 products and other polar-orbiting satellite-derived biophysical products with large gaps in northern latitudes.
- The spatio-temporal location of gap filled values has been analysed with the Bit 3 of the Quality Flag. Filled values are mainly obtained over northern latitudes (mainly in winter time) and equatorial areas. The maximum percentage of filled values reaches 50% of land pixels, slightly lower than for VGT Version 2 products.

Spatial Consistency

- PROBA-V Version 2 products displays very smooth and reliable spatial distributions of retrievals around the globe, including those regions where gap filled techniques were used. No anomalous patterns were detected over sub-continental regions at the full resolution. Good autocorrelation obtained over homogeneous sites (similar to VGT Version 2, but slightly higher spatial variability).
- Quality indicators displayed consistent spatial distribution of values with SPOT/VGT showing reasonable discrepancies, and in agreement with the PUM and ATBD information.
- PROBA-V Version 2 NRT (RT0) product displays in overall consistent spatial distributions as compared to the consolidated estimate (RT6) with 94% of residuals in optimal levels for LAI and 89% of residuals in optimal levels for FAPAR and FCOVER. For the LAI, RT0

tends to provide slight negative residuals over most dates with percentages of negative residuals beyond optimal levels up to 40% mostly in the southern hemisphere, although the opposite trend is also observed in some regions and periods but with less percentage of positive residuals beyond optimal levels. For FAPAR and FCOVER, larger residuals are evenly distributed ranging between ± 0.1 .

- PROBA-V Version 2 product is linearly related to VGT Version 2 over the northern hemisphere (fall and winter time during the overlap period) with correlations of 0.99, no offset and slopes of 1.02 for LAI and 1.01 for FCOVER and FAPAR over BELMANIP2.1. However, departures from linearity were detected over the south hemisphere (Africa, South America) when the vegetation is active. Differences appear mainly over deciduous forest areas in Africa and are mostly observed for medium to high vegetation values.
 - For the LAI, the discrepancies are mostly systematic and go up to 2 LAI units, with increasing differences as the vegetation increases (mean bias ranges from 4% in November to 12% in March). This could have an impact for some users such as those dealing with anomalies that have to be better quantified. Meanwhile, users are advised to use the LAI product with caution, and make use of quality indicators.
 - For FAPAR and FCOVER, discrepancies are mostly random and goes up to 0.15, but only a slight positive bias is observed for fully developed canopies
- The comparison with PROBA-V Version 1 products shows main inconsistencies over equatorial areas as expected and northern latitudes. Furthermore, in northern latitudes regions, negative residuals (Version 2 < Version 1 up to -2 LAI units) are observed in spring time (growing period), and positive in summer-time and even more positive during the fall. For FAPAR, negative residuals up to -0.2 (lower Version 2 values) are generally obtained. As for LAI, a seasonality of residuals is observed. For the FCOVER, discrepancies are ranging between from -0.2 to 0.2 but more evenly distributed between positive and negative values. The seasonality observed in the residuals seems to be mainly related to the different input and compositing schemes used by Version 1 and Version 2 products. Further investigation is needed to determine the accuracy of the products over those periods showing larger discrepancies.
- As compared to MODIS, very large spatial discrepancies are observed, in particular for the FAPAR product: only about 50% of samples achieved optimal consistency and large areas shows very low fraction (<20%) of cases within optimal consistency levels). A seasonality in the residuals is also observed over north hemisphere regions (Canada, Siberia) as well as south hemisphere (Africa, South America), with higher values at the start of the season and lower values at the end. For some regions and periods, Version 2 provides the intermediate estimates between MODIS and Version 1 (MODISC5 < Version 2 < Version 1).

Temporal Consistency

- The different Version 2 modes displayed very consistent and smooth temporal profiles, with cross-correlations higher than 0.95 over B2.1 sites. RT0 shows lower values at the

maximum of the vegetation growth and slightly shifted temporal courses. RT1 to RT6 shows almost identical.

- The temporal profiles as compared with reference products were found consistent, except in Evergreen Broadleaf Forest (EBF) where reference products showed very noisy temporal profiles, with typically more than 75% of samples with cross-correlation values higher than 0.8 for all biomes (except EBF and sparse/bare with little temporal variations). However, in some cases, the Version 2 estimation introduces slight shifts at the beginning or at the end of the season.
- Version 2 removes temporal artefacts observed in Version 1 as: 1) a false vegetation growth around November mainly observed in northern latitudes (very low sun zenith angle), 2) a false seasonality observed for the FCOVER over desertic sites in wintertime, and 3) over Deciduous Broadleaf Forest (DBF), an anticipated decrease of LAI observed in Version 1, which is not consistent with other variables, reference products and ground observations profiles.
- Temporal profiles of Version 2 products show good cross-correlation values with reference products, typically higher than 0.8 in more than 70% of samples (up to 99% for DBF) as compared to Version 1, except in EBF and sparse/bare areas (SBA). The cross-correlation of PROBA-V Version 2 and VGT Version 2 improves that obtained between PROBA-V Version 1 and VGT Version 1.

Precision

- Version 2 products show smoother profiles as compared with the references product, with improved precision
- Very similar histograms of smoothness are obtained over BELMANIP2.1 sites for the several modes.

Overall assessment over BELMANIP2.1

- The several Version 2 RT estimates provide very consistent results over BELMANIP2.1 sites. RT0 shows RMSE of 0.21 for LAI and only 0.02 for FAPAR with the RT6 mode. RT1 improves the consistency with RT6 (RMSE 0.12 and 0.01 for LAI and FAPAR), and after only two decades (RT2), the Version 2 products value is almost stable.
- PROBA-V Version 2 is linearly related ($R^2=0.99$, bias<2%) with VGT Version 2 over BELMANIP2.1 sites in the overall period provided (October-March) for both gap filled and all values.
- As compared with reference products (PROBA-V Version 1 and MODIS C5) over one year:
 - For LAI, PROBA-V Version 2 tends to provide higher values than PROBA-V version 1 for high values, but most of the samples (90%) are within GCOS accuracy requirement. As compared to MODIS LAI, PROBA-V Version 2 tends to provide also higher LAI values.

- For FAPAR, PROBA-V Version 2 tends to provide lower values than PROBA-V Version 1 for medium ranges (around 0.5), and good agreement for low and high values. 80% of the cases were within GCOS requirements. As compared to MODIS, low agreement is found with only 47% of samples within GCOS requirements. MODIS displays higher values (well known positive bias) for very low values, and Version 2 tends to provide larger values for high FAPAR values, with large scattering between both products.
- For FCOVER, Version 2 provides slightly lower values for high FCOVER than Version 1, which is more consistent with the FAPAR values.

Analysis per biome type

- Version 2 products constitute an intermediate solution between Version 1 and MODIS both for FAPAR and LAI across biomes. Overall good agreement between Version 2 and Version 1 FCOVER is observed with residuals centered at zero for all biome types except for EBF where Version 2 corrects the observed underestimation of Version 1 values.
- Larger discrepancies with Version 1 and MODIS C5 are found for EBF sites, where Version 2 provides very stable values as compared to the others.
- Between Version 2 and Version 1, the largest discrepancies were found for DBF and Needle Leaf Forest (NFL) for FAPAR (Version 2 < Version 1), for cultivated sites for FCOVER (Version 2 < Version 1) and for LAI for the higher values of all biomes (Version 2 > Version 1).
- Between Version 2 and MODIS C5, large discrepancies are observed for Cultivated (Version 2 > MODIS C5). The value of Version 2 seems to be more accurate as MODIS C5 tends to underestimate LAI in croplands

Accuracy Assessment

- For LAI, PROBA-V Version 2 shows an RMSE of 1.06 (all samples) and 0.8 in croplands (concomitant data), with a tendency to overestimate (mean positive bias of 0.5 in both cases, similar to Version 1) and 65% of the samples (73% for croplands) within GCOS requirements. RT0 provides a slightly better accuracy results over this limited dataset (RMSE=0.83, bias=0.4), as well as Version 1 (RMSE=0.81, bias=0.23) and MODIS C5 (RMSE=0.79, bias=0.03).
- For FAPAR, PROBA-V Version 2 shows an RMSE of 0.10 (all samples) and 0.12 for concomitant cropland sites, with a tendency to overestimate the ground reference in about 0.06 units (0.1 for croplands), and 57% of all samples (33% for croplands) within GCOS requirements. Similar results are obtained for Version 1 (RMSE=0.11) and MODIS (RMSE=0.1). However, MODIS provides a lower bias (0.04 for concomitant croplands sites with 67% of samples within GCOS requirements).
- For FCOVER, both Version 2 and Version 1 provides low accuracy (RMSE =0.17) with a systematic trend to overestimate ground reference (mean bias=0.1).

- Version 2 overestimates the biophysical values in La Albufera site at the start of the season where the paddy rice fields are flooded, as other reference products do as well. This implies that values retrieved in the presence of background water are not reliable.
- The number of ground references used in the accuracy assessment is not large enough to be robust, and these accuracy results need to be updated with the whole time series and all available ground references.

Concluding remark

The Quality Assessment of PROBA-V Collection 1km Version 2 products show in overall good results for the several criteria of performance evaluated (Table 26), for both near real time products (RT0) and the consolidated estimates, showing good consistency between modes. RT0 is consistent with RT6 within GCOS requirements for ~90% of cases (pixels x dates). The near real time estimate tends to provide slightly lower values for LAI and a temporal shift as compared to the RT6 (consolidated) estimate for all variables. PROBA-V Version 2 shows complete spatial coverage and very smooth profiles with improves notable the spatio-temporal continuity and the precision of the reference products (Version 1, MODIS). Version 2 shows an overall good agreement with Version 1 FCOVER and constitutes an intermediate solution between Version 1 and MODIS both for FAPAR and LAI across biomes when evaluated over the BELMANIP2.1 sites. The highest discrepancies are observed over evergreen broadleaf forests where Version 2 efficiently corrects the underestimation of LAI, FAPAR and FCOVER values observed in Version 1 mainly. The consistency between PROBA-V Version 2 and VGT Version 2 is globally good, but some discrepancies have been identified over specific areas and periods covered by fully developed vegetation and high cloud coverage, in particular for LAI. It has been also found some sites where Version 2 profiles displays shifts at the start and end of the growing season compared to other satellite products, but the realism of temporal variations has not been assessed in this report. Several artefacts affecting Version 1 over northern latitudes or desertic areas are properly removed in Version 2. The accuracy assessment, over a limited number of sites, shows an overall accuracy of 1 for LAI products, 0.1 for FAPAR and 0.17 for FCOVER, with a tendency to slightly overestimate FAPAR and mainly FCOVER ground references, even if part of the discrepancies may be attributed to the ground references. Compared to Version 1, these performances are similar for FAPAR and FCOVER and slightly lower for LAI. The percentage of retrievals within GCOS requirements on accuracy are 65% for LAI, 57% for FAPAR, and 35% for FCOVER.

With this validation, PROBA-V Collection 1km LAI, FAPAR, FCOVER Version 2 products are validated Stage 1 in the CEOS LPV hierarchy.

Table 26: Summary of PROBA-V Version 2 products evaluation. The plus (minus) symbol means that the product has a good (poor) performance according to this criterion.

QA Criteria	Performance	Comments
Product Completeness	+	No missing values in the Version 2 products.
Spatial Consistency	±	<p>Smooth and reliable distributions over the globe, and good autocorrelation over homogeneous sites.</p> <p>Overall good spatial consistency between Version 2 modes, with residuals lower than 1 LAI unit (99% of samples), or 0.1 FAPAR/FCOVER units (98% of samples).</p> <p>Spatial inconsistencies GEOV2/PV vs GEOV2/VGT mainly for LAI observed over areas with growing and fully developed vegetation (non EBF), such as Southern Africa. Systematic differences with GEOV2/PV LAI > GEOV2/VGT LAI (up to 2 units).</p> <p>Spatial inconsistencies with Version 1 LAI (up to ±2 LAI units) and FAPAR/FCOVER (up to ±0.15 units) observed with different sign in spring (negative residual) and fall (positive residual).</p> <p>Large spatial discrepancies between Version 2 and MODIS products, as between Version 1 and MODIS.</p>
Temporal Consistency	+	<p>Consistent seasonal variations.</p> <p>Improvements as compared to Version 1 over EBF (correction noisy profiles), DBF (anticipated decrease in Version 1 LAI), NLF (artefacts in fall) and bare areas (false seasonality in deserts).</p> <p>Good cross-correlations between Version 2 and reference products.</p> <p>Improved cross-correlation GEOV2/PV vs GEOV2/VGT as compared to GEOV1/PV vs GEOV1/VGT.</p> <p>Locally, slight shift in the temporal profiles at the start and end of season, compared to Version 1 and MODIS product.</p>
Intra-Annual Precision	+	Very low short-time variability (smoothness) much better than Version 1 and MODIS.
Statistical Analysis of Discrepancies	+	<p>Overall good consistency between Version 2 and Version 1 for LAI (90% samples within GCOS), FAPAR (80% of samples within GCOS) and FCOVER (77%).</p> <p>GEOV2 > GEOV1 for LAI values larger than 3, GEOV2<GEOV1 for FAPAR over medium ranges. For FCOVER, GEOV2<GEOV1 for very high values and consistent with FAPAR.</p>
Accuracy	±	<p>Acceptable accuracy for LAI, matching the GCOS requirements in 65% of cases (RMSE= 1.06, B=0.50)</p> <p>Slight positive bias for FAPAR (RMSE=0.10, B=0.05), mainly over croplands, matching GCOS requirements in 57% of cases</p> <p>Positive bias for FCOVER (RMSE=0.17, B=0.104)</p>

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ANNEX I. ADDITIONAL VALIDATION SITES

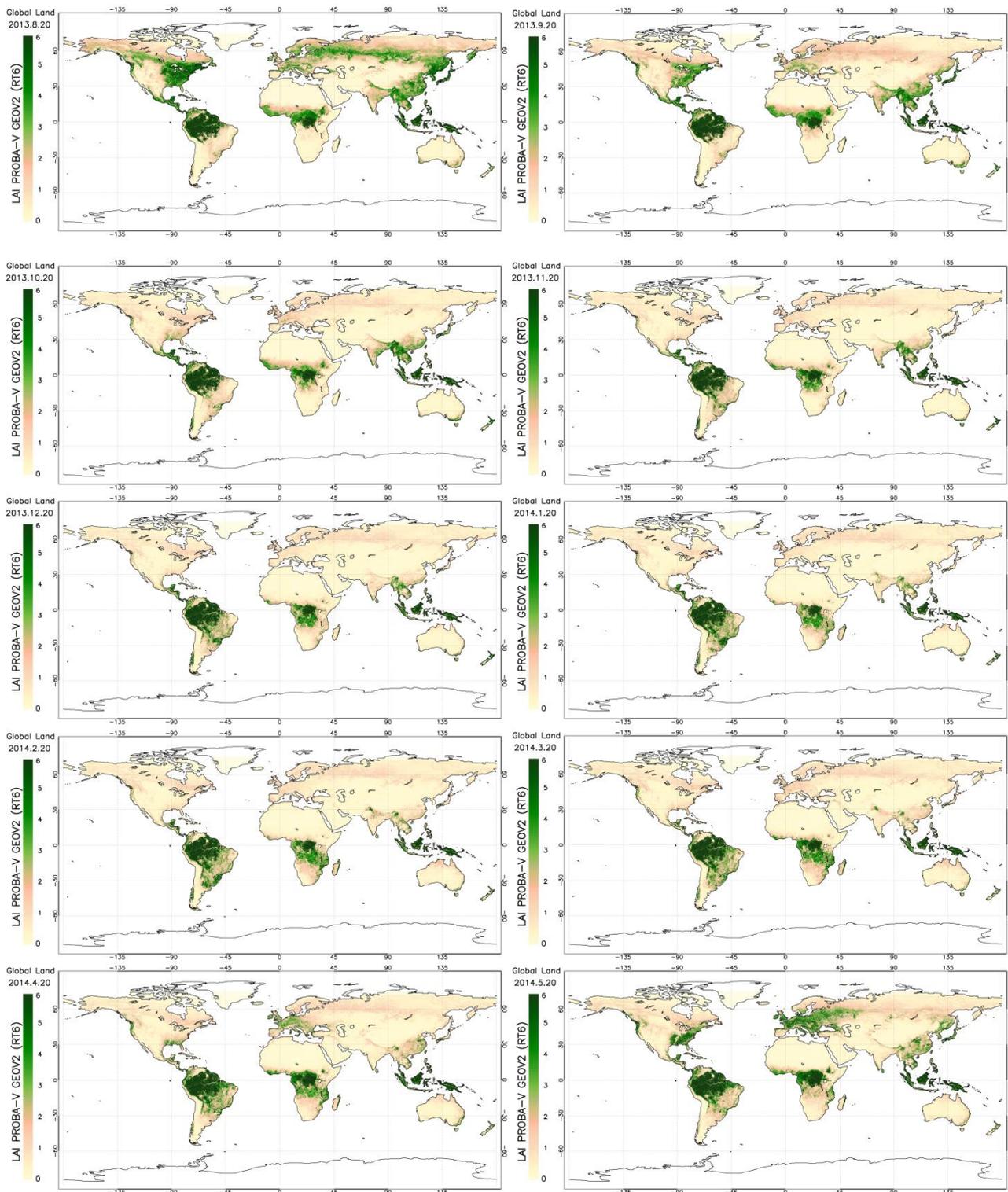
Characteristics of the validation sites and associated ground biophysical maps used in the direct validation for non concomitant dates.

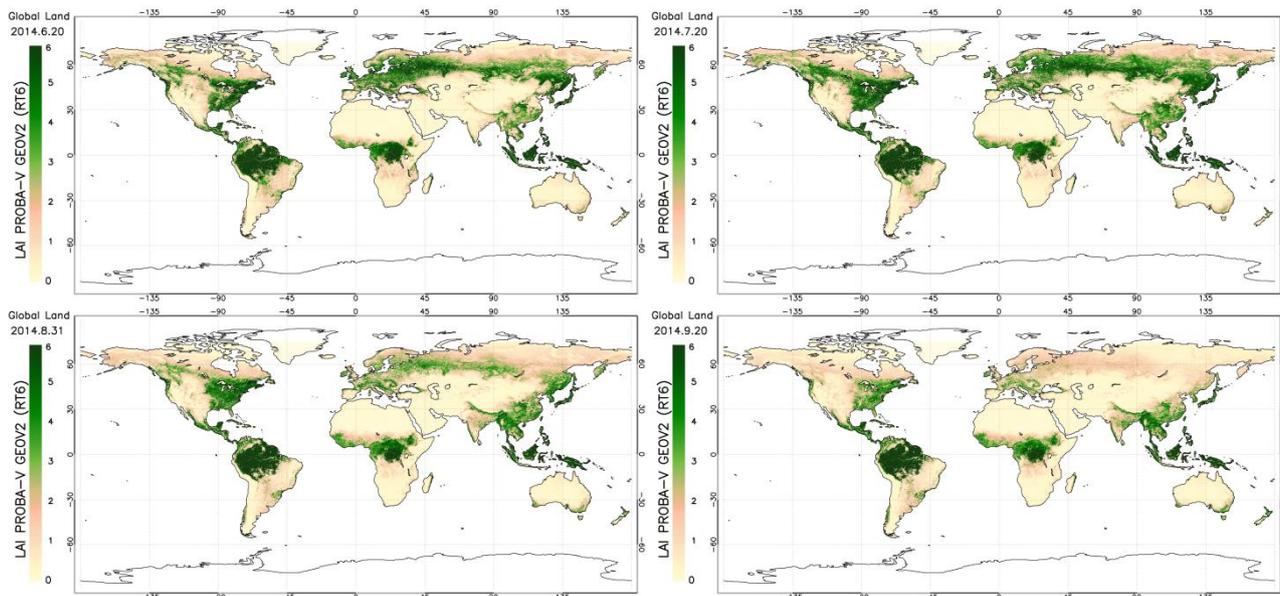
Site	Country	Lat (deg)	Lon (deg)	LandCover	date	LAI	FAPAR	FCOVER	Clumping	Ref.	Method
KONZ	USA	39.09	-96.57	Herbaceous	06/2000	2.17	N/A	N/A	N/A	BigFoot	1
					08/2000	2.16	N/A	N/A	N/A		
SEVI	USA	34.35	-106.69	Shrubs	07/2002-11/2003	0,05 - 0,40	N/A	N/A	N/A	BigFoot	1
Larose2	Canada	45.38	-75.17	Needle-leaf F.	08/2003	2.86	N/A	N/A	N/A	CCRS	1
Appomattox	USA	37.22	-78.88	Needle-leaf F.	08/2002	1.89	N/A	N/A	N/A	U.S. EPA	6
Cameron	Australia	-32.60	116.25	Evergreen F.	03/2004	2.08	0.47	0.41	0.49	VALERI	3
GN/Agara	Australia	-31.53	115.88	Deciduous F.	03/2004	0.44*	0.27	0.22	N/A	VALERI	3
Hirsikangas	Finland	62.64	27.01	Needle-leaf F.	08/2003	-1	N/A	0.64	N/A	VALERI	2
Jarvselja	Estonia	58.30	27.26	Needle-leaf F.	07/2000	N/A	N/A	0.75	N/A	VALERI	2
					06/2001	N/A	N/A	0.78	N/A		
					06/2005	4.03*	N/A	0.84	N/A		
Nezer	France	44.57	-1.04	Needle-leaf F.	07/2000	N/A	N/A	0.54	N/A	VALERI	2
					06/2001	N/A	N/A	0.87	N/A		
Puechabon	France	43.72	3.65	Needle-leaf F.	04/2002	2.54	0.53	N/A	0.56	VALERI	3
					06/2001	2.84	0.6	0.54	0.55		
Rovaniemi	Finland	66.46	25.35	Needle-leaf F.	06/2004	-1	N/A	0.42	N/A	VALERI	2
Sonian	Belgium	50.77	4.41	Needle-leaf F.	06/2004	5.66	0.91	0.9	0.63	VALERI	3
Turco	Bolivia	-18.24	-68.18	Sparse	07/2001	0.3	N/A	0.11	N/A	VALERI	1; 3
					08/2002	0.04	0.03	0.02	0.81		
Wankama	Niger	13.65	2.64	Herbaceous	04/2003	N/A	0.05	0.04	N/A	VALERI	3
					06/2005	N/A	0.07	0.04	0.57		
Mongu	Zambia	-15.44	23.25	Shrubs	02/2000-05/2000	N/A	0,55 - 0,59	0,46 - 0,58	N/A	SAFARI	2; 4; 5
DahraNorth	Senegal	15.43	-15.40	Shrubs	07/2001-08/2001	N/A	0.02-0.03	N/A	N/A	U.Copen hagen	6
Tessekre South	Kenya	15.819	-15.06	Herbaceous	07/2001	N/A	0.03	N/A	N/A	U.Copen hagen	6
Budongo 8	Uganda	1.77	31.61	Evergreen F.	11/2003	6.52*	N/A	N/A	0.56	BIOTA	2; 3
HarthForest	France	47.81	7.45	Deciduous F.	06/2013-09/2013	3.8-4.58	0.85-0.86	N/A	0.5-0.55	ESA VALSE-2	3
Collelongo	Italy	41.85	13.59	Deciduous B.F.	07/2015	4.53	0.85	0.82	0.74	ImagineS	3
					09/2015	3.78	0.85	0.84	0.76		

