Copernicus Global Land Operations "Vegetation and Energy"

" CGLOPS-1"

Framework Service Contract N° 199494 (JRC)

SCIENTIFIC QUALITY EVALUATION

LAI, FAPAR, FCOVER

COLLECTION 1KM

VERSION 1 & VERSION 2

Issue I1.00

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Document Release Sheet

Book captain:	Jorge Sánchez-Zapero	Sign Date 12.04.2019
Approval:	Roselyne Lacaze	Sign Date 08.07.2019
Endorsement:	Michael Cherlet	Sign Date
Distribution:	Restricted	

Change Record

Issue/Rev	Date	Page(s)	Description of Change	Release
	12.04.2019	All	Scientific Quality Evaluation of LAI/FAPAR/FCOVER Collection 1km Version 1 and Version 2 products during January-December 2018	I1.00

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List of Acronyms

AD	Applicable document
ALBEDOVAL	Surface Albedo Validation
AMIS	Agricultural Market Information System
ATBD	Algorithm Theoretical Basis Document
AFRI	Africa
AsiaFlux	Regional research FLUXNET network in Asia
BA	Bare Areas
BELMANIP	BEnchmark Land Multisite ANalysis and Intercomparison of Products
CAL/VAL	Calibration and Validation group of CEOS
CEOS	Committee on Earth Observation Satellite
CGLS	Copernicus Global Land Service
CNES	Centre National d'Études Spatiales
CUL	Cultivated
CYCLOPES	Carbon cYcle and Change in Land Observational Products from an Ensemble of Satellites
C6	Collection 6
DBF	Deciduous Broadleaf Forest
DOY	Day Of Year
EBF	Evergreen Broadleaf Forest
EC	European Commission
EDO	European Drought Observatory
EFFIS	European Forest Fire Information System
EOLAB	Earth Observation LABoratory
EPS	EUMETSAT Polar System
ESU	Elementary Sampling Unit
EURO	Europe
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FCOVER	Fraction of Vegetation Cover
FP7	Seventh Framework Programme
GBOV	Ground-Based Observations for Validation
GCOS	Global Climate Observing System
GEOGLAM	Group on Earth Observations Global Agricultural Monitoring Initiative
GEOV1	Collection 1km Version 1 LAI, FAPAR, FCover products
GLC	Global Land Cover
G20	Group of Twenty
H	Herbaceous
ImagineS	Implementation of Multi-scale Agricultural Indicators Exploiting Sentinels
INRA	Institut National de la Recherche Agronomique
JRC	Joint Research Centre
LAI	Leaf Area Index
LANDVAL	LAND Validation
LP	Land Product
LPV	Land Product Validation Subgroup
LSASAF	Satellite Apllication Facility on Land Surface Analysis
LUT	Look Up Table
MAR	Major Axis Regression
MARS	Monitoring Agricultural ResourceS
MCD15A2H	MODIS/Terra+Aqua Leaf Area Index/FPAR 8-Day Global 500m SIN Grid

MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
N	Number of samples
NARMA	Natural Resource Monitoring in Africa
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NEON	National Ecological Observatory Network
NIR	Near-infrared
NLF	Needle-Leaf Forest
NNT	Neural Network
NOAM	North America
OCEA	Oceania
OLIVE	On Line Validation Exercise
OLS	Ordinary Least Squares
OzFlux	TERN (Terrestrial Ecosystem Research Network) network of observation sites across Australia and New Zealand
PAR	Photosynthetically Active Radiation
PDF	Probability Density Function
PUM	Product User Manual
PROBA-V	Project for On-Board Autonomy satellite, the V standing for vegetation
QAR	Quality Assessment Report
QA4ECV	Quality Assurance for Essential Climate Variable
RM	Reference Measurements
RMSD	Root Mean Square Deviation
ROI	Region of Interest
RT	Real Time
S	Standard deviation
SA	Surface Albedo
SAVS	Surface Albedo Validation Sites
SBA	Sparse vegetated and Bare Areas
SOAM	South America
SQE	Scientific Quality Evaluation
SPOT /VGT	Satellite Pour l'Observation de la Terre / VEGETATION
SVP	Service Validation Plan
TOA	Top Of Atmosphere
TOC	Top Of Canopy
TUG	Technical Users Group
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
V1	Version 1
V2	Version 2
VALERI	Validation of Land European Remote sensing Instruments
VR	Validation Report
WGCV	Working Group on Calibration and Validation (CEOS)
WGS	World Geodetic System
WMO	World Meteorological Organization

EXECUTIVE SUMMARY

The Copernicus Global Land Service (CGLS) is earmarked as a component of the Land 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 Scientific Quality Evaluation of recent PROBA-V LAI, FAPAR, FCOVER Collection 1km Version 1 and Version 2 products (2018 year) is carried out in order to check if the operational products keep the same level of quality than the fully validated products (year 2014). The methodology follows, as much as possible, the guidelines, protocols and metrics defined by the Land Product Validation (LPV) group of the Committee on Earth Observation Satellite (CEOS).

The analysis focuses mainly on the comparison between recent PROBA-V Collection 1km V1 and V2 products (2018) with reference validated PROBA-V V1 and V2 products (year 2014) as well as with SPOT/VGT Collection 1km V1 and V2 products (year 2012) to evaluate the impact of the change of the input data (from SPOT/VGT to PROBA-V). Several criteria of performance are evaluated at global scale. Additionally, temporal variations over cropland areas were evaluated over Europe, as well as the temporal trends over specific locations around the world showing specific environmental events in 2018 (i.e., fires or floods). The evaluated criteria include product continuity, spatial and temporal consistency, statistical consistency and precision. The analysis at global scale is performed over a network of 725 validation sites (LANDVAL) representing global conditions. The accuracy of PROBA-V Collection 1km V1 and V2 products (and MODIS C6) was evaluated with 20 sites coming from Ground-Based Observations for Validation (GBOV) database, with availability of multi-temporal ground-based maps during the 2014-2017 period.

In overview, results demonstrate that the recent PROBA-V LAI, FAPAR, FCOVER Collection 1km V1 and V2 products keep a similar level of quality than the validated PROBA-V V1 and V2 (2014) products. As compared to SPOT/VGT V1 and V2 products (year 2012), results show also a similar consistency, but higher bias was obtained mainly for FCOVER V1 and FAPAR V2 where around 5% of positive bias was found (PROBA-V > SPOT/VGT). In addition, PROBA-V Collection 1km V1 and V2 products captures quite well the impact of most of environmental events, and temporal trajectories of GBOV ground-based maps are generally properly reproduced by satellite products.

The accuracy evaluated over 20 GBOV multi-temporal sites (2014-2017 period) shows an overall accuracy (RMSD) of 0.84, 0.15 and 0.14 for LAI, FAPAR and FCOVER respectively. PROBA-V Collection 1km V2 shows improved accuracy than V1 with RMSD values of 0.83, 0.13 and 0.14 for LAI, FAPAR and FCOVER. The accuracy (RMSD) of MODIS C6 LAI/FAPAR products was 0.91/0.14. All satellite products tend to provide higher values than GBOV data for low ranges, where the grassland biome is mainly affected, as well as forests sites during the leaf-off season. ***Note, however, that the upscaling approach of GBOV has not been validated yet by independent experts and that, therefore, the obtained accuracy estimates must be considered with caution.***

1 BACKGROUND OF THE DOCUMENT

1.1 SCOPE AND OBJECTIVES

This document presents the results of the annual Scientific Quality Evaluation (SQE) of the recent LAI, FAPAR and FCOVER Collection 1km Version 1 and Version 2 products based on PROBA-V observations.

The quality evaluation is performed over global datasets coming from the Copernicus Global Land Service Portal Distribution (http://land.copernicus.vgt.vito.be/PDF/portal/Application.html) covering a period from 1st of January to 31th of December 2018 at 10-days temporal frequency.

The main objective is to verify that the recent Collection 1km Version 1 and Version 2 products keep the same level of quality in the period under study than the validated products. For this purpose, a comparison with both SPOT/VGT V1 and V2 products (year 2012) and PROBA-V V1 and V2 products for the year 2014 is conducted. Additionally, the products are evaluated over a large region of interest (ROI) located in Europe, locations with specific environmental events reported in 2018, and compared with ground-based maps coming from GBOV database (https://land.copernicus.eu/global/gbov).

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 analysis.
- Chapter 5 summarizes the main conclusions of the study.
- Chapter 6 makes recommendations based upon the results.

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 – 26 May 2015.

1.3.2 Input

Document ID	Descriptor
CGLOPS1_SSD	Service Specifications of the Global Component of the Copernicus Land Service.
CGLOPS1_SVP	Service Validation Plan of the Global Land Service
GIOGL1_ATBD_LAI-V1	Algorithm Theoretical Basis Document of the SPOT/VGT LAI, FAPAR, FCOVER Collection 1km Version 1.
GIOGL1_ATBD_LAI1km-V1	Algorithm Theoretical Basis Document of the PROBA-V LAI, FAPAR, FCOVER Collection 1km Version 1.
CGLOPS1_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_ATBD_PROBA2VGT	Algorithm Theoretical Basis Document of PROBA to VGT Pre-processing.
CGLOPS1_VR_SA1km-PROBAV-V1.5	Validation Report of PROBA-V Surface Albedo Collection 1km product version 1.5
GIOGL1_VR_LAIV1	Validation report of the SPOT/VGT LAI, FAPAR and FCOVER Collection 1km Version 1.
GIOGL1_QAR_LAI1km-V1	Validation report of the PROBA-V LAI, FAPAR and FCOVER Collection 1km Version 1.
GIOGL1_QAR_LAI1km-VGT-V2	Quality Assessment Report of the Collection 1km LAI, FAPAR and FCOVER Version 2 derived from SPOT/VGT.
CGLOPS1_QAR_LAI1km-PROBAV-V2	Validation report of the PROBA-V LAI, FAPAR and FCOVER Collection 1km Version 2.
CGLOPS1_SQE2017_LAI1km-V1&V2	Scientific Quality Evaluation report of the PROBA-V LAI, FAPAR and FCOVER Collection 1 km Version 1 and 2 during the 2017 year.
CGLOPS1_SQE2018_NDVI1km-V2.2	Scientific Quality Evaluation report of the PROBA-V NDVI Collection 1km Version 2.2 during the 2018 year

1.3.3 Output

Document ID	Descriptor
CGLOPS1_PUM_LAI1km-V1	Product User Manual summarizing all information about the

	PROBA-V LAI Collection 1km Version 1 product.
CGLOPS1_PUM_FAPAR1km-V1	Product User Manual summarizing all information about the PROBA-V FAPAR Collection 1km Version 1 product.
CGLOPS1_PUM_FCOVER1km-V1	Product User Manual summarizing all information about the PROBA-V FCOVER Collection 1km Version 1 product.
CGLOPS1_PUM_LAI1km-V2	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**
GBOV-ATBD-LP3-LP4-LP5	GBOV Algorithm Theoretical Basis Document - Vegetation Products: LP3 (LAI), LP4 (FAPAR) and LP5 (FCOVER). https://land.copernicus.eu/global/gbov/public/docs/products/GBOV-ATBD-LP3-LP4-LP5_v1.2-Vegetation.pdf

2 REVIEW OF USERS REQUIREMENTS

According to the applicable document [AD2] and [AD3], the user's requirements relevant for LAI, FAPAR, FCOVER products of PROBA-V Collection 1km Version 1 and V2 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.
  - The target baseline location accuracy shall be 1/3rd 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 (40320 columns, 14673 lines):
    - Upper Left: 180W, 75N.
    - Bottom Right: 180E, 56S

- **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#200, 2016)" (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#200, 2016].

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

Additionally, the Technical User Group of the Copernicus Global Land [AD3] has recommended new uncertainty levels for FAPAR and FCOVER (Table 2) while for LAI the users did not come to an agreement. Some agreed on a 10% optimal accuracy while others thought it was unachievable.

Table 2: CGLOPS uncertainty levels for FAPAR and FCOVER products.

	Optimal	Target	Threshold
FAPAR / FCOVER	5%	10%	20%

- **Additional user requirements**

The GCOS requirements are supplemented by application specific requirements identified by the WMO (Table 3). 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 3: WMO Requirements for Global LAI and FAPAR products (From http://www.wmo-sat.info/oscar/requirements); G=goal, B=breakthrough, T=threshold.

<table>
<tr><th rowspan="2">Application</th><th rowspan="2">Variable</th><th colspan="3">Accuracy (%)</th><th colspan="3">Spatial Resolution (km)</th><th colspan="3">Temporal Resolution (days)</th></tr>
<tr><th>G</th><th>B</th><th>T</th><th>G</th><th>B</th><th>T</th><th>G</th><th>B</th><th>T</th></tr>
<tr><td rowspan="2">Global Weather Prediction</td><td>LAI</td><td rowspan="2">5</td><td rowspan="2">10</td><td rowspan="2">20</td><td rowspan="2">2</td><td rowspan="2">10</td><td rowspan="2">50</td><td rowspan="2">1</td><td rowspan="2">5</td><td rowspan="2">10</td></tr>
<tr><td>FAPAR</td></tr>
<tr><td rowspan="2">Regional Weather Prediction</td><td>LAI</td><td rowspan="2">5</td><td rowspan="2">10</td><td rowspan="2">20</td><td rowspan="2">1</td><td rowspan="2">5</td><td>40</td><td rowspan="2">0.5</td><td rowspan="2">1</td><td rowspan="2">2</td></tr>
<tr><td>FAPAR</td><td>20</td></tr>
<tr><td>Hydrology</td><td>LAI</td><td>5</td><td>8</td><td>20</td><td>0.01</td><td>0.1</td><td>10</td><td>7</td><td>11</td><td>24</td></tr>
<tr><td rowspan="2">Agricultural Meteorology</td><td>LAI</td><td rowspan="2">5</td><td>7</td><td>10</td><td>0.01</td><td>0.1</td><td>10</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td>FAPAR</td><td>8</td><td>20</td><td>5</td><td>13.6</td><td>100</td><td>1 h</td><td>0.25</td><td>7</td></tr>
<tr><td>Seasonal and Inter-annual Forecasts</td><td>FAPAR</td><td>5</td><td>7</td><td>10</td><td>50</td><td>100</td><td>500</td><td>7</td><td>12</td><td>30</td></tr>
<tr><td rowspan="2">Climate-Carbon Modelling</td><td>LAI</td><td rowspan="2">5</td><td rowspan="2">7</td><td rowspan="2">10</td><td rowspan="2">0.25</td><td>0.85</td><td>10</td><td rowspan="2">1</td><td rowspan="2">3</td><td rowspan="2">30</td></tr>
<tr><td>FAPAR</td><td>0.5</td><td>2</td></tr>
</table>