In the column "Method", the numbers refer to 1: destructive sampling, 2: LAI-2000, 3: digital hemispherical photos, 4: TRAC, 5: AccuPAR, and 6: PAR radiometer. More information and full list of validation sites can be found on the CEOS cal/val site (<http://calvalportal.ceos.org/cvp/web/olive/descriptions>)

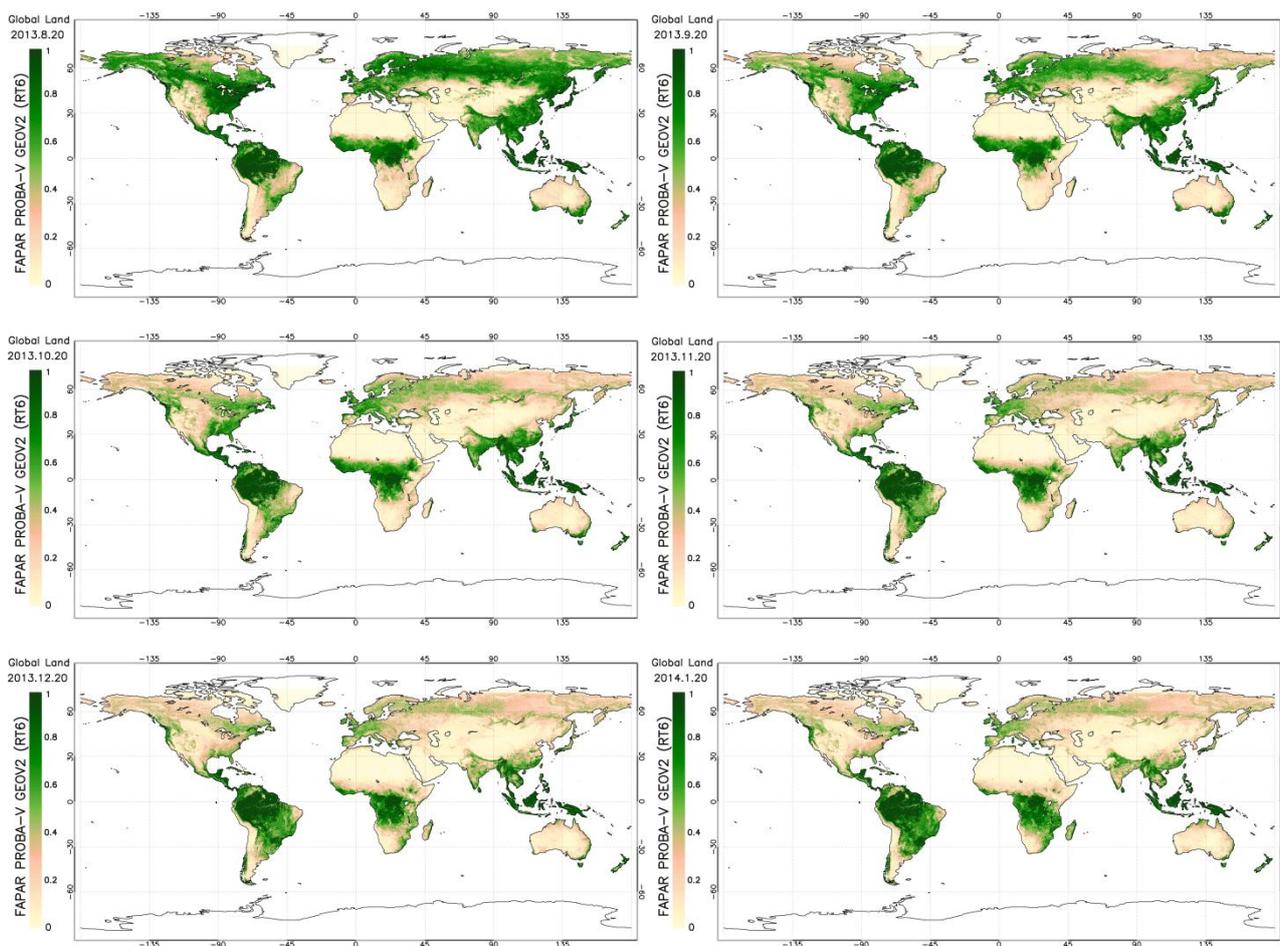
ANNEX II. GLOBAL MAPS OF PROBA-V VERSION 2 PRODUCTS