3 REVIEW OF THE PROBA-V COLLECTION 1KM PRODUCTS QUALITY

3.1 VERSION 1

The scientific validation of the PROBA-V LAI, FAPAR, FCOVER Collection 1km Version 1 products is described in the Quality Assessment Report [GIOGL1_QAR_LAI1km-V1]. The quality assessment of the PROBA-V LAI, FAPAR and FCOVER Collection 1km Version 1 products during the first year of data (2014) was conducted following the validation procedure described in the Copernicus Global Land Service Validation Plan in agreement with the CEOS LPV best practices for validation of LAI products. Moreover, MODIS C5 products were considered for inter-comparisons.

The validation results showed a good spatial consistency with the SPOT/VGT V1 products for the overlap period (November 2013-May 2014) for almost all the continental regions (90% of cases with differences lower than 0.5 for LAI, 80% of cases with differences lower than 0.05 for FAPAR/FCOVER) although some spatial discrepancies were found mainly over equatorial areas, South America and Europe. In particular, a positive bias, as compared to SPOT/VGT, was detected for the FCOVER mainly for values larger than 0.5. For the FAPAR, the PROBA-V V1 tends to slightly underestimate the SPOT/VGT product.

The impact on the anomaly class was assessed by comparison with a climatology calculated based on Version 1 SPOT/VGT products for the period 2000-2010. Then, the anomaly maps were derived using either SPOT/VGT or PROBA-V for the overlapping period (November 2013, May 2014). The impact on the anomaly class when it is calculated based on PROBA-V instead of SPOT/VGT input data ranged between 10% of sample for LAI and 20% of samples for FAPAR and FCOVER (mainly over South America, Central Africa and Europe) for the overlap period.

All the criteria evaluated showed in overall positive results (Table 4), with however a positive bias for FCOVER as compared to SPOT/VGT V1 products. The main drawback of the product is the completeness which is slightly lower than in SPOT/VGT V1 products.

Table 4: Summary of Product Evaluation (PROBA-V 1km V1). The plus (minus) symbol means that the product has a good (poor) performance according to this criterion.

QA Criteria	Performance	Comments
Product Completeness	**-**	Main limitations over Northern latitudes in wintertime and Equatorial areas.
Spatial Consistency	**+**	Optimal spatial consistency between PROBA-V and SPOT/VGT 1km V1 products. Most of the differences between both lies within 0.5 for LAI and 0.05 for FAPAR/FCOVER Good repeatability over well-known homogenous areas (Dense Forest and Shrublands). Good variability for known spatial gradients. Larger discrepancies between PROBA-V and MODIS over EBF and DBF for LAI and globally for FAPAR (similar than SPOT/VGT and MODIS).
Temporal Consistency	**+**	Good consistency of PROBA-V 1km V1 temporal variations, as compared to SPOT/VGT 1km V1 and MODIS C5. Cross-correlations between PROBA-V and SPOT/VGT 1km V1 (higher than 0.9 in more than 70% of the sites for most of biomes except in EBF). Realism of temporal profiles over deciduous forest. Unreliable seasonality of the FCOVER over some desertic sites.
Intra-Annual Precision	**+**	Very smooth temporal profiles
Statistical Analysis of Discrepancies	**+**	Good consistency between PROBA-V and SPOT/VGT 1km V1 (RMSE=0.3, 0.03, 0.04 for LAI, FAPAR and FCOVER) over BELMANIP2.1 sites. Larger discrepancies between both 1km V1 products and MODIS C5. FCOVER PROBA-V shows higher values than SPOT/VGT mainly for forest sites.
Accuracy	**±**	Good accuracy with limited ground dataset for LAI (RMSE= 0.52) and FAPAR (RMSE=0.11). Positive bias for FCOVER (RMSE=0.14, Bias=0.09).

3.2 VERSION 2

The scientific validation of PROBA-V LAI, FAPAR, FCOVER Collection 1km Version 2 products is described in the Quality Assessment Report [CGLOPS1_QAR_LAI1km-PROBAV-V2]. Version 2 products provides a near real time estimate (RT0) which is derived only with past-time observations and a number of consolidations estimates (RT1-RT6) once a new dekad of observations is available.

The quality assessment showed, in overall, good results for the several criteria of performance evaluated (Table 5), 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 residuals cases (slightly spatial discrepancies over Northern latitudes and East Asia). 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 V2 showed complete spatial coverage and very smooth profiles which improves the spatio-temporal continuity (using filled values based on a climatology) and the precision of the reference products (PROBA-V V1, MODIS). PROBA-V V2 showed an overall good agreement with PROBA-V V1 FCOVER and constitutes an intermediate solution between PROBA-V V1 and MODIS both for FAPAR and LAI across biomes when evaluated over the BELMANIP2.1 sites. The highest discrepancies were observed over evergreen broadleaf forests where PROBA-V V2 efficiently corrects the underestimation of LAI, FAPAR and FCOVER values observed in PROBA-V V1 mainly. The consistency between PROBA-V V2 and SPOT/VGT V2 is globally good during the overlap period (winter time in northern hemisphere), but a positive bias was identified over specific areas of Africa covered by fully developed vegetation and high cloud coverage, in particular for LAI. It has been also found some sites where PROBA-V V2 profiles displays shifts at the start and end of the growing season compared to other satellite products. Several artefacts affecting PROBA-V V1 over northern latitudes or desertic areas are properly removed in PROBA-V V2. The accuracy assessment, over a limited number of sites, showed an overall accuracy (RMSD) 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. Compared to PROBA-V V1, similar performance was found for FAPAR and FCOVER and slightly lower for LAI. The percentage of retrievals within GCOS requirements on accuracy were 65% for LAI, 57% for FAPAR, and 35% for FCOVER.

A pending study in the QAR was to evaluate if the positive bias observed between PROBA-V 1km V2 and SPOT/VGT V2 in the south hemisphere is a local problem or more general problem. To assess this, the inter-annual precision and bias of PROBA-V V2 (2017) as compared to PROBA-V V2 (2014) or to SPOT/VGT V2 (2012) was investigated during the SQE performed during the 2017 year [CGLOPS1_SQE2017_LAI1km-V1&V2] over the LANDVAL global network of sites and one year of data including summer in northern latitudes. In overview, results demonstrate that the recent PROBA-V LAI, FAPAR, FCOVER Collection 1km V2 products for 2017 year kept a similar level of quality than the validated PROBA-V V2 (2014) products. As compared to SPOT/VGT V2 products (year 2012), results showed also a similar consistency, but higher bias was obtained mainly for FAPAR where around 6% of bias was found. Furthermore, slight bias was found for LAI (3.6%) and FCOVER V2 (3.0%).

Table 5: Summary of Product Evaluation (PROBA-V 1 km V2). 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 PROBA-V 1km V2 products.
Spatial Consistency	±	Smooth and reliable distributions over the globe, and good autocorrelation over homogeneous sites. Overall good spatial consistency between PROBA-V V2 modes, with residuals lower than 1 LAI unit (99% of samples), or 0.1 FAPAR/FCOVER units (98% of samples). Spatial inconsistencies PROBA-V 1km V2 vs SPOT/VGT 1km V2 mainly for LAI observed over areas with growing and fully developed vegetation (non EBF), such as Southern Africa. Systematic differences with PROBA-V V2 LAI > SPOT/VGT V2 LAI (up to 2 units). Spatial inconsistencies with PROBA-V 1km V1 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). Large spatial discrepancies between PROBA-V V2 and MODIS products, as between PROBA-V V1 and MODIS.
Temporal Consistency	+	Consistent seasonal variations. Improvements as compared to PROBA-V 1km V1 over EBF (correction noisy profiles), DBF (anticipated decrease in V1 LAI), NLF (artefacts in fall) and bare areas (false seasonality in deserts). Good cross-correlations between PROBA-V V2 and reference products. Improved cross-correlation PROBA-V V2 vs SPOT/VGT V2 as compared to PROBA-V V1 vs SPOT/VGT V1. Locally, slight shift in the temporal profiles at the start and end of season, compared to PROBA-V V1 and MODIS product.
Intra-Annual Precision	+	Very low short-time variability (smoothness) much better than V1 and MODIS.
Statistical Analysis of Discrepancies	+	Overall good consistency between PROBA-V V2 and PROBA-V V1 for LAI (90% samples within GCOS), FAPAR (80% of samples within GCOS) and FCOVER (77%). PROBA-V V2 > PROBA-V V1 for LAI values larger than 3, PROBA-V V2 < PROBA-V V1 for FAPAR over medium ranges. For FCOVER, PROBA-V V2 < PROBA-V V1 for very high values and consistent with FAPAR.
Accuracy	±	Acceptable accuracy for LAI, matching the GCOS requirements in 65% of cases (RMSD= 1.06, B=0.50) Slight positive bias for FAPAR (RMSD=0.10, B=0.05), mainly over croplands, matching GCOS requirements in 57% of cases Positive bias for FCOVER (RMSD=0.17, B=0.104)

4 Scientific Quality Evaluation Method

4.1 Overall procedure

The quality evaluation method follows the procedures described in the Global Land Service Validation Plan [CGLOPS1_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 (http://calvalportal.ceos.org/web/olive), the recent CEOS LPV Global LAI product validation good practices (Fernandes et al., 2014) as well as recommendations provided by reviewers of the Copernicus Global Land Service.

The analysis was mainly focused on the comparison between recent PROBA-V 1km V1 and V2 products with the validated PROBA-V 1km V1 and V2 (year 2014) and SPOT/VGT (year 2012) products. This study covers the period during 1st of January to 31th of December 2018, and the equivalent period of the reference datasets was included in the analysis.

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). Global maps of the percentage of missing values or filled land pixels, distribution of gaps or filled land pixels as a function of the season per biome type and the length of the gaps or filled land pixels are analyzed.

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 patterns or artefacts (e.g., missing values, stripes, unrealistic low values, etc.) can be achieved through systematic visual analysis of all maps based on the expert knowledge of the scientist. The spatial consistency can be quantitatively assessed by comparing the spatial distribution of a reference validated product with the product biophysical maps under study. Probability Density Function (PDFs) of retrievals and residuals per biomes are analyzed.

Temporal Consistency

The realism of the temporal variations over sites with specific events during 2018 year, anomalies of croplands over Europe, and GBOV sites are qualitatively assessed.

Additionally, the temporal variations of the vegetation variables are qualitatively analyzed as compared to reference validated products. The consistency of temporal variations from the current period under study with reference products and previous years is investigated. Here, 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:

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

where mx and my are the mean values of x and y series, respectively.

Histograms of cross correlation between SPOT/VGT (2012) products and PROBA-V (2018 and 2014) products temporal variations are analyzed for V1 and V2 per biomes over LANDVAL sites.

Precision

Anomalies of an upper and lower percentile of variable are indicators of inter-annual precision (i.e., dispersion of variable values from year to year), (Fernandes et al., 2014). It can be assessed providing a box-plot of the median absolute deviation of anomalies versus product per bins. Note that Cultivated were not considered in this analysis due to the non-natural variability in these land cover types due to agricultural practices (e.g., crop rotation). Evergreen Broadleaved Forest sites were also not included because they are typically affected by cloud coverage.

Intra-annual precision (smoothness) corresponds to temporal noise assumed to have no serial correlation within a season. In this case, the anomaly of a variable from the linear estimate based on its neighbours can be used as an indication of intra-annual precision or smoothness. 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(dn+1) and the corresponding linear interpolation between the two extremes P(dn) and P(dn+2) was computed:

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

Histograms of the smoothness are presented adjusted to a negative exponential function. The exponential decay constant is used as quantitative indicator of the typical smoothness value.

Overall Statistical Consistency

The inter-comparison of products offers a means of assessing discrepancies (systematic or random) between products. The global statistical analysis is performed over a globally representative set of sites (LANDVAL) considering all the dates available. The LANDVAL network of sites was designed to represent globally the variability of land surface types (see section 4.1.1). For V1, pixels flagged as 'low quality' pixels according to Table 10 were removed from the computation. For V2, two cases were considered: “all pixels” and “best-quality” (pixels flagged as 'low quality' according to Table 10, and filled pixels in case of V2 products, were removed from the computation) to see the effects introduced by the filled pixels. The consistency between the products under study and the reference products is further quantified based on uncertainties metrics associated to the scatter plots between pairs of products (Table 7). The analysis is complemented with box-plots of uncertainty metrics (Bias and RMSD) per bin.

Here three levels of uncertainty (optimal, target and threshold) were defined based on our expert knowledge (Table 6). Note that the optimal level of uncertainty has been selected according to the GCOS accuracy requirements for LAI and FAPAR (see Table 1). Figure 1 displays the selected uncertainty levels as a function of the LAI, FAPAR and FCOVER product value. These uncertainty levels have been recently adopted by LSA SAF as accuracy requirement for MSG and EPS LAI, FAPAR and FCOVER products. Furthermore, these levels have been considered more appropriate than the CGLOPS (Table 2) uncertainty levels because they also consider absolute levels which are appropriate for very low values.