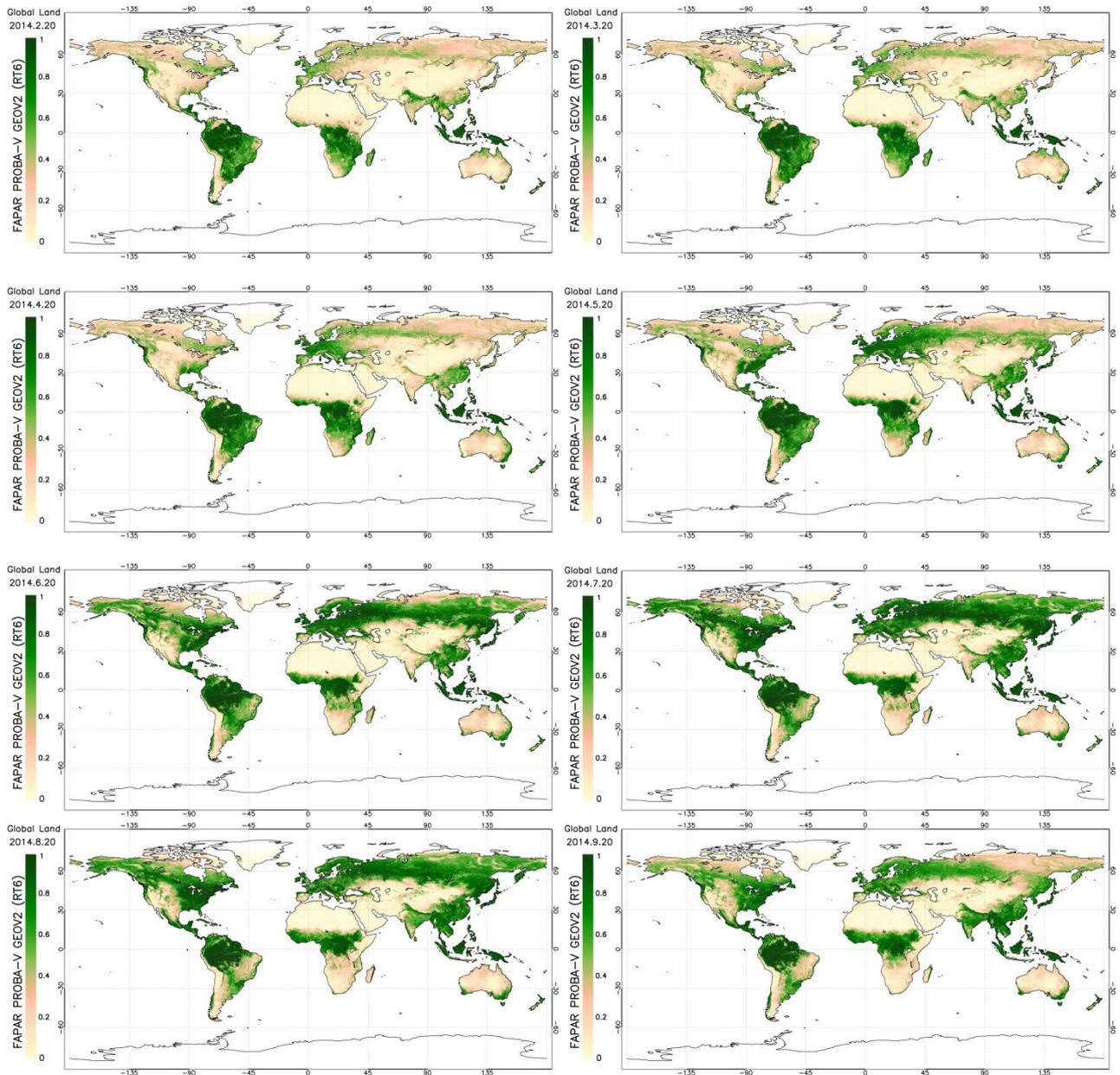
LAI



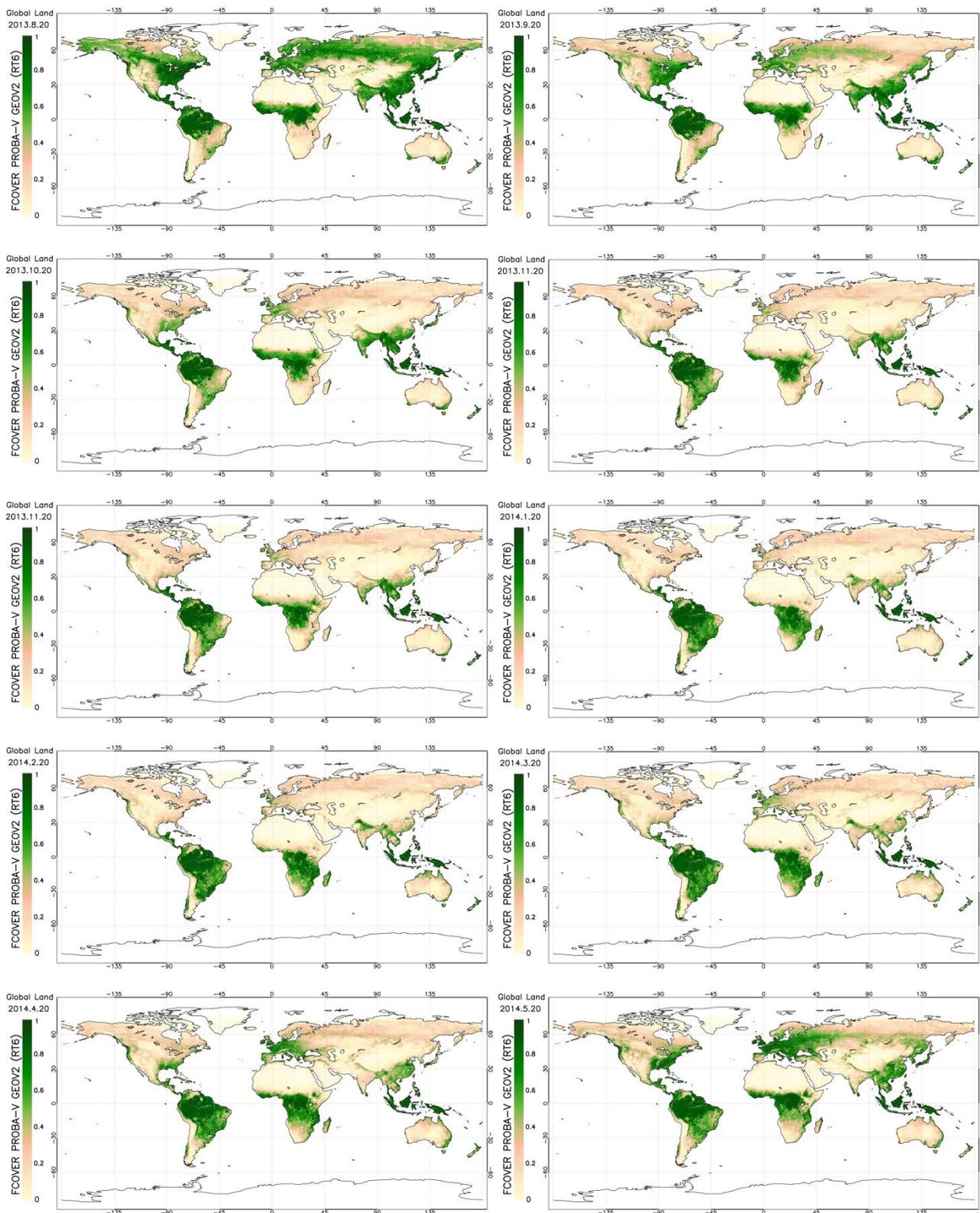


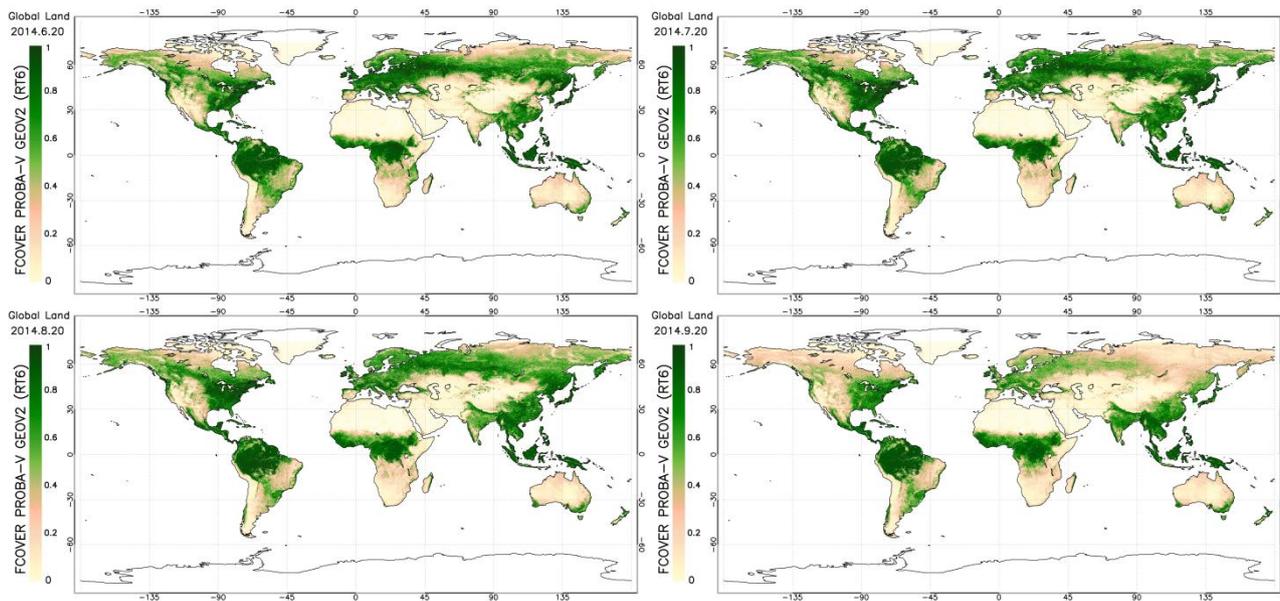
FAPAR





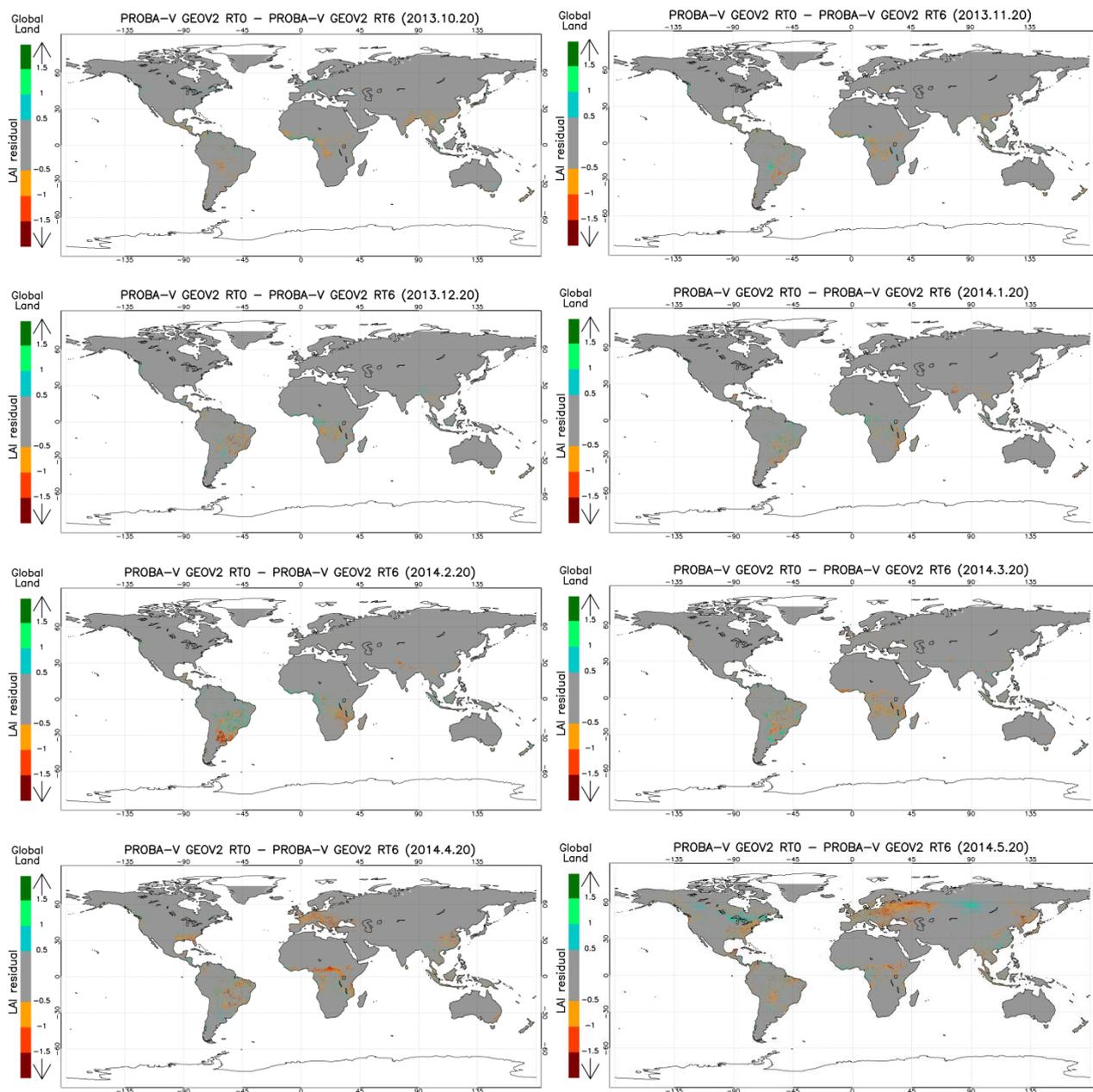
FCOVER

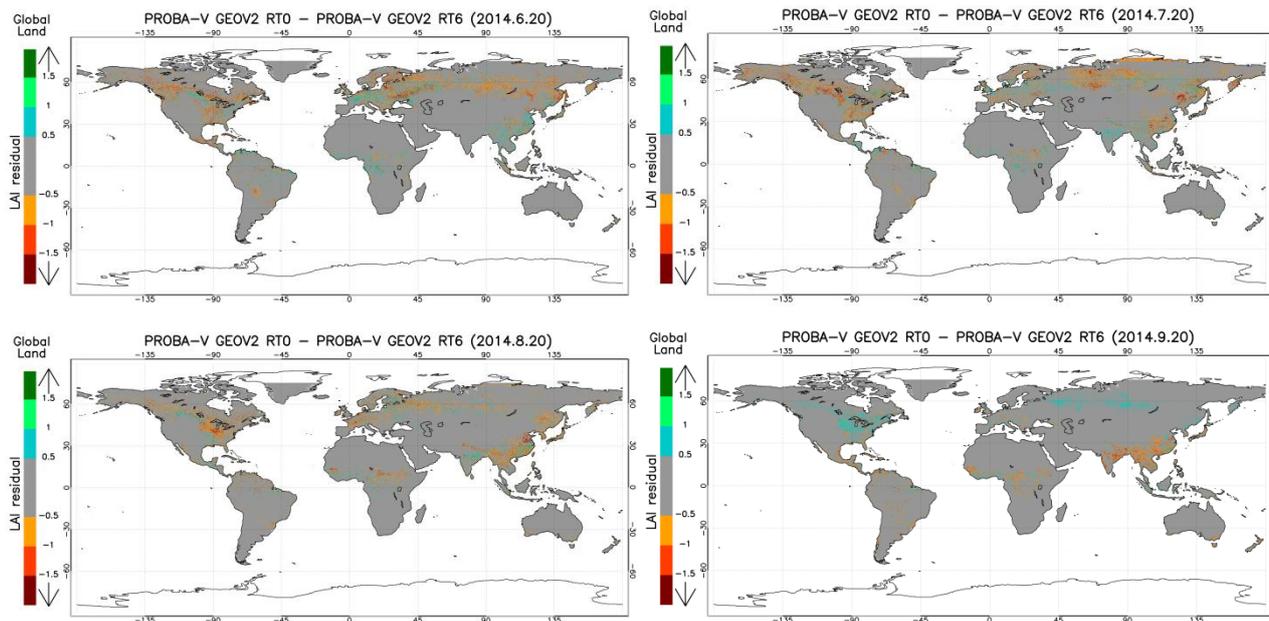




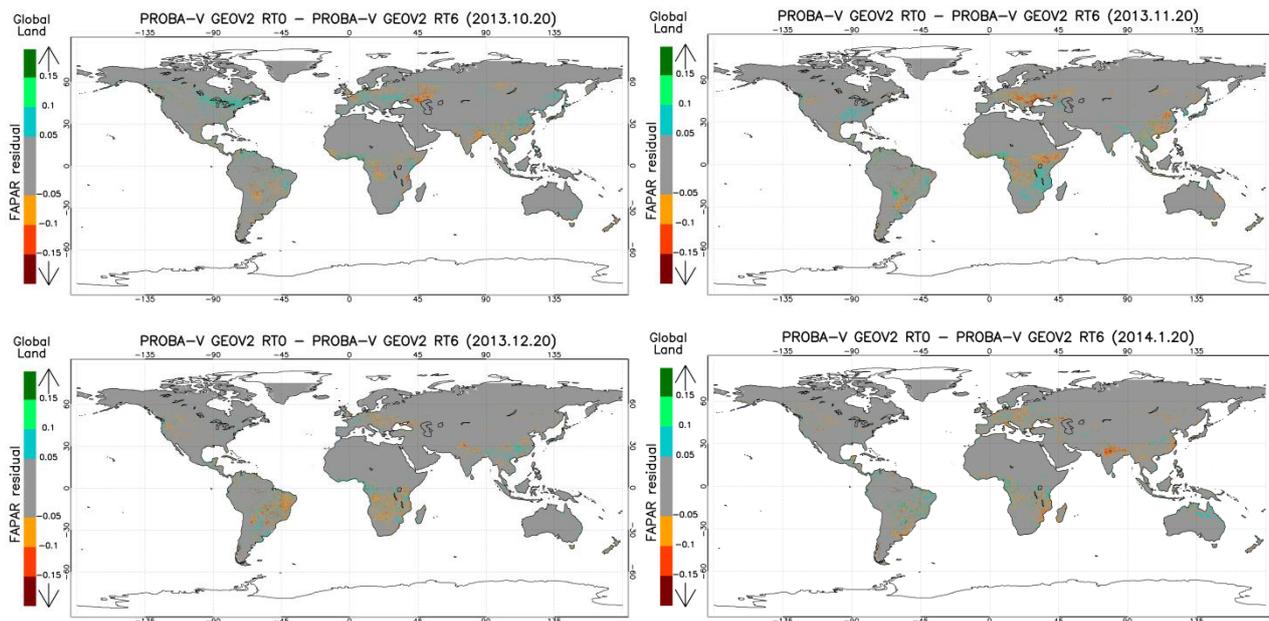
ANNEX III. GLOBAL MAPS OF RESIDUALS (GEOV2/PV RT0 - GEOV2/PV RT6)

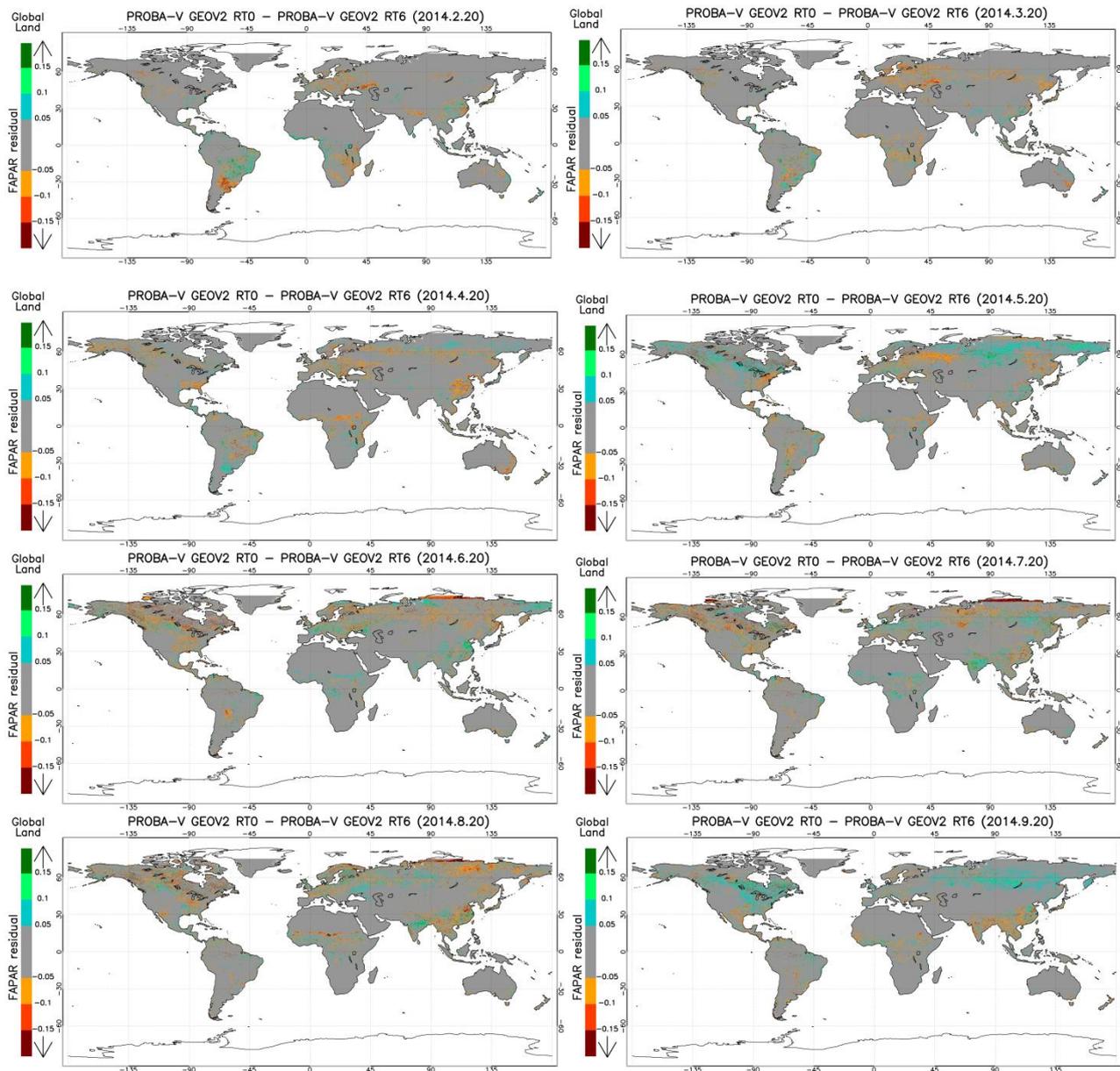
LAI



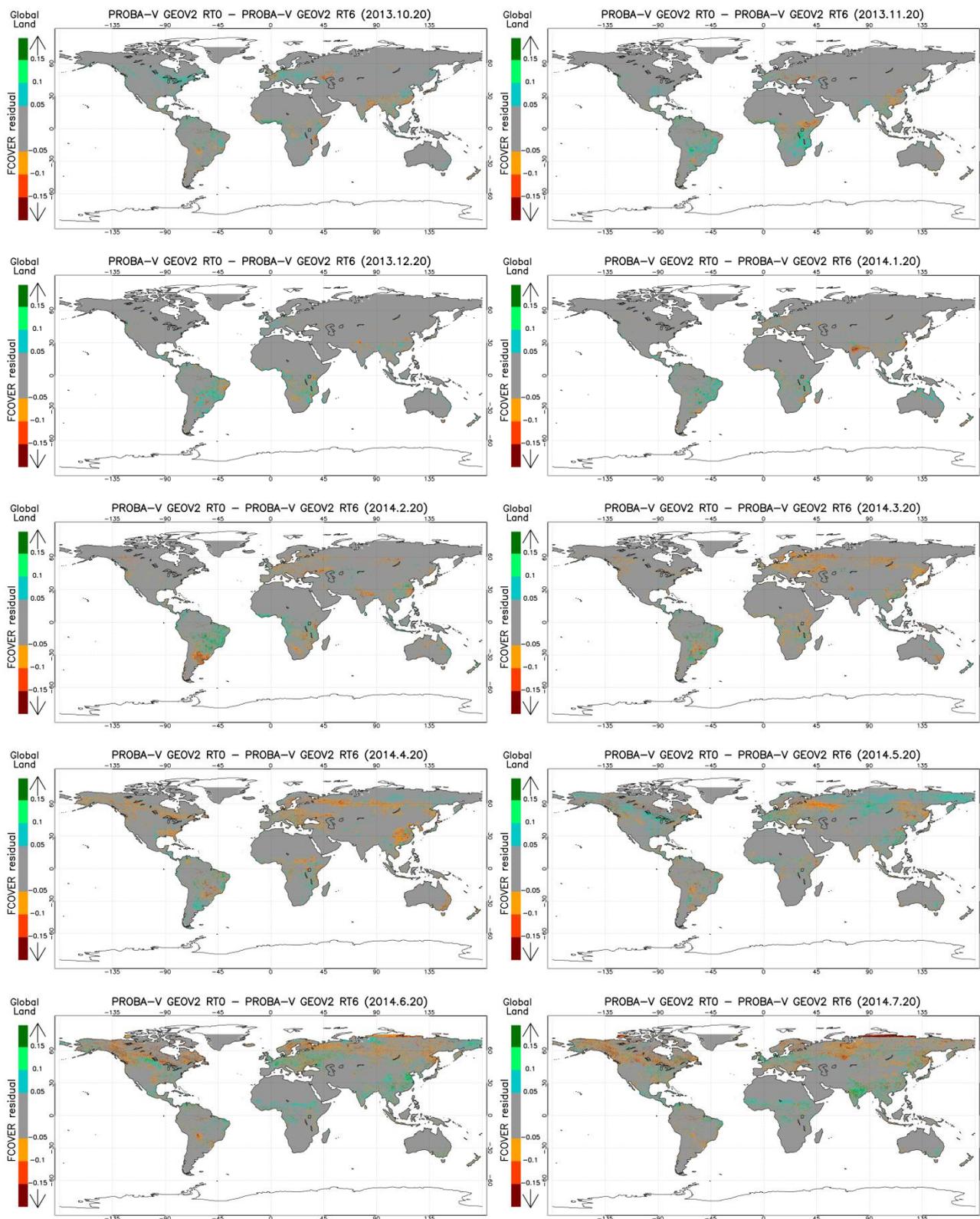


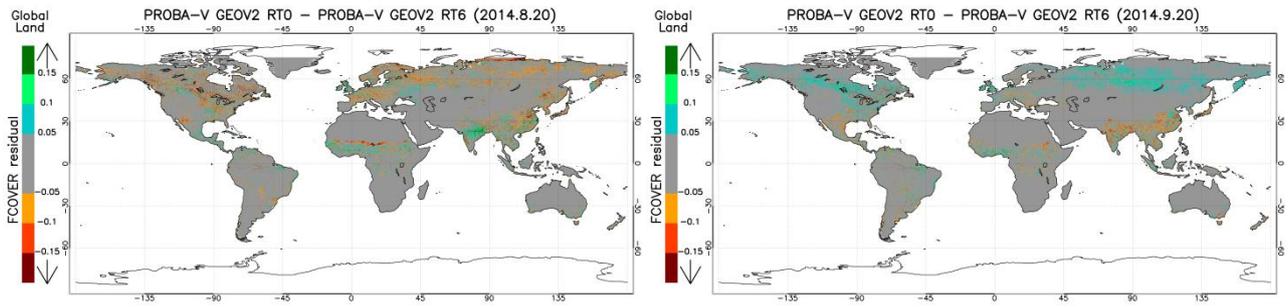
FAPAR





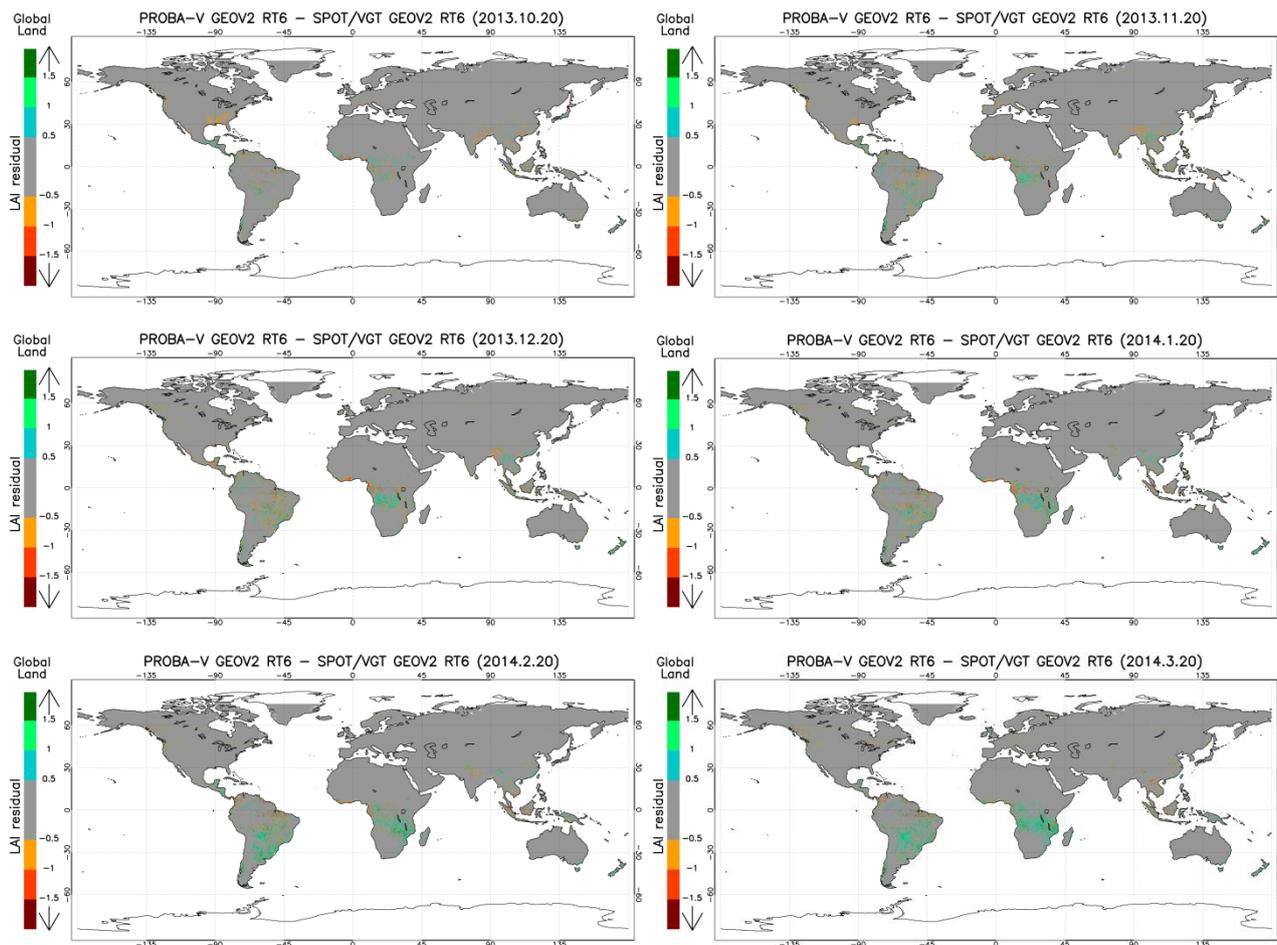
FCOVER



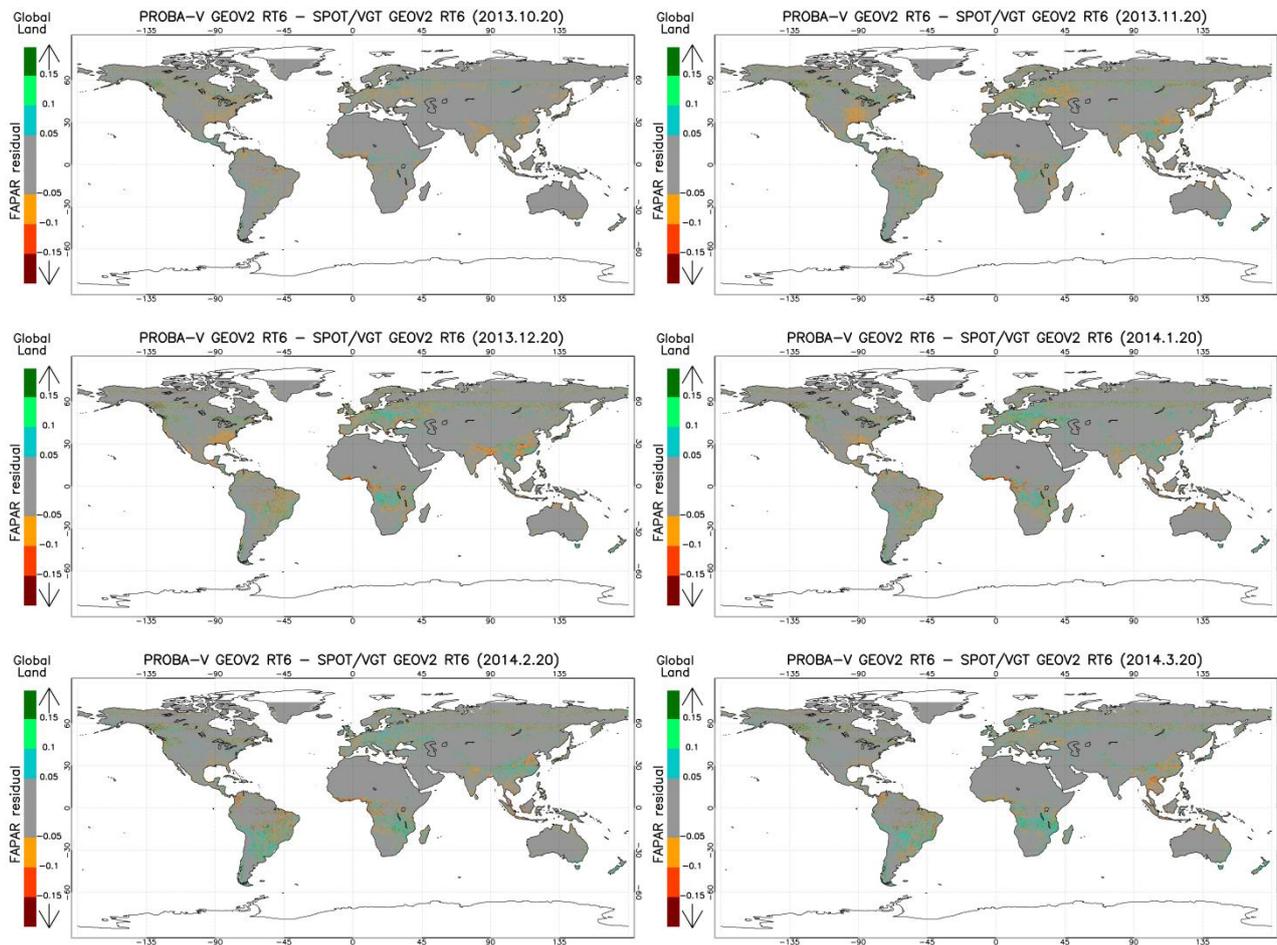


ANNEX IV. GLOBAL MAPS OF RESIDUALS (GEOV2/PV - GEOV2/VGT)