Table 6: Uncertainty levels used for LAI, FAPAR and FCOVER products.

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

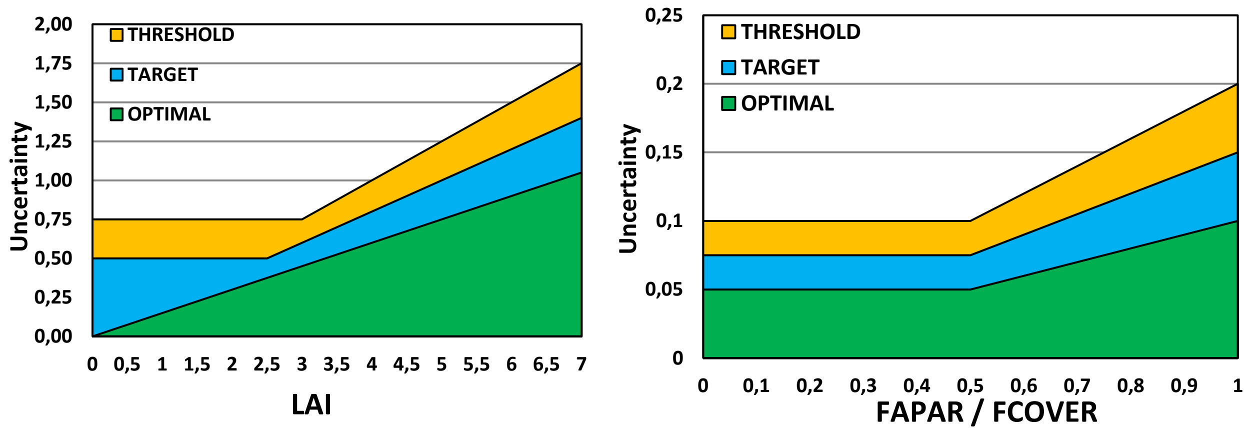


Figure 1: Uncertainty levels as a function of LAI (left) and FAPAR/FCOVER (right) products.

Accuracy Assessment

Accuracy is quantified by several metrics reporting the goodness of fit between the products and the corresponding ground measurements (Table 7). Total measurement uncertainty (i.e., root mean square deviation, RMSD) includes systematic measurement error (i.e. Bias) and random measurement error (i.e., Standard deviation of bias). RMSD corresponds to the Accuracy as there is only one product estimate for each mapping unit (Fernandes et al., 2014). RMSD 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 (optimal), target and threshold levels (Table 6) and the CGLOPS technical user group requirements (Table 2) are quantified.

Table 7: Metrics for product validation

Gaussian Statistics	Comment
N: Number of samples	Indicative of the power of the validation
RMSD: Root Mean Square Deviation	RMSD is the square root of the average of squared errors between x and y. 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 x and y. 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.
R: Correlation coefficient	Indicates descriptive power of the linear accuracy test. Pearson coefficient was used.
MAR: Major Axis Regression (slope, offset)	Indicates some possible bias.
p-value	Test on whether the slope is significantly different to 1.
% uncertainty levels	Percentage of pixels matching the optimal and target uncertainty predefined levels (Table 6), and CGLOPS requirements (Table 2)

The accuracy assessment is performed against ground data of during the 2014-2017 period up-scaled according with the CEOS LPV recommendations (Morisette et al., 2006). Multi-temporal ground-based maps coming from 20 GBOV sites (Table 14) were used in this study. Although the main objective of this report is to evaluate the quality of the 2018 products, the 2014-2017 period is considered because GBOV datasets are available until end of 2017 only. For the accuracy assessment the closest product date to the ground-based map was used. A ground reference dataset representative of an area of approximately 3kmx3km that allows limiting the effects of point spread function and geometric accuracy was used (Morisette et al., 2006).

Summary of Scientific Quality Evaluation Procedure

The analysis was focused on the comparison between recent PROBA-V 1km V1 and V2 products (January-December, 2018) with reference validated PROBA-V V1 [GIOGL1_QAR_LAI1km-V1] and V2 [CGLOPS1_QAR_LAI1km-PROBAV-V2], as well as with the validated SPOT/VGT V1 [GIOGL1_VR_LAIV1] and V2 [GIOGL1_QAR_LAI1km-VGT-V2]. Furthermore, it is complemented, for benchmarking, with MODIS (MCD15A2H) C6 LAI and FAPAR products for the regional analysis.

Two main domains in terms of spatial coverage have been considered: global and regional. Summary of quality criteria is showed in Table 8 for global analysis and in Table 9 for regional analysis.

Table 8: Summary of the quality criteria for global analysis of PROBA-V 1km products

Quality Criteria	Product Evaluated	Reference Product	Coverage
Completeness	PROBA-V V1 & V2 2018	PROBA-V V1 & V2 2014 SPOT/VGT V1 & V2 2012	Global LANDVAL
	-Global Gap distribution (average maps, temporal variations per biome). -Length of gaps over LANDVAL.		
Spatial Consistency	PROBA-V V1 & V2 2018	PROBA-V V1 & V2 2014 SPOT/VGT V1 & V2 2012	LANDVAL
	-PDFs of retrievals & histograms of residuals per biome.		
Temporal Consistency	PROBA-V V1 & V2 2018	PROBA-V V1 & V2 2014 SPOT/VGT V1 & V2 2012	LANDVAL
	-Histograms of Cross-correlation		
Inter-annual Precision	PROBA-V V1 & V2 2018	PROBA-V V1 & V2 2014 SPOT/VGT V1 & V2 2012	LANDVAL
	-Box-plot per bin and median absolute anomaly of 95th percentile and 5th percentile. PROBAV 2018 vs 2014, PROBA-V 2018 vs SPOT/VGT 2012		
Intra-annual Precision (smoothness)	PROBA-V V1 & V2 2018	PROBA-V V1 & V2 2014 SPOT/VGT V1 & V2 2012	LANDVAL
	-Histograms of the smoothness		
Overall Statistical Consistency	PROBA-V V1 & V2 2018	PROBA-V V1 & V2 2014 SPOT/VGT V1 & V2 2012	LANDVAL
	-Scatter-plots (R, RMSD, Bias, Scattering, Major Axis Regression). Percentage of differences between the different uncertainty levels. -Box-plots of uncertainties statistics (Bias and Absolute Bias) per bin.		

Table 9: Summary of the quality criteria for the Regional Analysis of PROBA-V 1km products

Quality Criteria	Product Evaluated	Reference Product	Coverage
Spatial Consistency	PROBA-V V1 & V2	Specific events	Locations with specific events (4.1.2.2)
	-Visual inspection 1ºx1º maps over specific events		
Temporal Consistency	PROBA-V V1 & V2 MCD15A2H C6	Specific events GBOV ground data	-ROI over Europe (4.1.2.1) -Locations with specific events (4.1.2.2) -GBOV sites (4.3)
	-Qualitative inspection of temporal variations over locations with new ground values or specific events (fires).		
Accuracy Assessment	PROBA-V V1 & V2 MCD15A2H C6	GBOV ground data	GBOV sites (4.3)
	-Scatter-plots, Pearson's correlation, Root Mean Square Deviation (RMSD), bias, linear fit (offset, slope).		

The following Quality Flag information was used to filter pixels flagged as out of range, saturated or invalid (Table 10) for the overall statistical consistency.

Table 10: Quality Flag information used to filter low quality or invalid pixels.

Product	Quality Flag
PROBA-V Collection 1km Version 1	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)
PROBA-V Collection 1km Version 2	Sea (bit 1), Input status out of range or invalid (bit 6), LAI/FAPAR/FCOVER out of range or invalid (bits 7,8,9)

4.1.1 Global analysis: LANDVAL Network

The LANDVAL network of 725 sites (Figure 2) was used for inter-comparison instead of BELMANIP2.1, used for the calibration of the Collection 1km V1 and V2 algorithms [GIOGL1_ATBD_LAI1km-V1 and CGLOPS1_ATBD_LAI1km-V2]. This network is composed with 521 sites coming from SAVS 1.0 (Surface Albedo Validation Sites) network (Loew et al., 2016), available at http://savs.eumetsat.int. SAVS 1.0 was created during the ALBEDOVAL-2 study (Fell et al., 2015), in the framework of QA4ECV (Quality Assurance for Essential Climate Variable) project. Note that this SAVS 1.0 network contains 256 sites from BELMANIP2.1 network. In addition, 20 sites ('*calibration sites*') in the Sahara Desert and Arabia desert are included in order to increase the sampling over desertic areas and African region. These reference sites, well known for their high temporal stability, are used by CNES for the absolute calibration of remote sensing sensors. Finally, 184 sites coming from existing (e.g. ImagineS (http://fp7-imagines.eu/), AsiaFlux , NARMA or OzFlux) networks or Geo-Wiki platform (http://www.geo-wiki.org/) were included in order to cover under sampled regions (Asia, Africa, Oceania) and biome types (Shrub, deciduous broadleaf forest (DBF), needle leaf forest (NLF)).

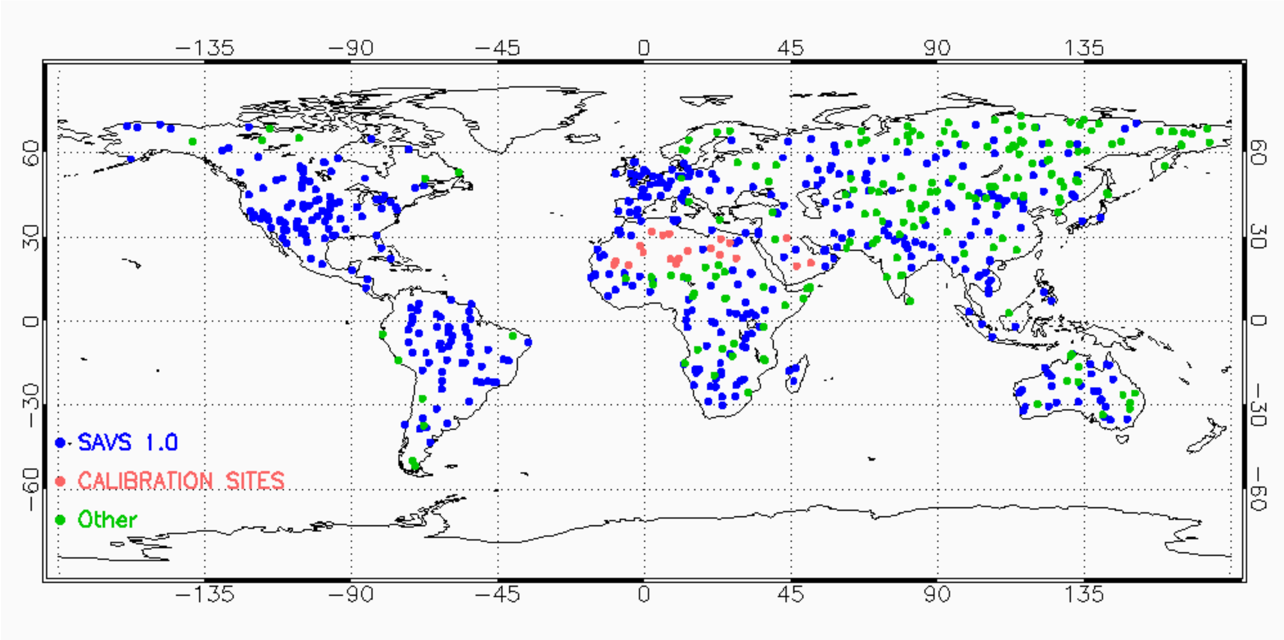


Figure 2: Global distribution of the selected LANDVAL sites.

The methodology for the selection of sites is described in the QAR of PROBA-V Surface Albedo product [CGLOPS1_VR_SA1km-PROBAV-V1.5]. The selection criteria that have been chosen for each LANDVAL site are showed in Table 11.

Table 11: Criteria of selection of sites coming from SAVS 1.0

Parameter	Threshold	Purpose
Distance to open water bodies [km]	5	Avoid open water bodies and their changing reflectance behavior with viewing geometry
Minimum fraction of majority land cover type at 5 km distance	60%	Avoid areas with heterogeneous land cover.
Land Cover Majority at 5km	Exclude 'Water bodies' and 'Urban areas'	
Vertical range [m] within a distance of 5km	<300m	Avoid areas with significant terrain variability close to a site.
Location (Latitude)	60ºS to 80ºN	Exclude sites over extreme latitudes, where Global Land products does not provide data

The 725 LANDVAL 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). The main biome

are obtained aggregating similar land cover classes from the GLC2000 classification (Bartholome and Belward, 2005): Evergreen Broadleaf Forest (EBF), Deciduous Broadleaf Forest (DBF), Needle leaf Forest (NLF), Shrublands (S), Herbaceous (H), Crop, Sparse and Bare areas (BA).

The regional analysis is made per continental regions as defined in the Copernicus Global Land Service. The six continental regions are: North America (NOAM), South America (SOAM), Europe (EURO), Africa (AFRI), Asia (ASIA) and Oceania (OCEA) (Figure 3).