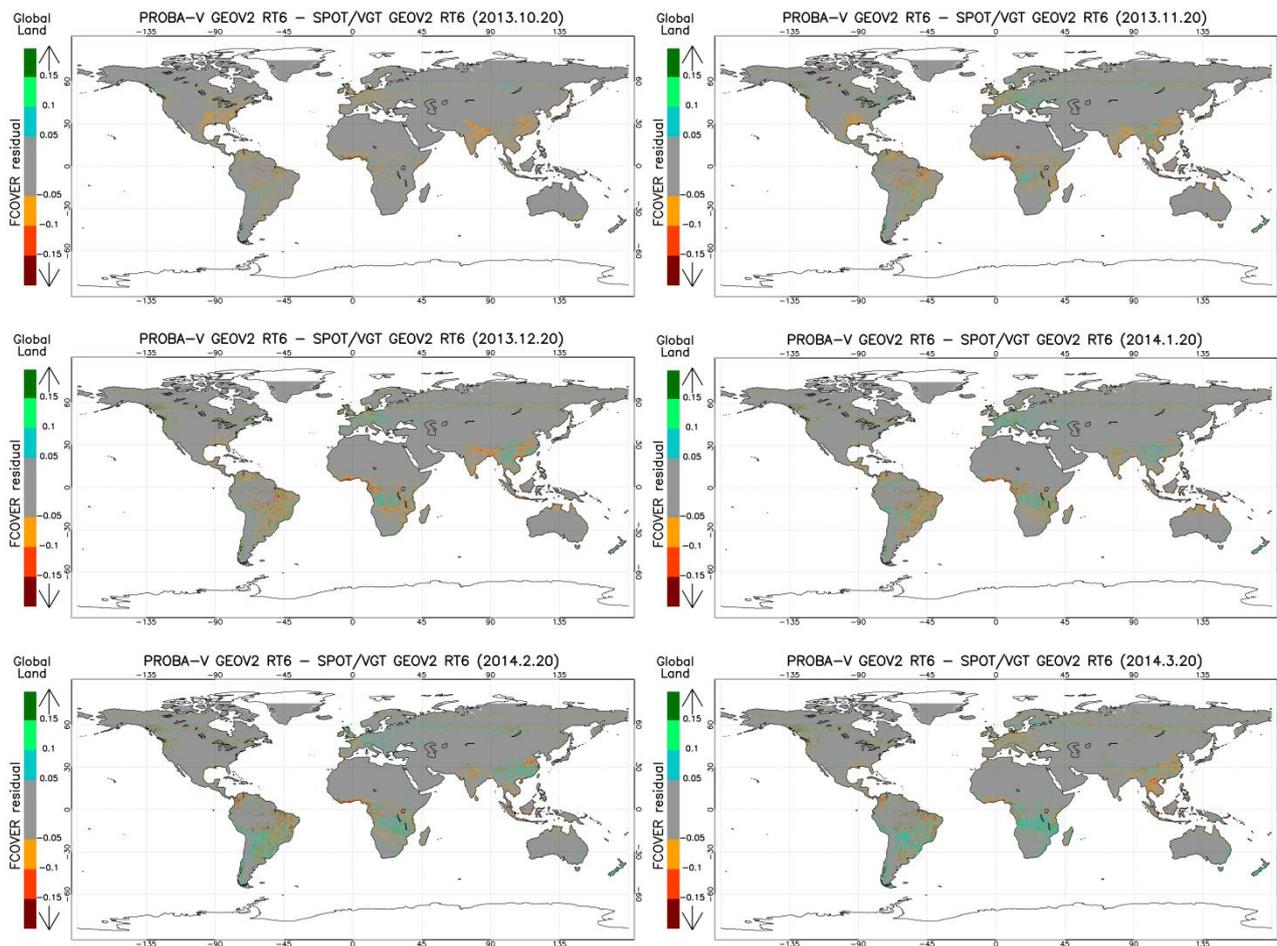
LAI



FAPAR

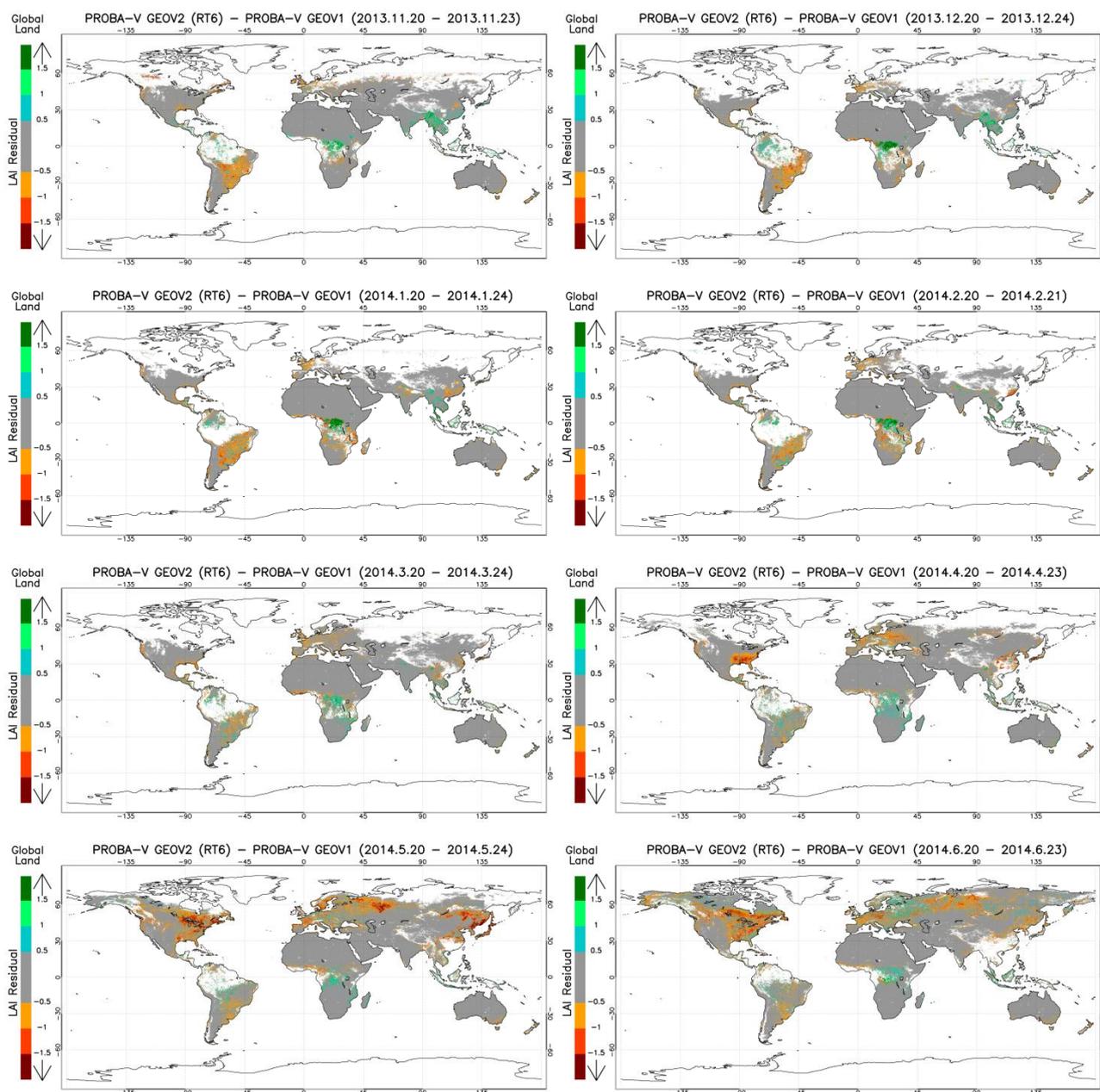


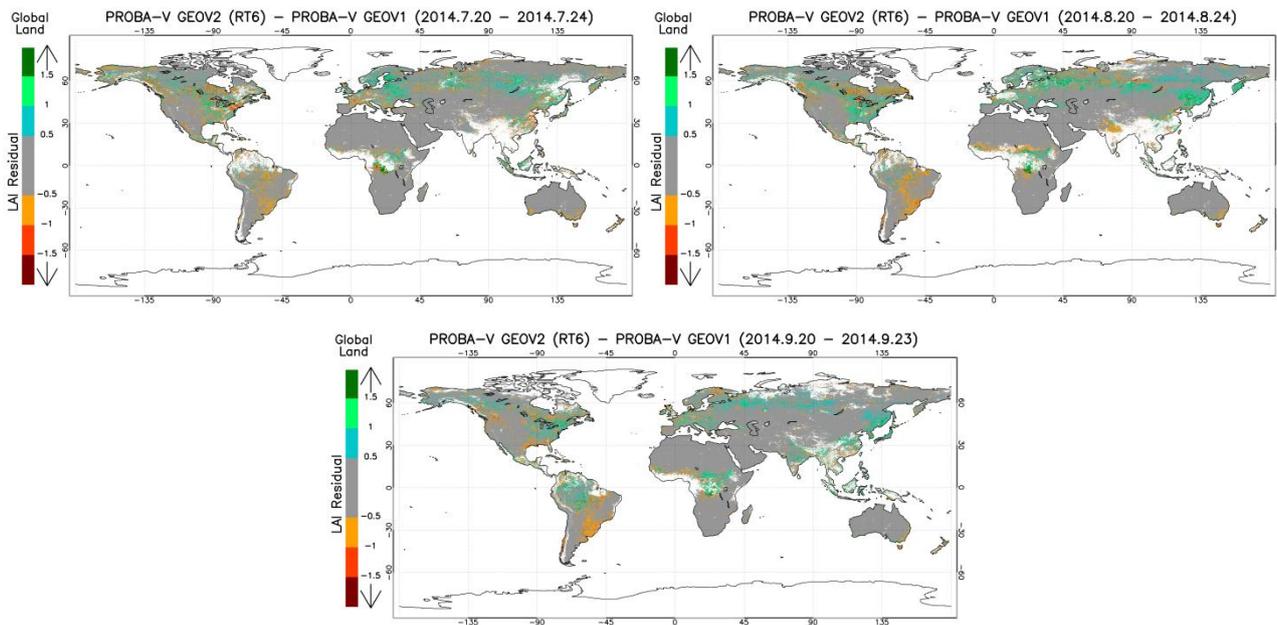
FCOVER



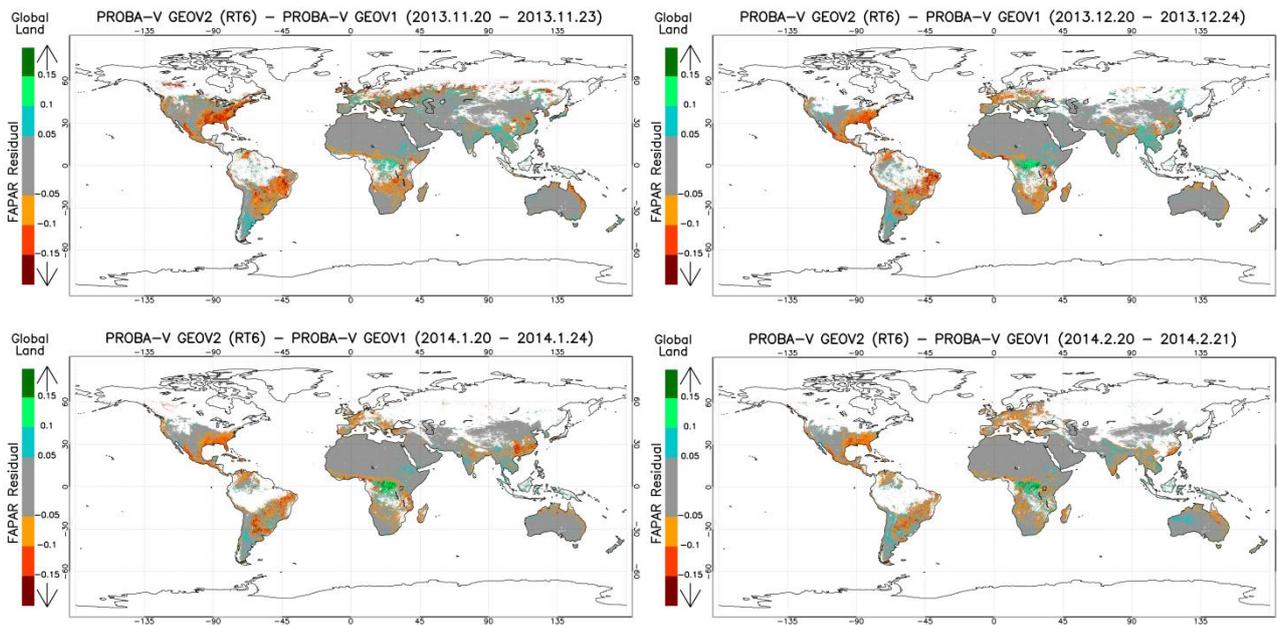
ANNEX V. GLOBAL MAPS OF RESIDUAL (GEOV2/PV - GEOV1/PV)

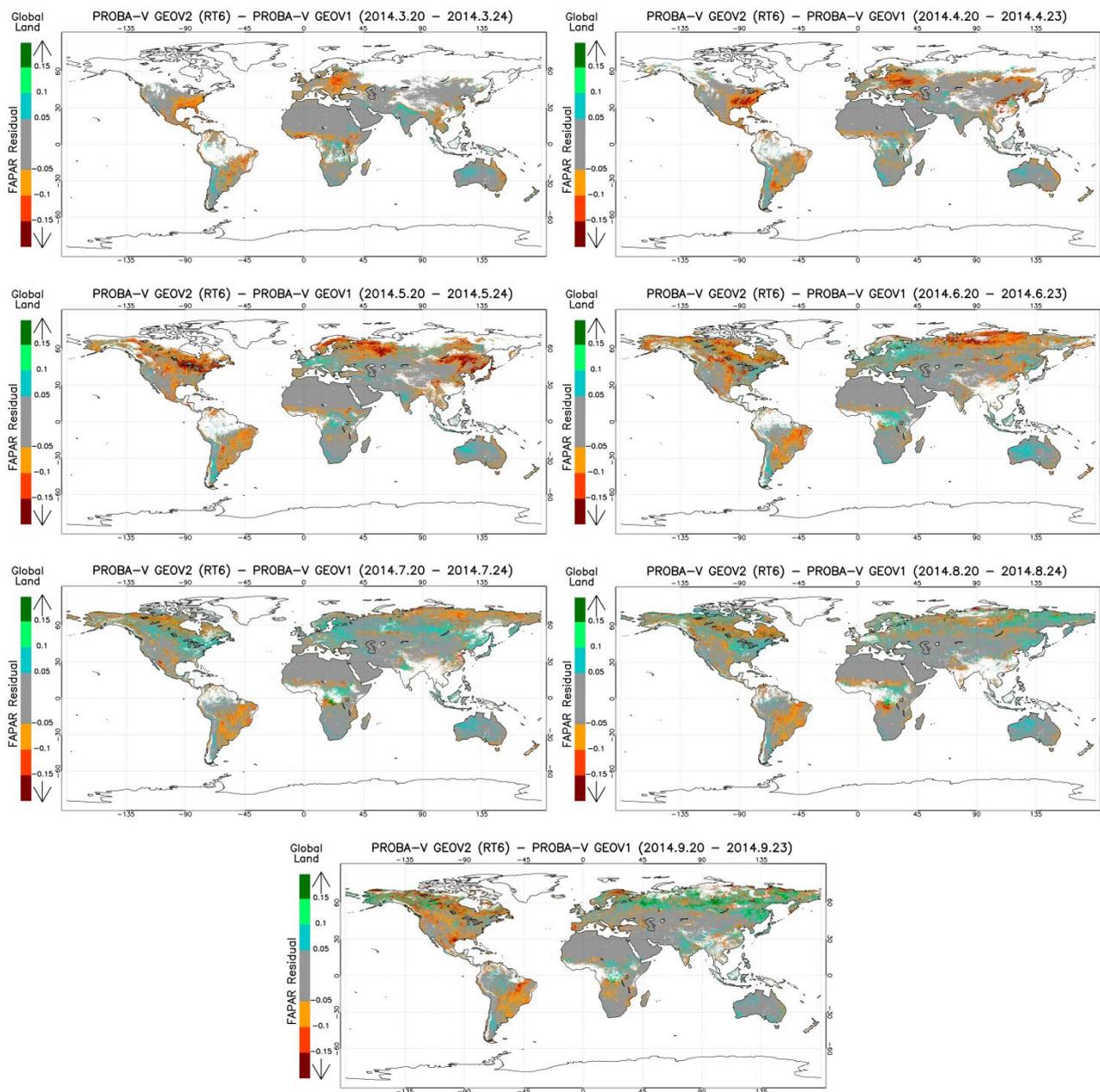
LAI



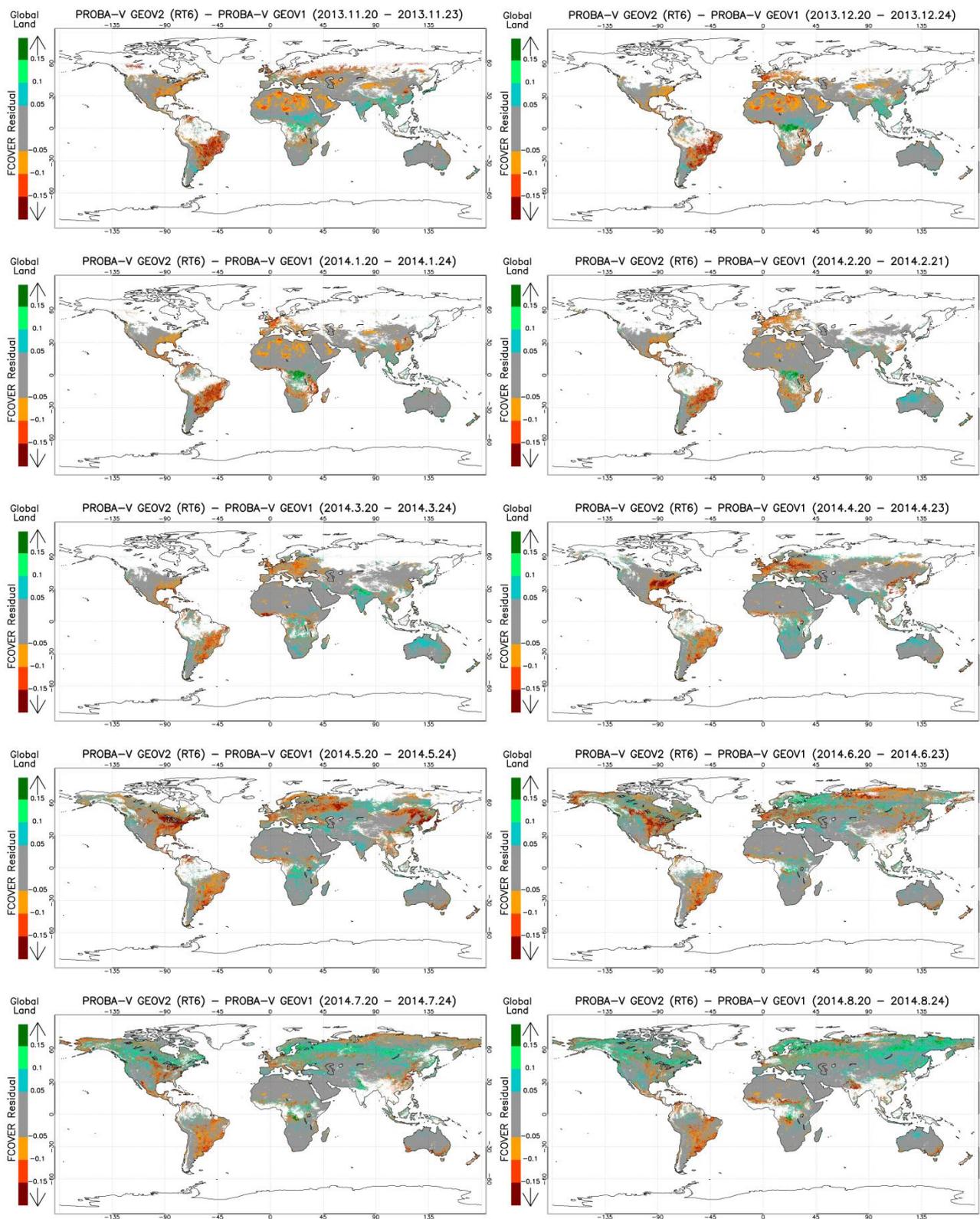


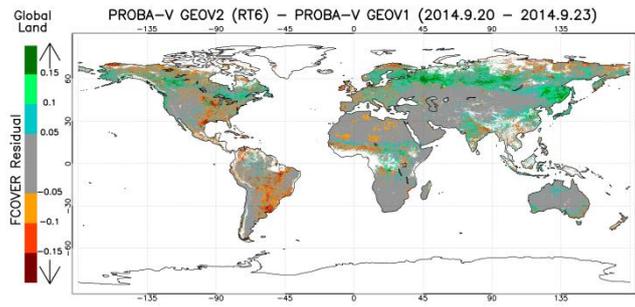
FAPAR





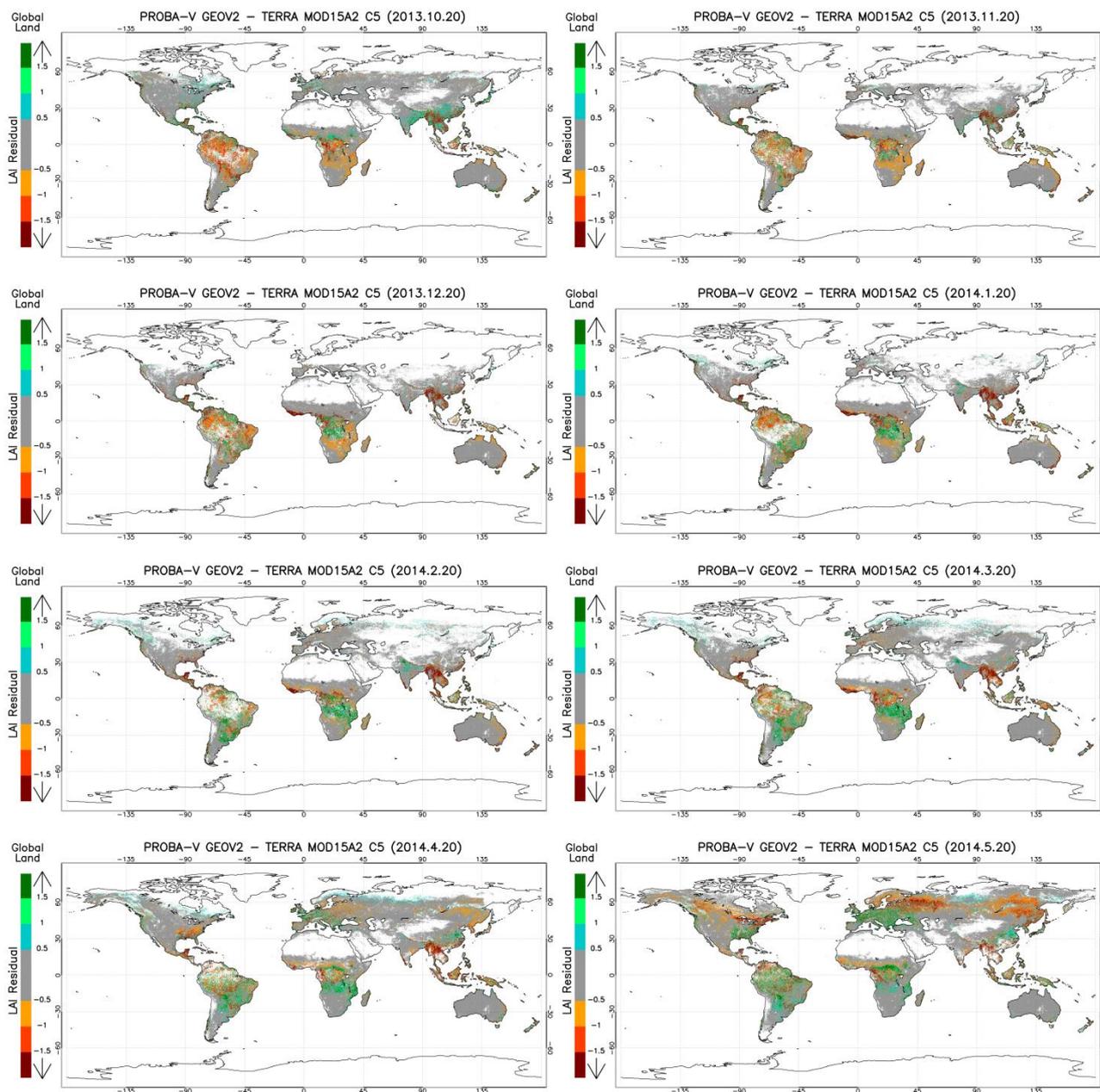
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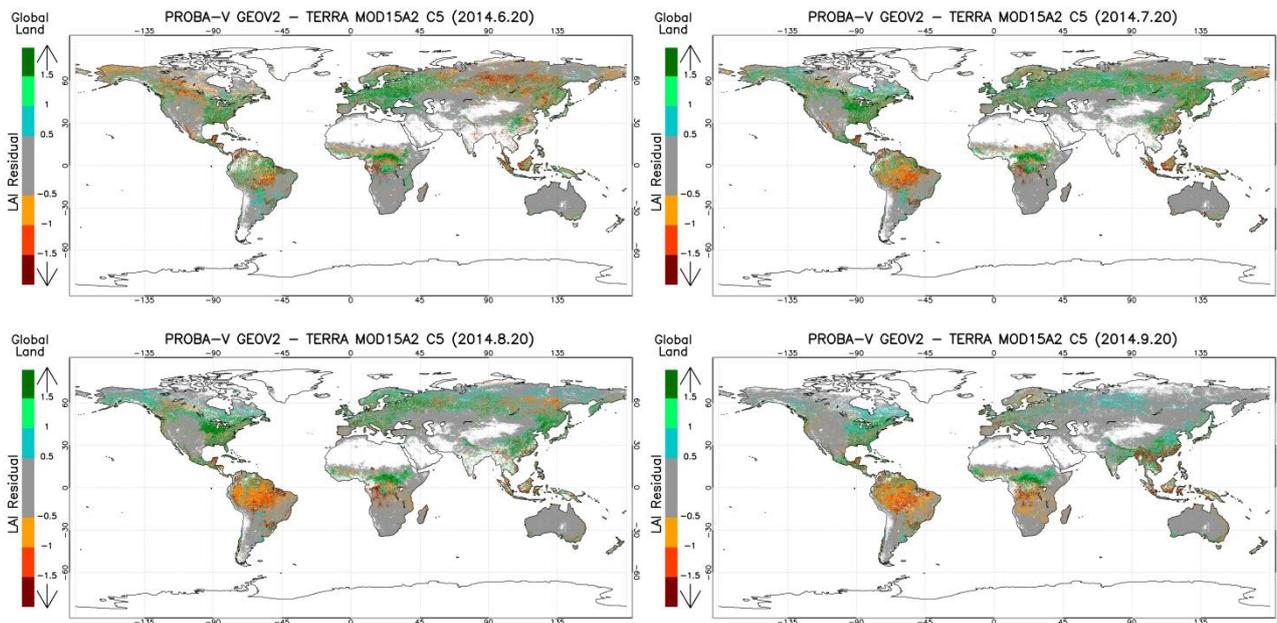




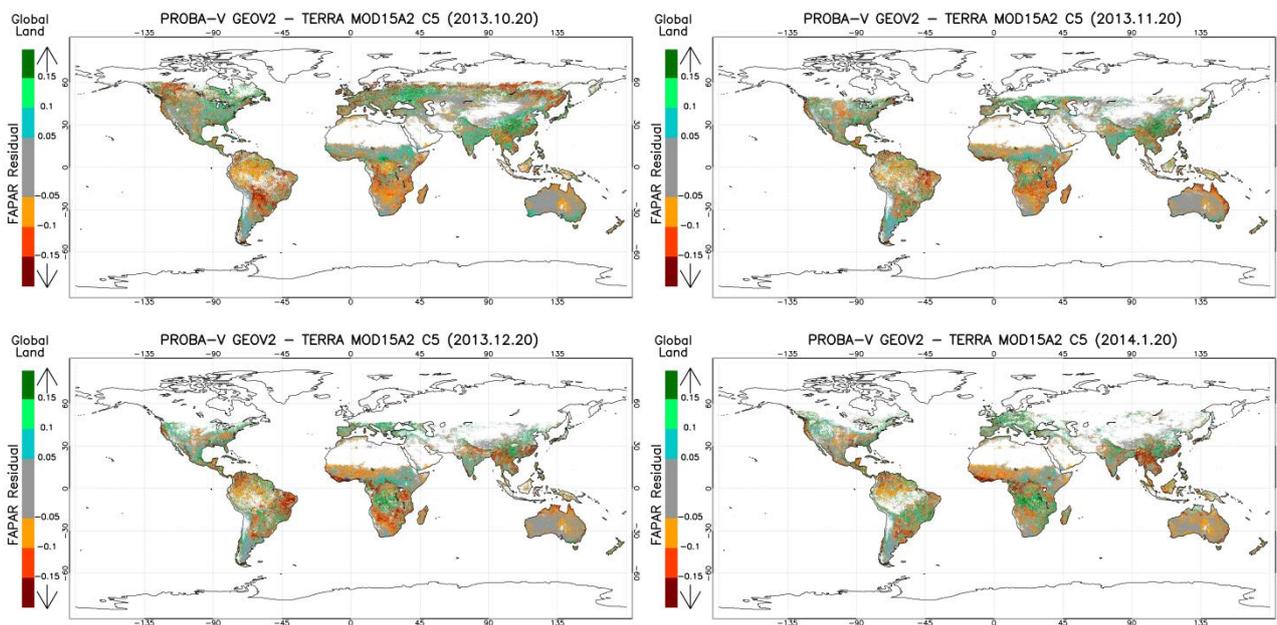
ANNEX VI. GLOBAL MAPS OF RESIDUALS (GEOV2/PV - MODIS C5)

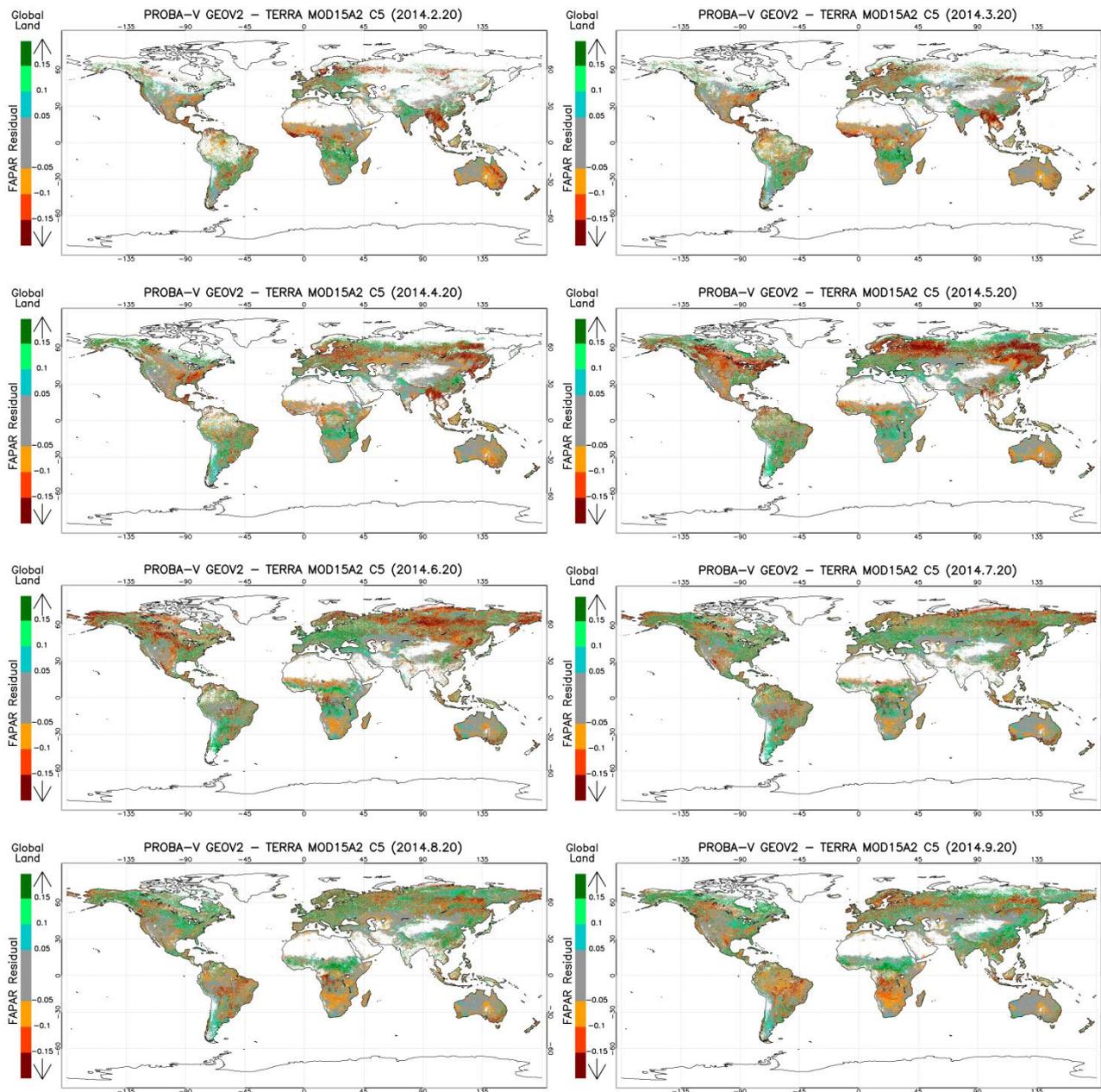
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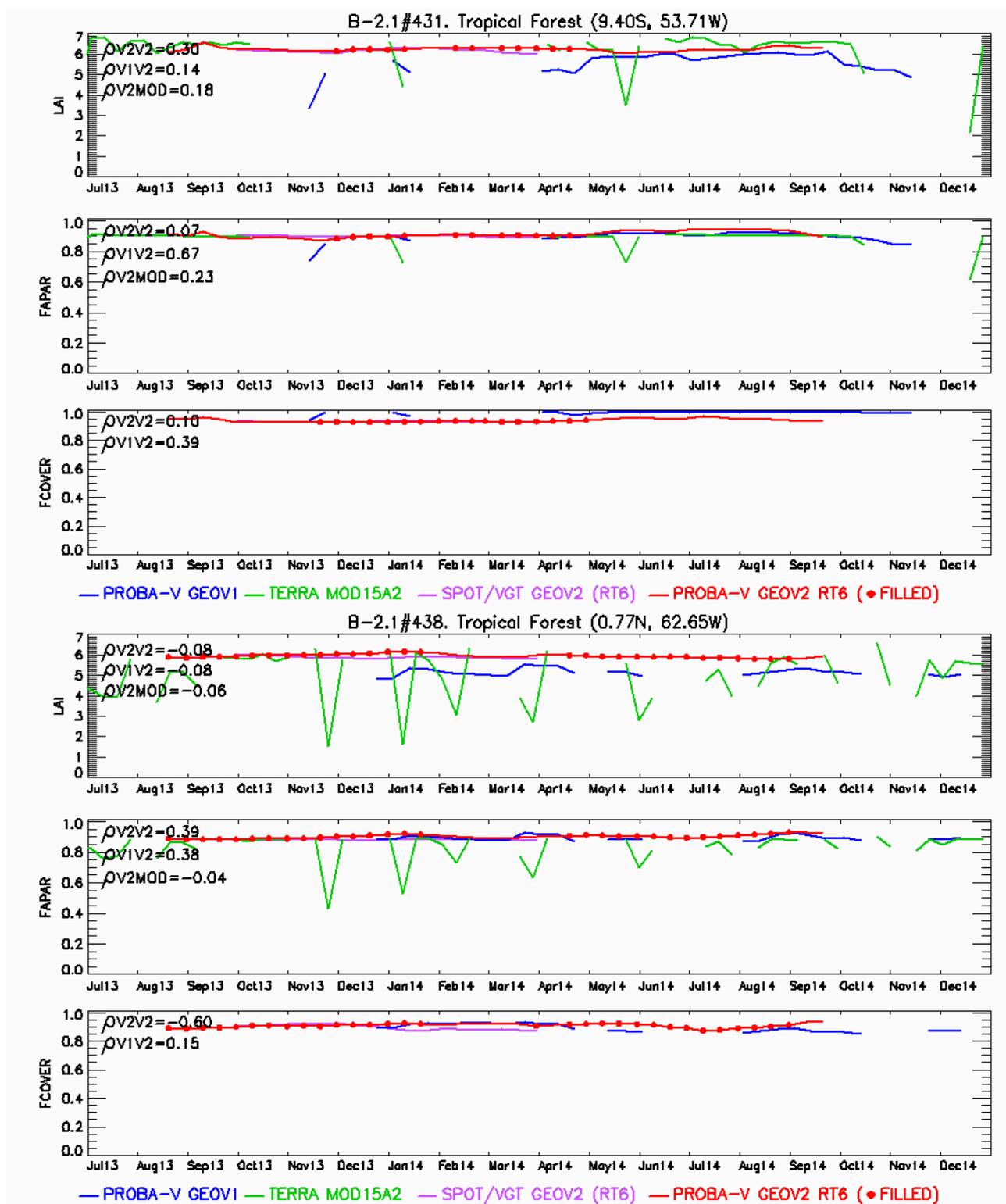
FAPAR