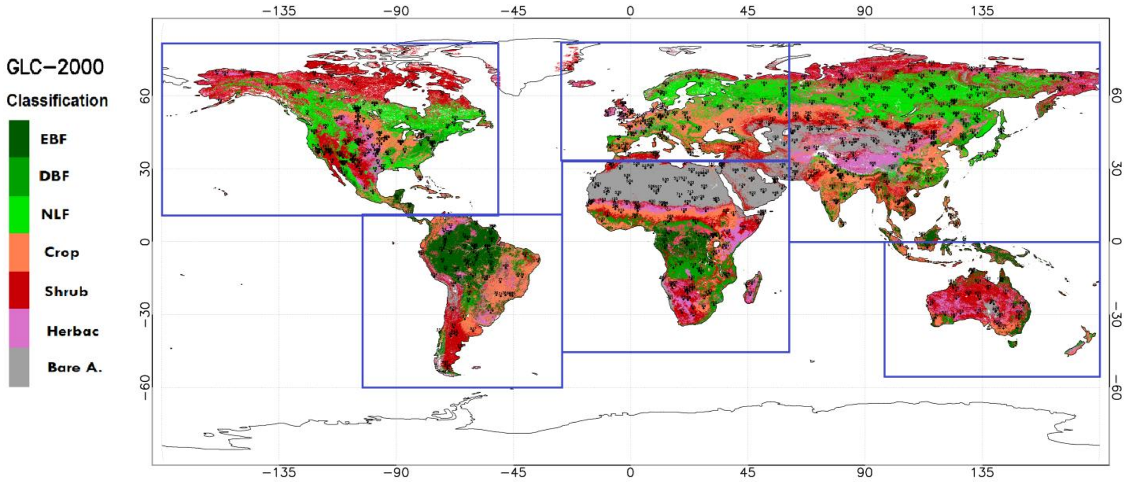


Figure 3: Location of the LANDVAL sites over an aggregated land cover (GLC-2000) map. Blue squares correspond to the six continental regions.

4.1.2 Regional analysis

4.1.2.1 Sub-continental region over Europe

The regional analysis focuses on a Region of Interest (ROI) over Europe, with boundary coordinates: 33° - 72° N, -12° - 49° E. This European region was chosen because it was an exceptional warm and dry year with several heat waves during summer. As a consequence, crop production was highly impacted throughout the growing season in many places, but also exceptionally good in other areas.

Figure 4 shows the map of the aggregated land cover types from GLC-2000 (Bartholome and Belward, 2005). The percentages of land pixels per main biome are: Deciduous Broadleaved Forest (9.4%), Needle-leaf Forest (16%), Croplands (35.5%), Shrublands (13.8%), Herbaceous (5.3%) and Bare Areas (3.7%). Note that inland waters are classified as land pixels in the land/sea mask of Collection 1km V1 products. The classes were aggregated according to the scheme in Table 12.

The dominant class of the ROI European region is cropland, and this study focusses on the temporal variations over cropland areas during the 2018 year compared to 2014 year.

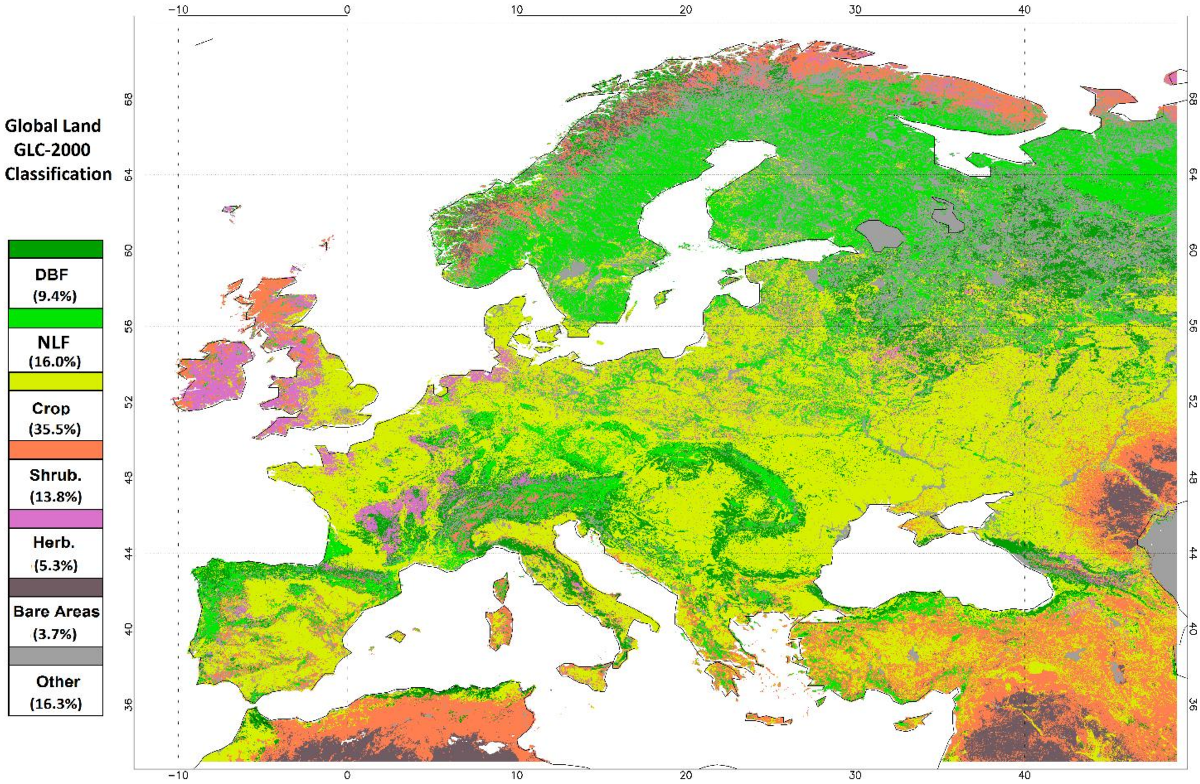


Figure 4: Map of aggregated land cover from GLC-2000 over the European ROI. All the classes are aggregated in the following main biomes (up to down in the legend): Broadleaved Evergreen Forest, Broadleaved Deciduous Forest, Croplands, Shrublands, Herbaceous, Bare Areas and Other.

Table 12: Aggregation scheme for GLC2000 classes into 7 major biomes and proportion of each biome at global scale

Abbreviation	Name	GLC2000 classes	Proportion at global scale (%)
EBF	Evergreen Broadleaved Forests	1	7.1
DBF	Deciduous Broadleaved Forests	2-3	7.1
NLF	Needle-leaf Forests	4-5	12.8
SHR	Shrubland	11-12, 14	22.6
HER	Herbaceous cover	13	9.7
CUL	Cultivated areas and cropland	16-18	16.5
BA	Bare areas	19	13.4
	Other (not considered in the analyses)	6-10, 15, 20-22	10.8

Sources of information:

- European Drought Observatory (EDO) is part of the Copernicus Emergency Management Service and provides drought-relevant information and early-warnings for Europe. It issues 10-daily maps of drought conditions in Europe. The maps of the combined drought indicator show that the drought occurred in January in Spain and southern France. In April, there was a drought situation in southern Finland. The exceptional warm summer with below-average rainfall caused drought conditions in Scandinavia, north Germany and Poland (June), and moved south to the Netherlands, Belgium, west Germany, UK in July and then moved more south to France and Germany from September on.
- GEOGLAM is the Group on Earth Observations Global Agricultural Monitoring Initiative. It was initially launched by the Group of Twenty (G20) Agriculture Ministers in June 2011, in Paris. The G20 Ministerial Declaration states that GEOGLAM “will strengthen global agricultural monitoring by improving the use of remote sensing tools for crop production projections and weather forecasting”. By providing coordinated Earth observations from satellites and integrating them with ground-based and other in-situ measurements, the initiative will contribute to generating reliable, accurate, timely and sustained crop monitoring information and yield forecasts. The GEOGLAM AMIS Crop Monitor has published maps which show favorable crop growth conditions in Europe until March 2018, and exceptionally good conditions east of the Black Sea. In July, most of northeastern Europe have less favorable conditions that move into poor conditions in August until the end of the year. In contrast, the Baltic states have exceptionally good crop conditions from April to June and from August till the end of the year.
- The EC JRC MARS bulletins have issued several crop forecasts with yield forecasts that were revised downward from June onwards.