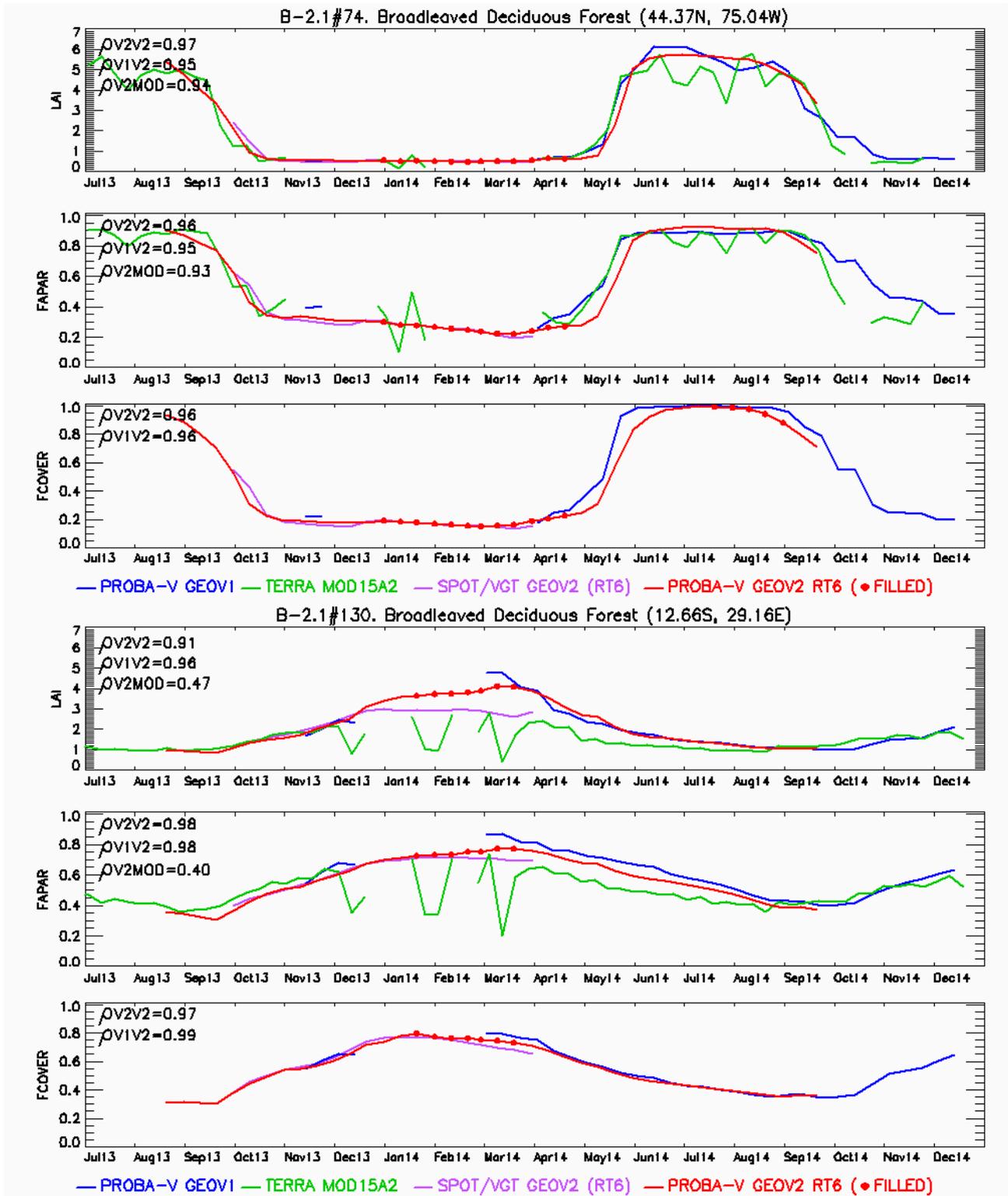


ANNEX VII. ADDITIONAL TEMPORAL PROFILES

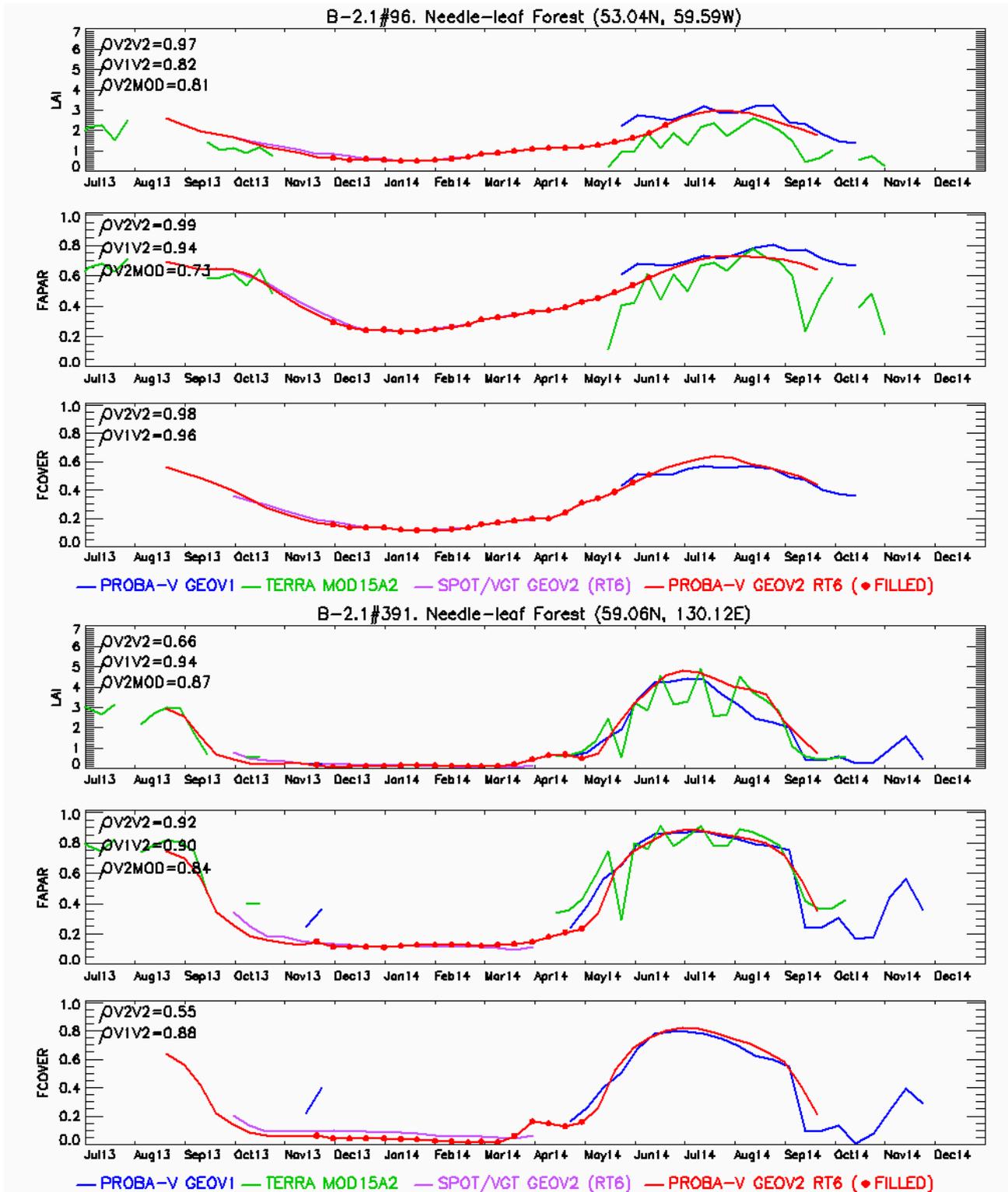
Broadleaved Evergreen Forest



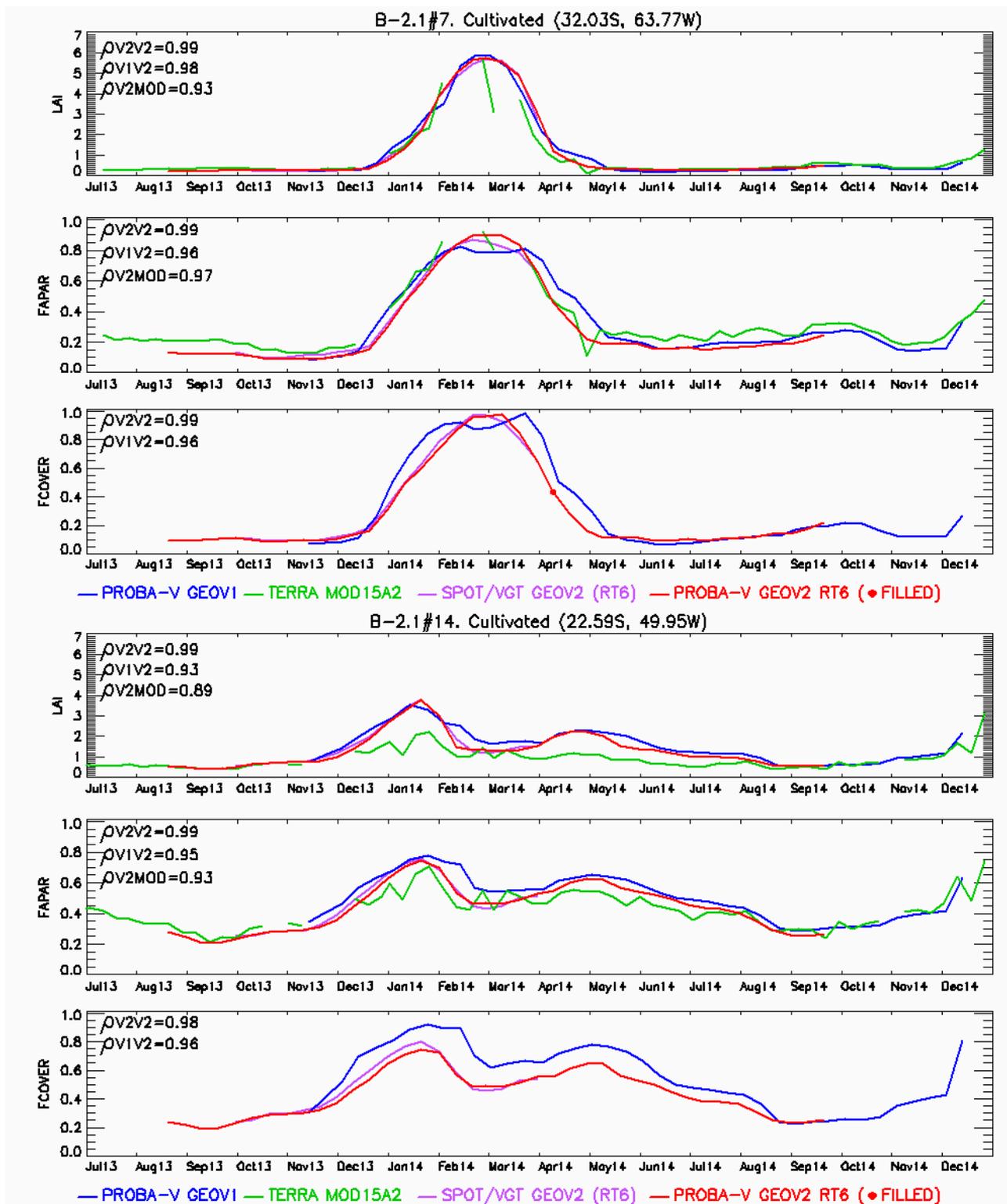
Broadleaved Deciduous Forest



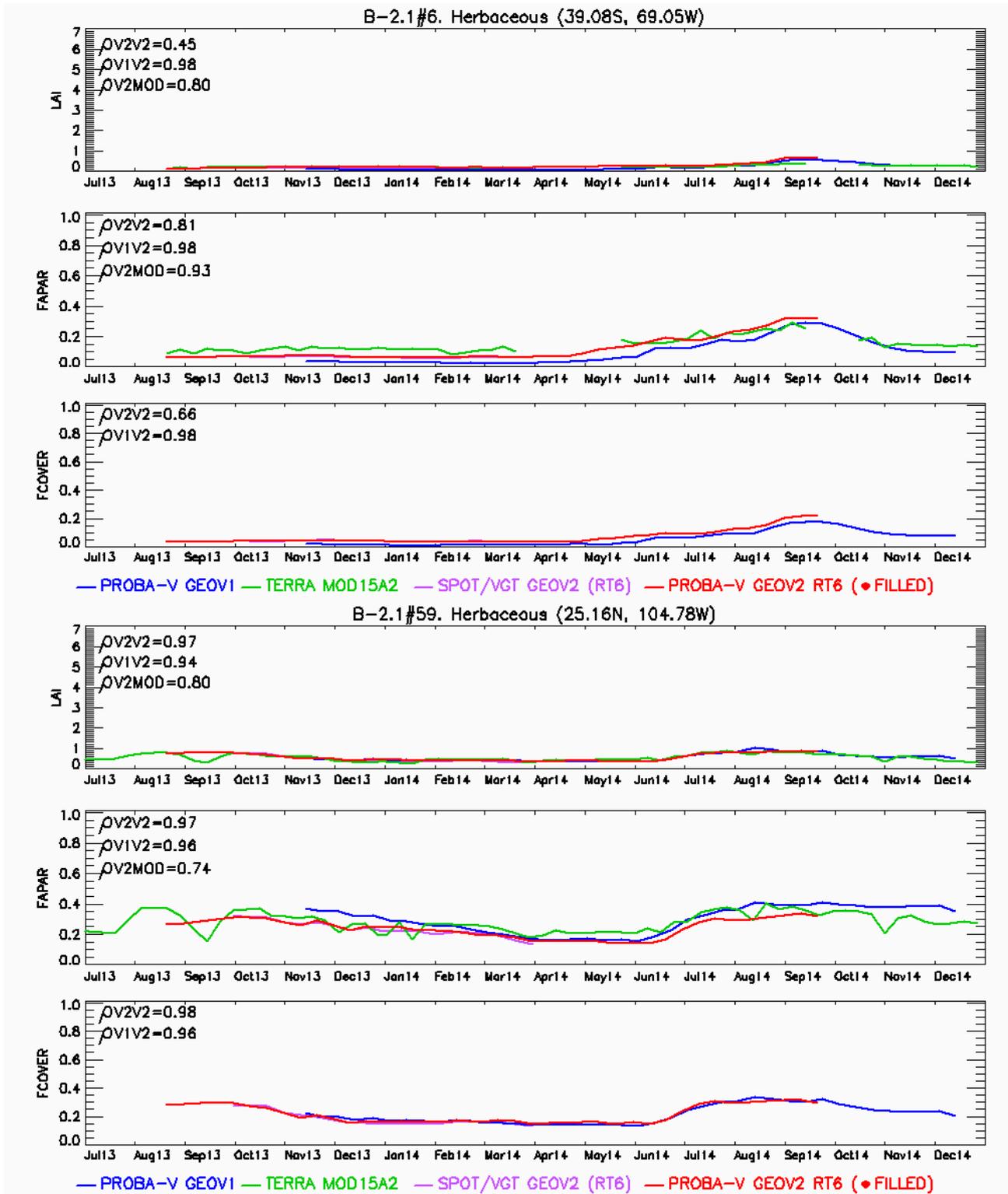
Needle-leaf Forest



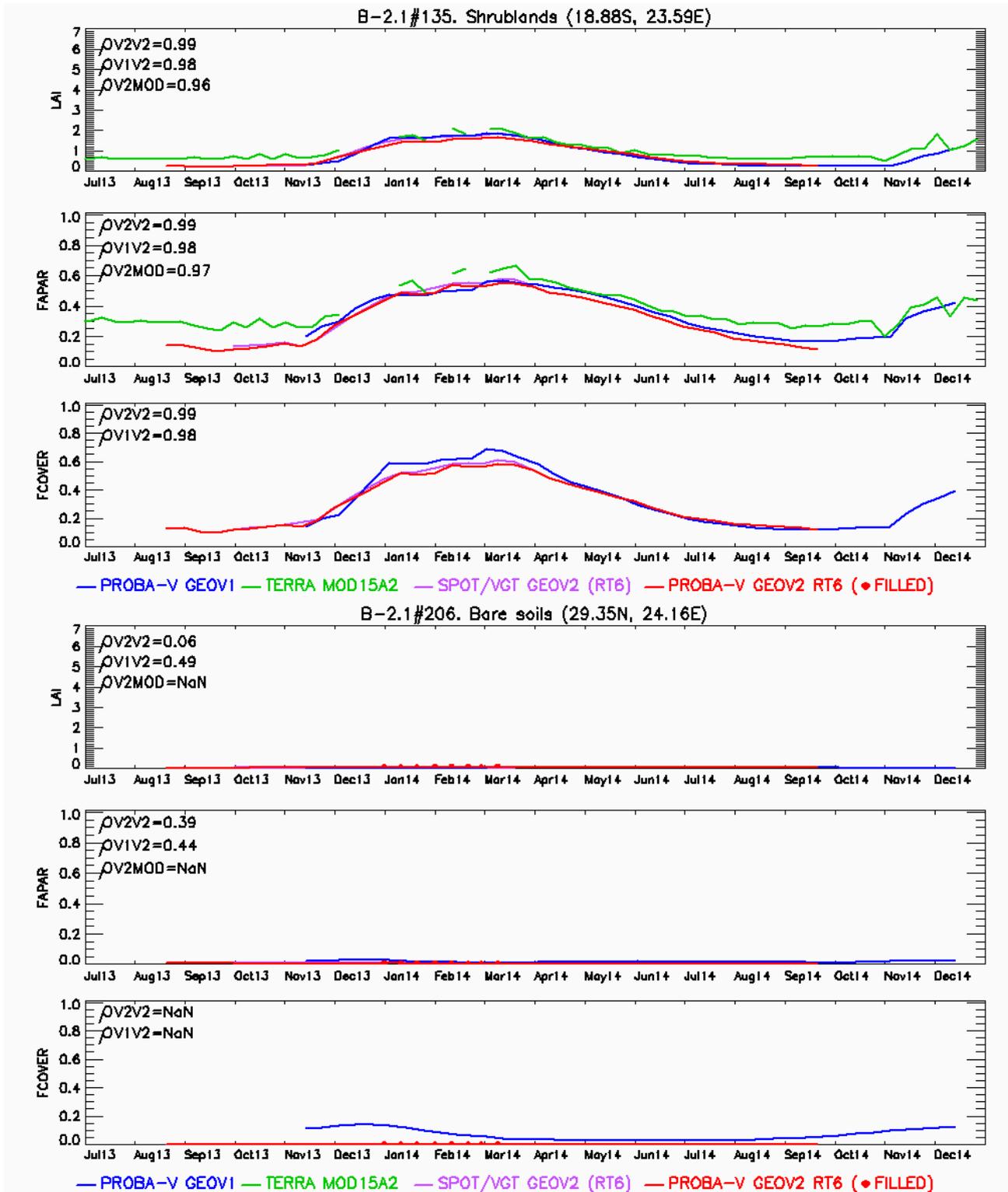
Cultivated



Herbaceous

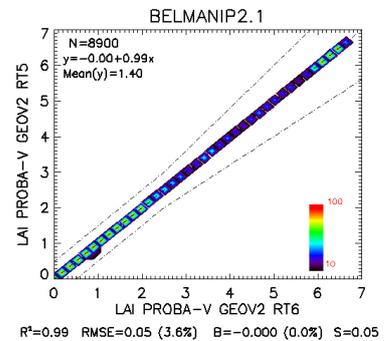
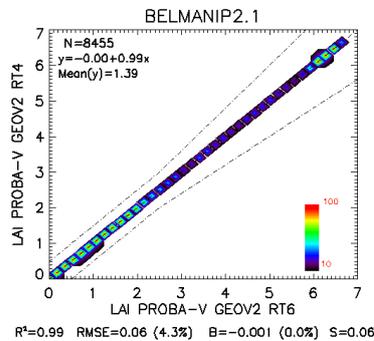
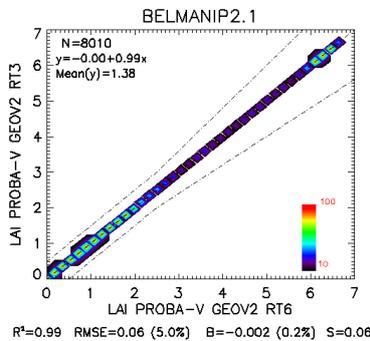
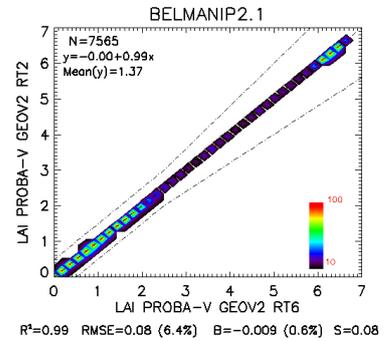
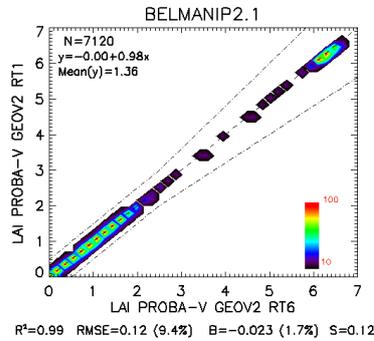
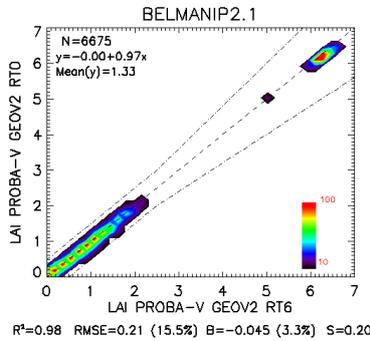


Shrublands / Sparse / Bare Areas

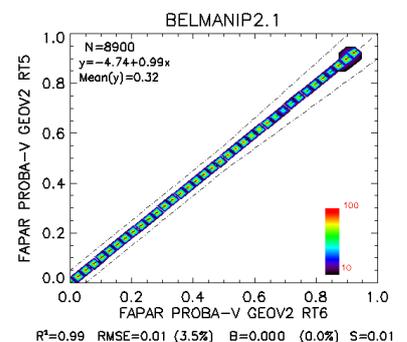
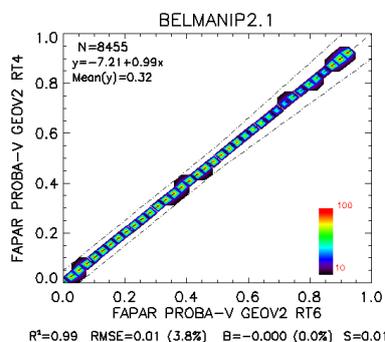
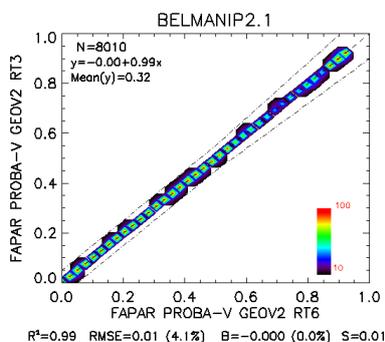
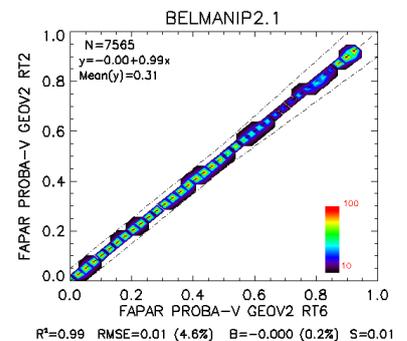
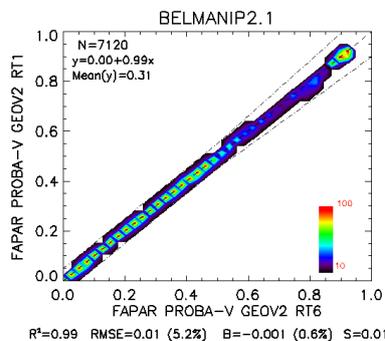
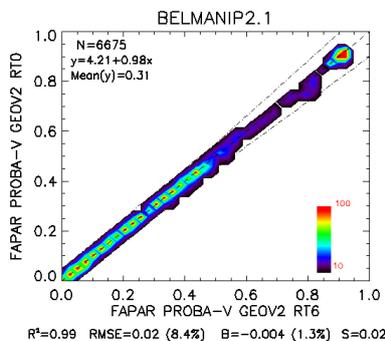


ANNEX VIII. SCATTER-PLOTS BETWEEN PROBA-V VERSION 2 MODES

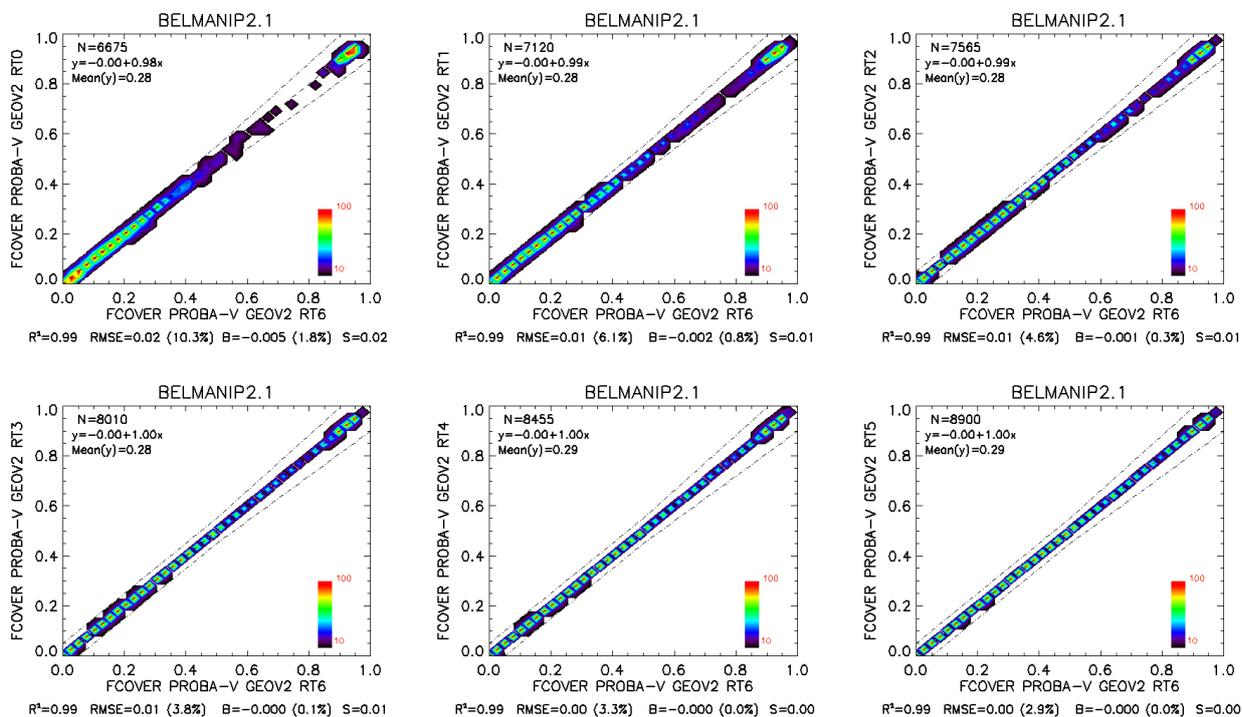
LAI



FAPAR



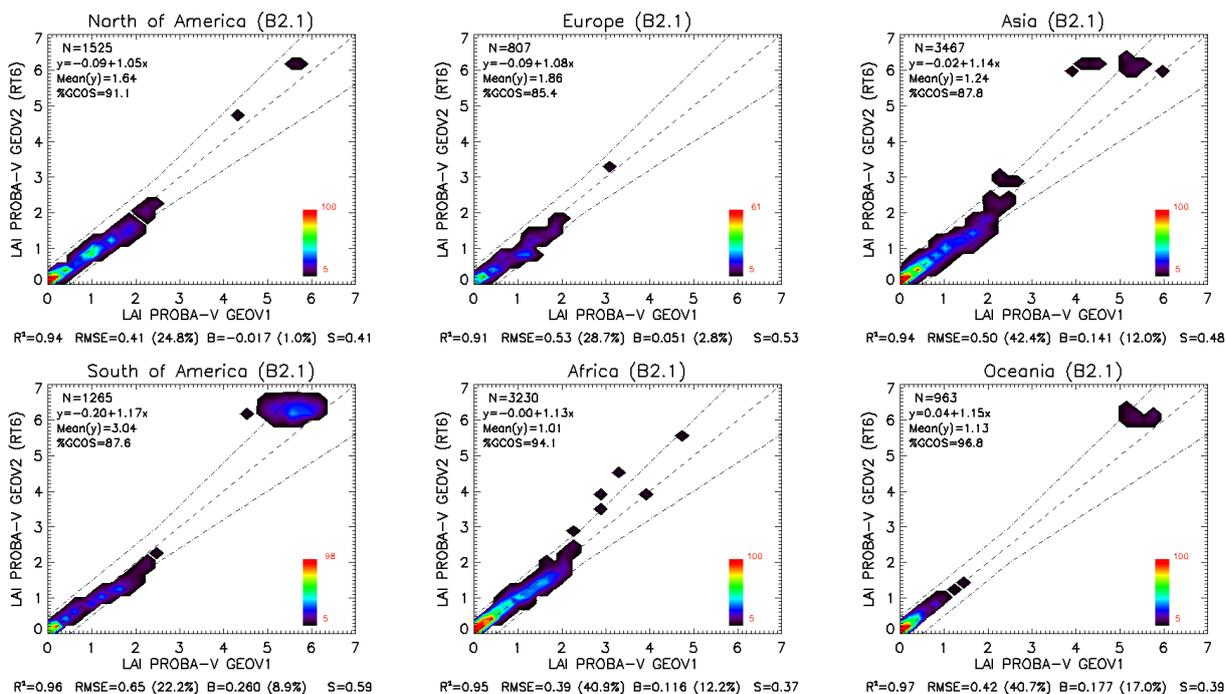
FCOVER



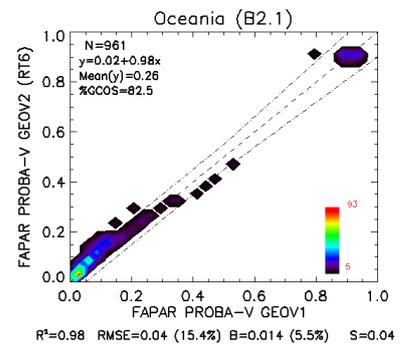
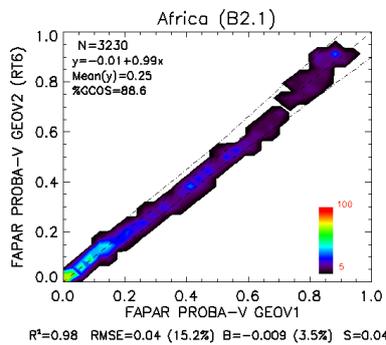
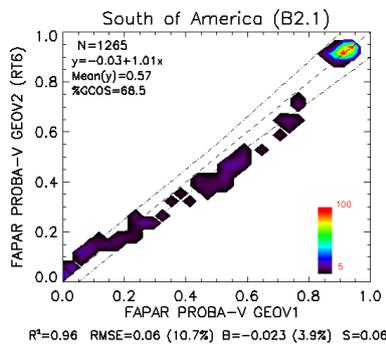
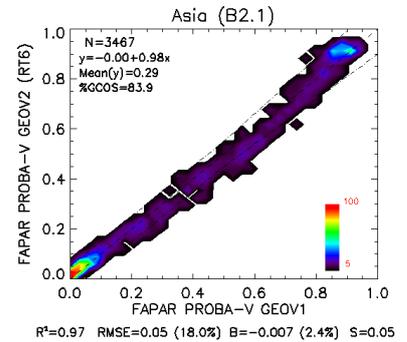
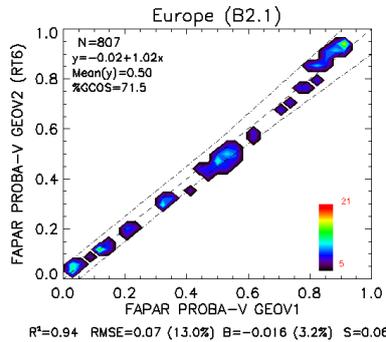
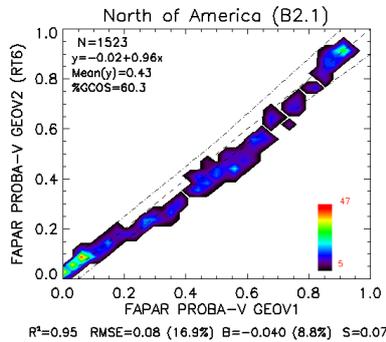
ANNEX IX. ANALYSIS PER CONTINENTAL REGION

PROBA-V Version 2 vs PROBA-V Version 1

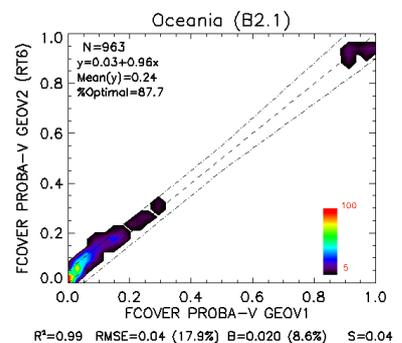
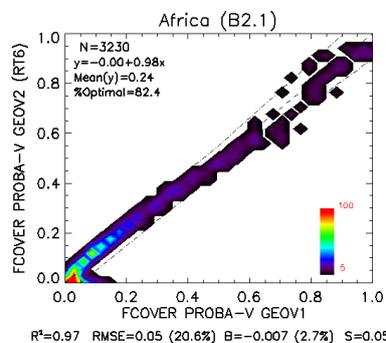
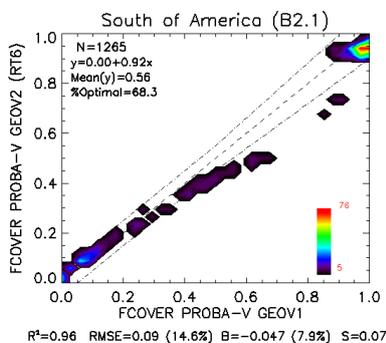
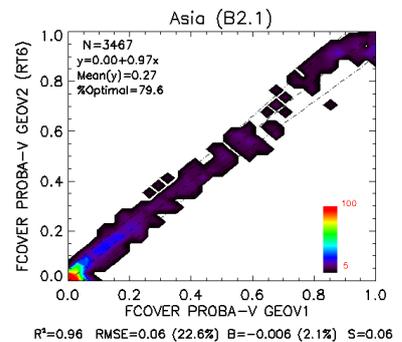
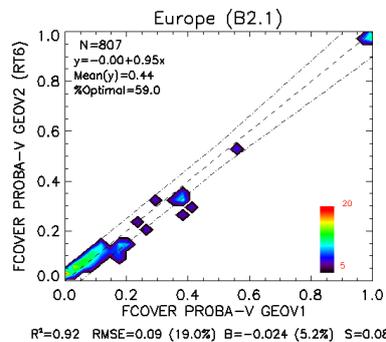
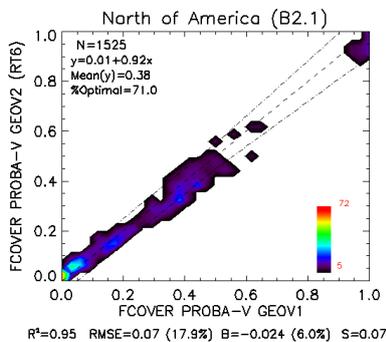
LAI



FAPAR

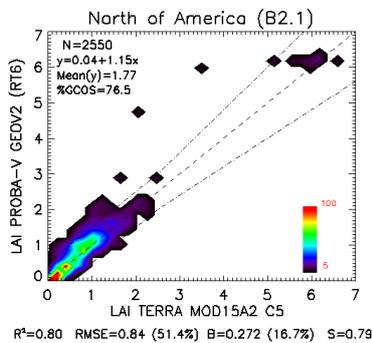


FCOVER

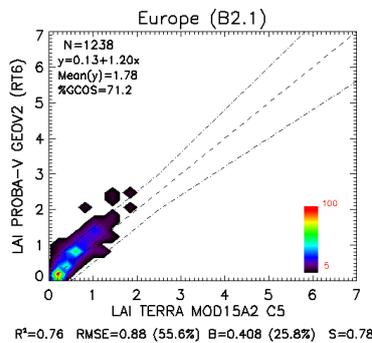


PROBA-V Version 2 vs TERRA MODIS C5

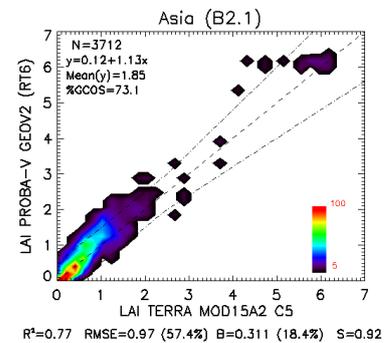
LAI



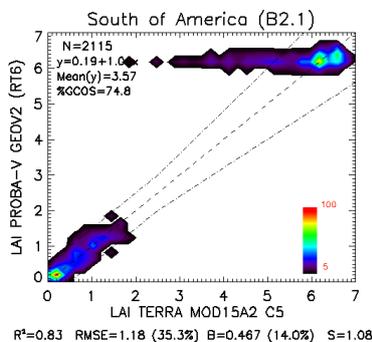
$R^2=0.80$ $RMSE=0.84$ (51.4%) $B=0.272$ (16.7%) $S=0.79$



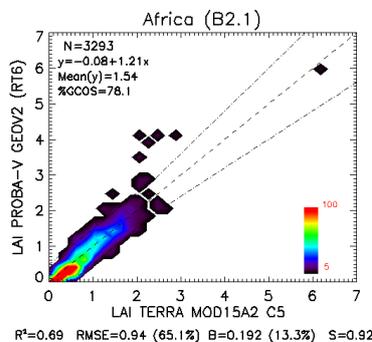
$R^2=0.76$ $RMSE=0.88$ (55.6%) $B=0.408$ (25.8%) $S=0.78$



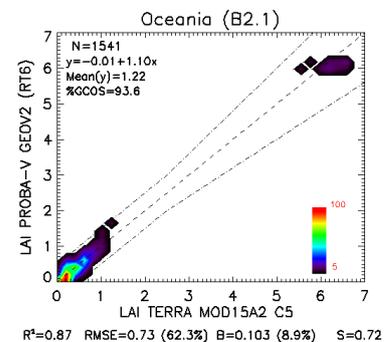
$R^2=0.77$ $RMSE=0.97$ (57.4%) $B=0.311$ (18.4%) $S=0.92$



$R^2=0.83$ $RMSE=1.18$ (35.3%) $B=0.467$ (14.0%) $S=1.08$

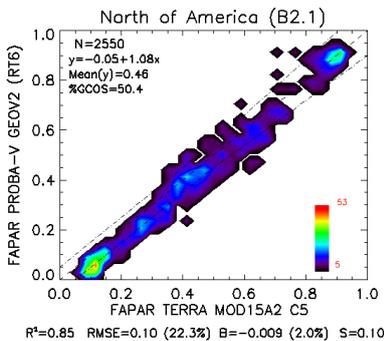


$R^2=0.69$ $RMSE=0.94$ (65.1%) $B=0.192$ (13.3%) $S=0.92$

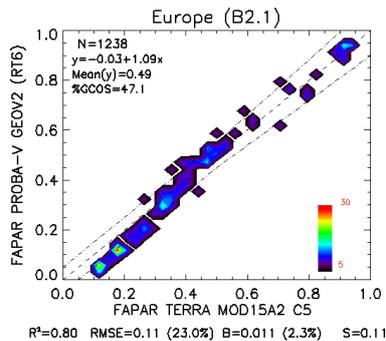


$R^2=0.87$ $RMSE=0.73$ (62.3%) $B=0.103$ (8.9%) $S=0.72$

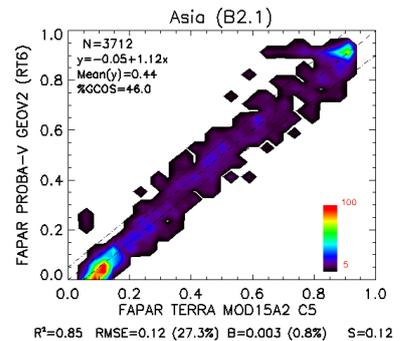
FAPAR



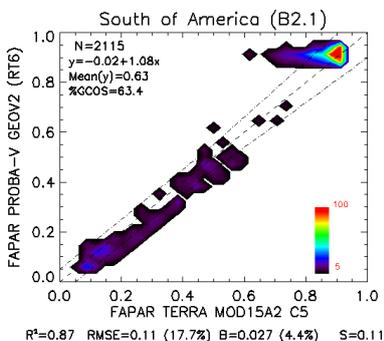
$R^2=0.85$ $RMSE=0.10$ (22.3%) $B=-0.009$ (2.0%) $S=0.10$



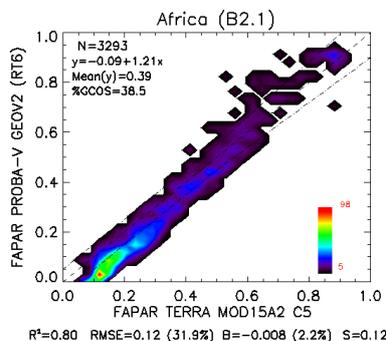
$R^2=0.80$ $RMSE=0.11$ (23.0%) $B=0.011$ (2.3%) $S=0.11$



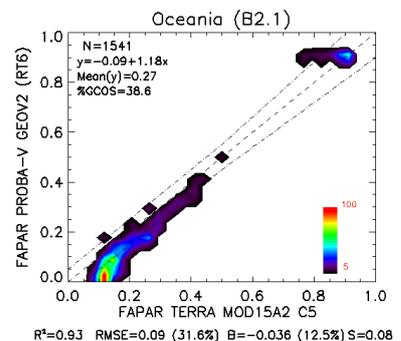
$R^2=0.85$ $RMSE=0.12$ (27.3%) $B=0.003$ (0.8%) $S=0.12$



$R^2=0.87$ $RMSE=0.11$ (17.7%) $B=0.027$ (4.4%) $S=0.11$



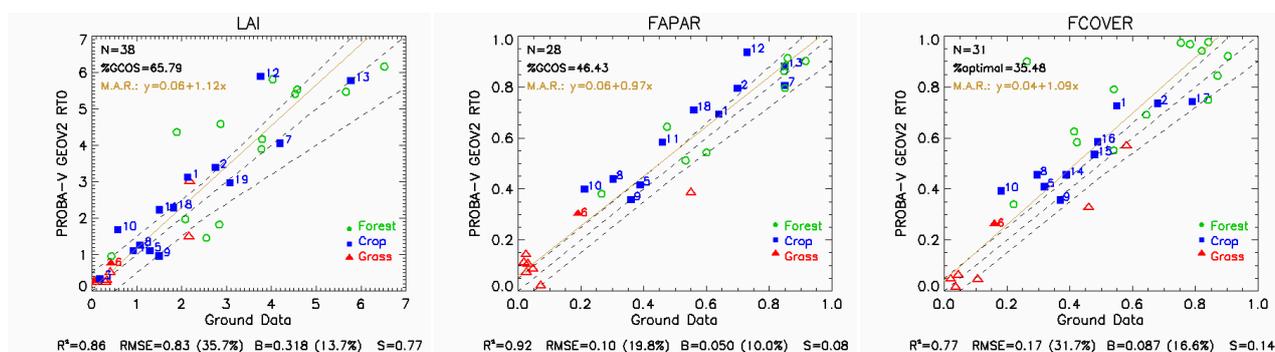
$R^2=0.80$ $RMSE=0.12$ (31.9%) $B=-0.008$ (2.2%) $S=0.12$



$R^2=0.93$ $RMSE=0.09$ (31.6%) $B=-0.036$ (12.5%) $S=0.08$

ANNEX X. ACCURACY ASSESSMENT PROBA-V VERSION 2 RT0

Direct Validation of PROBA-V Version 2 RT0 LAI, FAPAR and FCOVER with the ground-based maps.



Filled symbols correspond to concomitant values and unfilled symbols to a different year. Forest stands for Broadleaf Evergreen Forests, Deciduous Broadleaf Forests and Needle-leaf Forests, Crops stands for Cultivated and Grass refers to Herbaceous, Shrubs, Sparse and Bare Areas. Numbers identify the ground data (Table 11). Dashed lines correspond to the 1:1 line and GCOS uncertainty levels, and continuous yellow line to Major Axis Regression (M.A.R.).

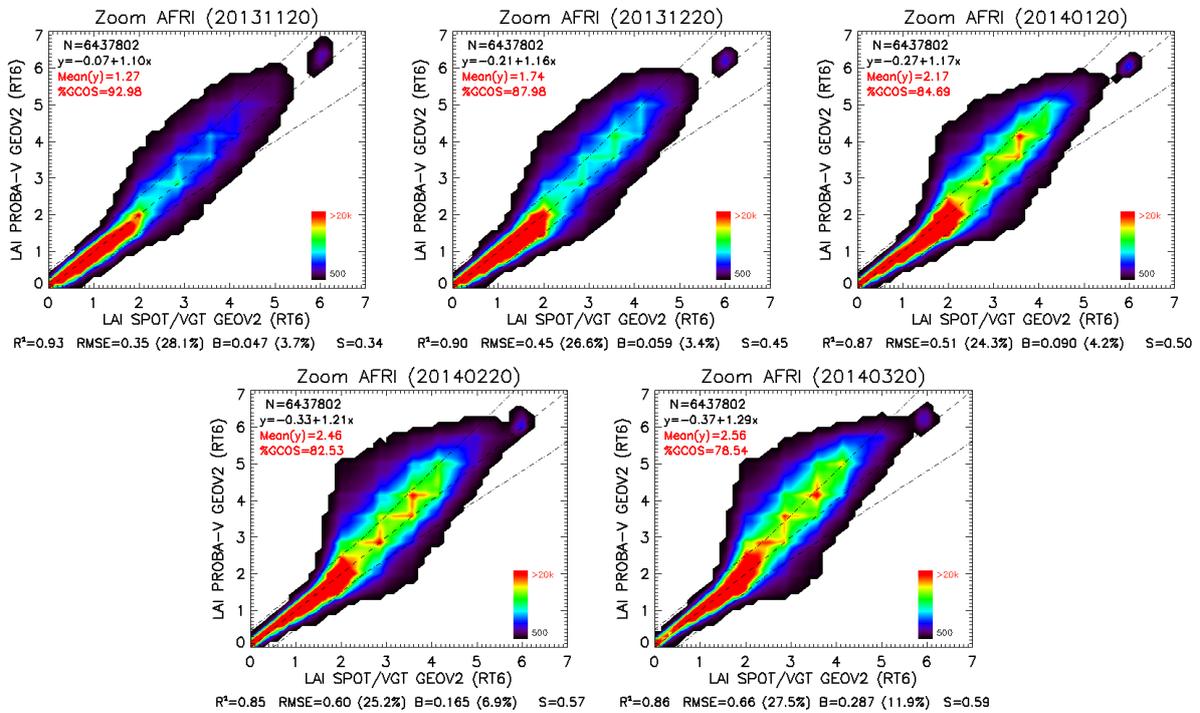
Table 27: Performance of PROBA-V Version 2 RT0 against reference ground based maps.

		Concomitant data			All data		
		LAI	FAPAR	FCOVER	LAI	FAPAR	FCOVER
PROBA-V GEOV2 RT0 vs Ground Data	N	15	12	11	38	28	31
	Correlation	0.86	0.89	0.85	0.86	0.92	0.77
	Bias	0.38	0.09	0.08	0.32	0.05	0.09
	RMSE	0.74	0.12	0.11	0.83	0.1	0.17
	Offset	0.16	0.12	0.15	0.06	0.06	0.04
	Slope	1.11	0.95	0.85	1.12	0.97	1.09
	p-value	0.51	0.619	0.221	0.127	0.55	0.203
	%optimal (LAI, FAPAR GCOS)	66.7	41.7	21.3	65.8	43.4	35.48

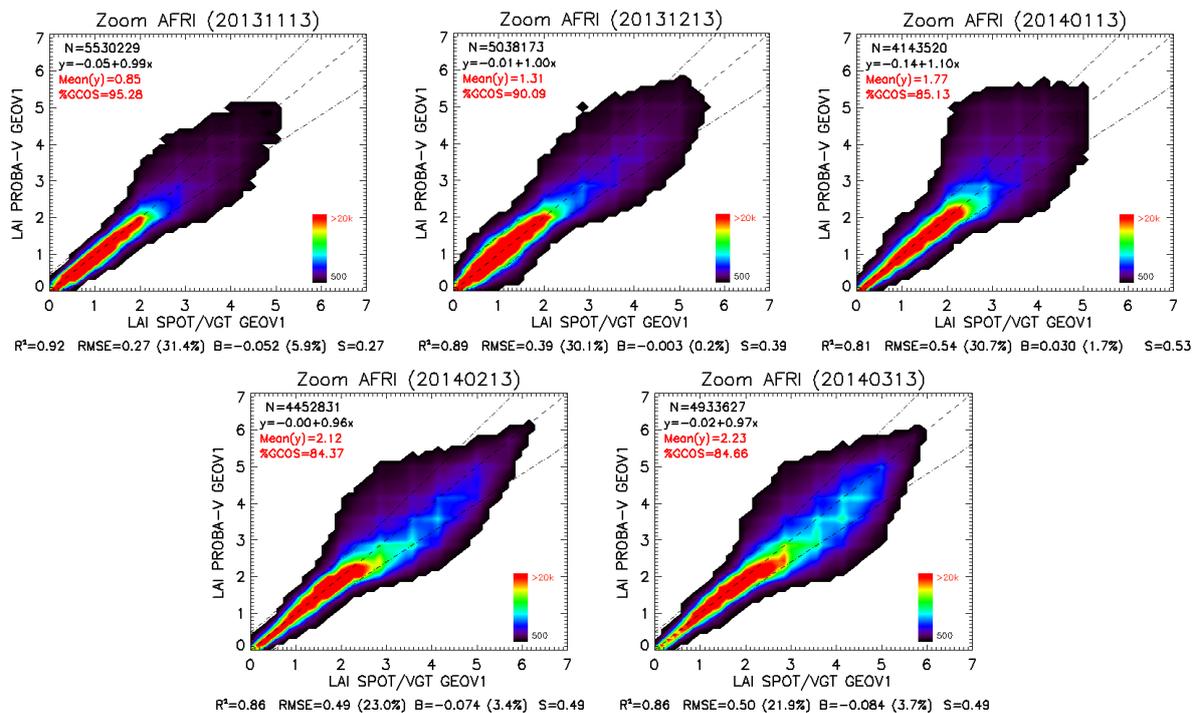
ANNEX XI. MONTHLY SCATTER-PLOTS OVER AFRICA REGION (20°x35°)

LAI

PROBA-V Version 2 vs VGT Version 2

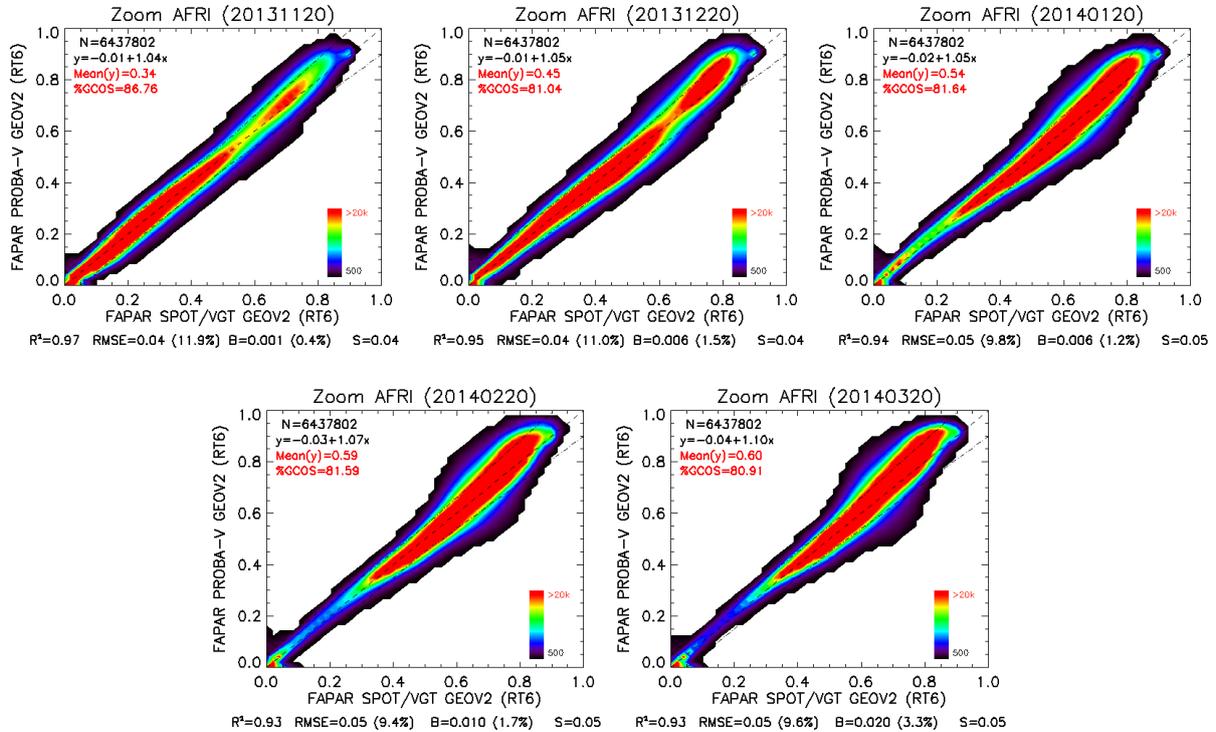


PROBA-V Version 1 vs VGT Version 1

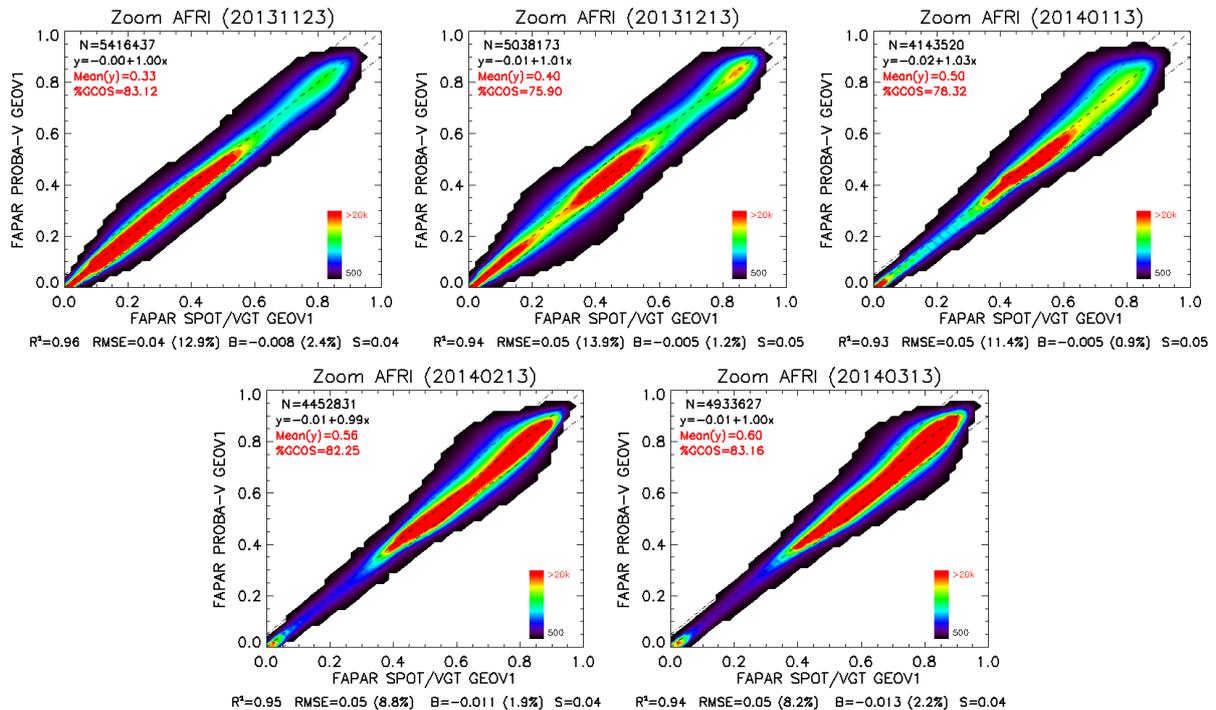


FAPAR

PROBA-V Version 2 vs VGT Version 2

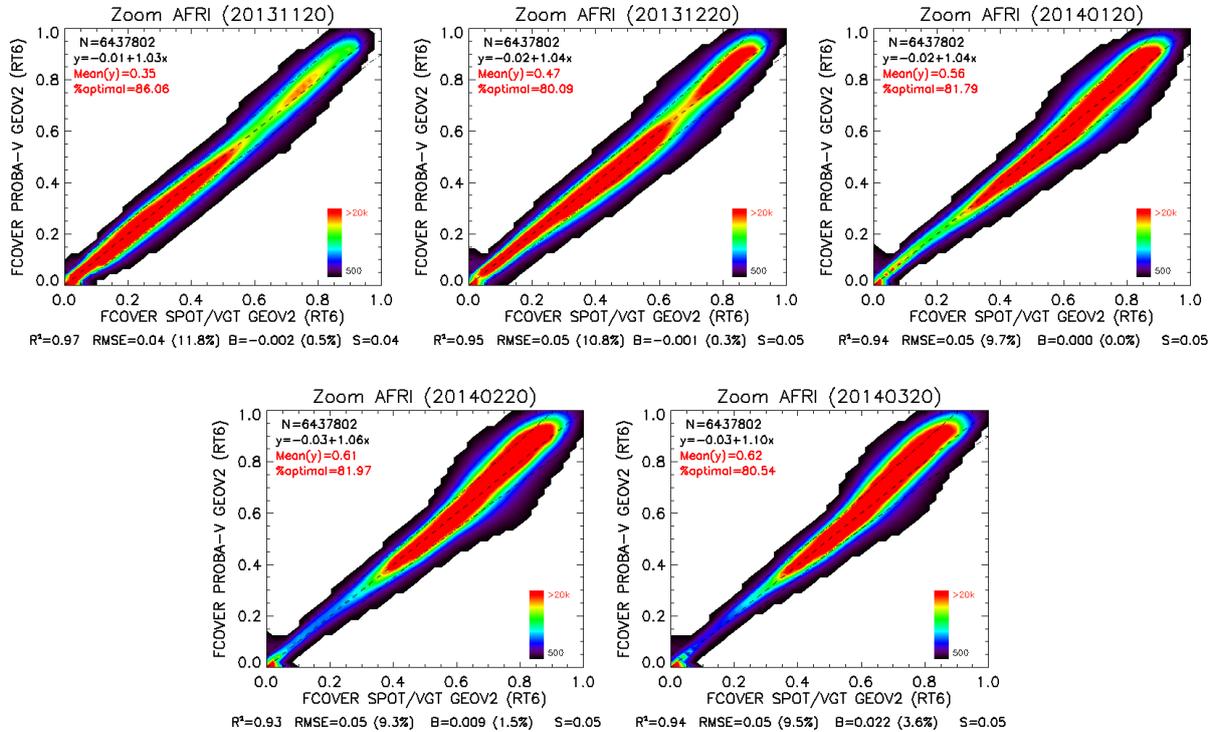


PROBA-V Version 1 vs VGT Version 1

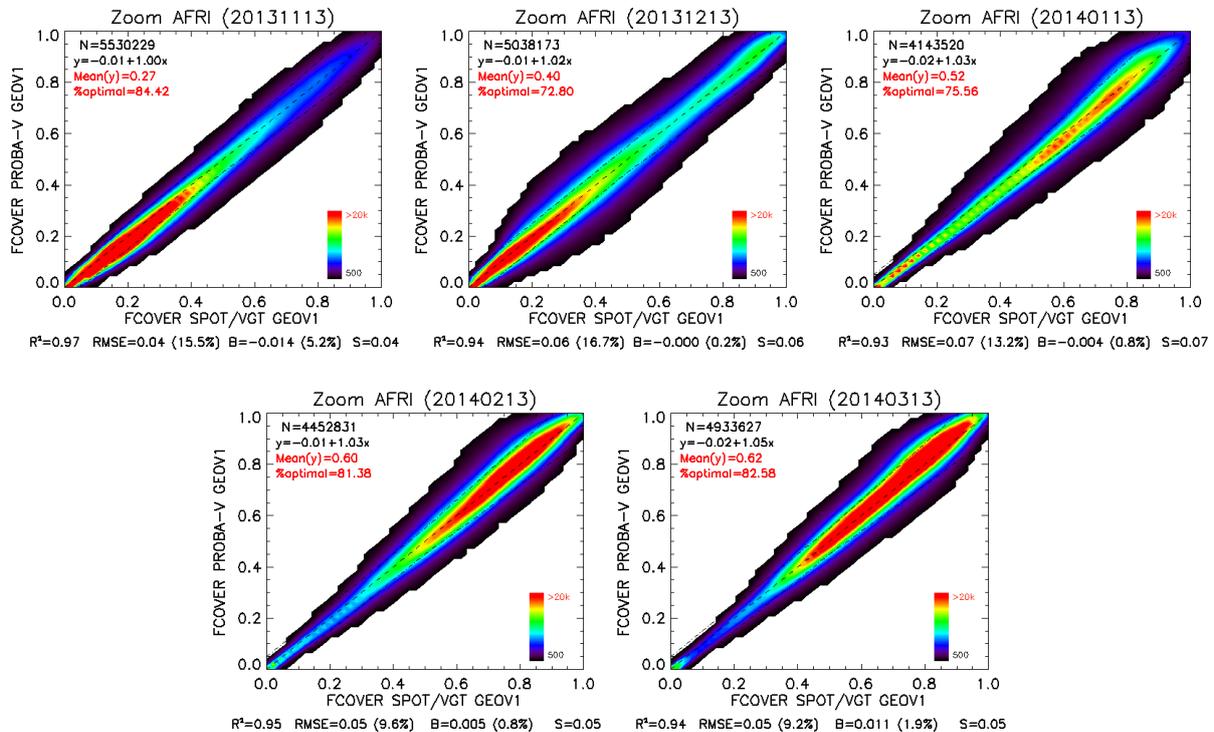


FCOVER

PROBA-V Version 2 vs VGT Version 2



PROBA-V Version 1 vs VGT Version 1



ANNEX XII. DIGITAL ANNEX

Digital Annex can be downloaded in the “Documents” tabs from the following links:

<https://land.copernicus.eu/global/products/lai>

<https://land.copernicus.eu/global/products/fapar>

<https://land.copernicus.eu/global/products/fcover>

The Digital Annex contains the following folders and information:

- **FILLED_PIXELS_MAPS:** maps of percentage of filled pixels for LAI, FAPAR and FCOVER (graphic and raster files):
 - o Annual over the period from 2013-11-10 to 2014-10-31 for RT0 mode.
 - o Annual over the period from 2013-09-10 to 2014-08-31 for RT6 mode.
 - o Monthly over the period from 2013-11-10 to 2014-10-31 for RT0 mode.
 - o Monthly over the period from 2013-09-10 to 2014-08-31 for RT6 mode.

Information to read the raster files:

- SAMPLES = 40320
 - LINES = 20160
 - DATA TYPE = byte
 - SCALE FACTOR = 100/254 such as Physical_Value = Digital_Number * 100/254
 - A header file with georeferentiation (Geographic Lat/Lon, WGS-84) is provided.
- **PLOTS:**
 - o Maps of Version 2 LAI, FAPAR and FCOVER for RT0 and RT6 modes.
 - o Maps of the RMSE LAI, FAPAR and FCOVER field for RT0 and RT6 modes.
 - **PLOTS_RESIDUALS:** Residual maps among different products for LAI, FAPAR and FCOVER and maps of the percentage within and beyond optimal levels:
 - o GEOV2/PV RT6– GEOV1/PV
 - o GEOV2/PV RT0 – GEOV2/PV RT6
 - o GEOV2/PV RT6 – GEOV2/VGT RT6
 - o GEOV2/PV RT6 – MODIS
 - **TEMPORAL_PROFILES:** Temporal profiles for all the sites under study over BELMANIP2.1 (organized per biome type) and over OTHER networks.
 - o All_Modes: It contains the several modes of Version 2.
 - o All_Products: It contains the Version 2 RT6 and reference products (Version 1 and MODIS).
 - **SCATTERS:** Scatter-plots of the quality indicators between PROBA-V V2 and SPOT/VGT V2 (one per month).
 - o RMSE: It contains LAI, FAPAR and FCOVER for RT0 and RT6 modes.
 - o NOBS: It contains LAI, FAPAR and FCOVER for RT0 and RT6 modes.
 - o LENGTH_BEFORE: It contains LAI, FAPAR and FCOVER for RT0 and RT6 modes.
 - o LENGTH_AFTER: It contains LAI, FAPAR and FCOVER for RT6 mode.