4.1.2.2 Specific Events

A total of 10 specific events have been selected to evaluate the temporal consistency of the recent PROBA-V Collection 1km LAI, FAPAR, FCOVER V1 and V2 products. They consist of 5 major fires in Europe reported by the European Forest Fire Information System (EFFIS, http://effis.jrc.ec.europa.eu), and 5 other environmental events elsewhere in the world, reported by the NASA Earth Observatory (https://earthobservatory.nasa.gov/). In order to evaluate temporal consistency, temporal profiles of Collection 1km V1 and V2 products over point locations were extracted. Also 1° x 1° maps (before and after the event) were visually analyzed.

Table 13 summarizes the different events studied for each region. Two main sources were used to identify these events:

- The European Forest Fire Information System (EFFIS) for fire events, where the events were selected in basis of their size due the spatial resolution of the products under study (1 km in this case). The EFFIS has been established by the European commission (EC) in collaboration with the national fire administrations to support the services in charge of the protection of forests against fires in the EU and neighbor countries, and also to provide the EC services and the European Parliament with harmonized information on forest fires in Europe. (http://effis.jrc.ec.europa.eu). In 2015, EFFIS became one of the components of the emergency Management Services in the EU Copernicus program. The European forest Fire Information system (EFFIS) consists of a modular web geographic information system that provides near real-time and historical information on forest fires and forest fires regimes in the European, Middle Eastern and North African regions. Fire monitoring in EFFIS comprises the full fire cycle, providing information on the pre-fire conditions and assessing post-fire damages. In 2018, EFFIS reported 10 major fire events in the Mediterranean area, of which 5 were selected for the analysis.

- The NASA Earth Observatory for natural hazards issues weekly updates of global natural hazards, like fires, droughts, flooding etc. Its mission is to share with the public the images, stories, and discoveries about climate and the environment that emerge from NASA research, including its satellite missions, in-the-field research, and climate models (https://earthobservatory.nasa.gov/). Five major events were selected from these weekly updates. Five events were reported:
    - In March 2018, several watersheds in central and northern Queensland were flooded after heavy rains in the Channel County, a desert region that is known for vegetation growth after floods. More information can be found in https://earthobservatory.nasa.gov/images/91912/rivers-swell-in-channel-country
    - The Kerala region in southwestern India received was flooded after abnormally high monsoon rains on August 8th 2018. It was reported that the flooding was the worst since 1924. The flooding caused the displacement of nearly a million people, hundreds of fatalities and washed away homes. More information can be found here: https://earthobservatory.nasa.gov/images/92669/before-and-after-the-kerala-floods?src=nha
    - The tropical cyclone Mekunu dropped enough rain over the Arabian Peninsula to form lakes between the sand dunes in the Rub' al-Khali. The area is considered as one of the driest places on earth and usually receives only 3 cm of rain during an entire year. More information can be found here: https://earthobservatory.nasa.gov/images/92295/rain-soaks-the-empty-quarter
    - Thunderstorms caused hail storm damage in South Dakota (USA) leading to long scars in the landscape where grasslands and crops are seriously damaged. More information can be found here: https://earthobservatory.nasa.gov/images/92401/hail-cuts-swaths-of-damage-across-south-dakota?src=nha
    - The fire season in California (USA) has been record-breaking in 2018. The Camp Fire in November was the deadliest and most destructive in state history, completely burning down the town of Paradise. More information can be found here: https://earthobservatory.nasa.gov/images/144300/camp-fire-adds-another-scar-to-2018-fire-season?src=nha

Table 13: Specific events included in the Scientific Quality Evaluation of Collection 1km Version 1 and Version 2 LAI/FAPAR/FCOVER products for 2018 year.

# EVENT	Site	Country	Lat (°)	Long (°)	Event	Date (yyyy/mm/dd)
1	Psachna	Greece	38.6311	23.6262	Fire	2018/08/12
2	Monte Serra	Italy	43.7497	10.5459	Fire	2018/09/25
3	Taipas, Monchique	Portugal	37.3964	-8.6160	Fire	2018/08/03
4	Llutxent	Spain	38.9451	-0.3516	Fire	2018/08/07
5	Nerva	Spain	37.7303	-6.5681	Fire	2018/08/03
6	Queensland	Australia	-25.2783	140.4690	Flooding	2018/03/03
7	Kerala	India	9.4640	76.7077	Flooding	2018/08/11
8	Rub' al-Khali	Arabia	19.7183	53.4005	Rainfall (Flooding)	2018/05/25
9	South Dakota	USA	44.6981	-100.4949	Hail Storm Damage	2018/06/27
10	California	USA	39.7922	-121.6236	Fire	2018/11/25

4.2 Satellite Reference Products

- **PROBA-V Collection 1km Version 1 (PROBA-V V1)**

The SPOT-VEGETATION mission finished in May 2014 and the provision of Collection 1km Version 1 products in the Copernicus Global Land Service continues based on PROBA-V. The algorithm has been defined by INRA in the framework of the FP7/geoland2 project (Baret et al., 2013). It generates the Leaf Area Index (LAI), associated with the Fraction of absorbed PAR (FAPAR) and the fraction of vegetation cover (FCOVER). The algorithm was first applied to the SPOT-1&2/VEGETATION-1&2 data for the production of SPOT/VGT V1 products (see SPOT/VGT V1 below). The PROBA-V V1 products are derived from the SPOT/VGT-like Top of Atmosphere (TOA) PROBA-V reflectances generated by the PROBA2VGT module [GIOGL1_ATBD_PROBA2VGT]. The details are described in the ATBD [GIOGL1_ATBD_LAI1km-V1].

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], the PROBA-V V1 products are disseminated as "operational" products on the Copernicus Global Land service portal (http://land.copernicus.eu/global). A summary of the validation results is written in section 3.1.

- **SPOT/VGT Collection 1km Version 1 (SPOT/VGT V1)**

The algorithm of the Collection 1km Version 1 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.

In previous validation exercise (Camacho et al., 2013), the accuracy of SPOT/VGT V1 products was computed using a ground reference data set representative of an area of approximately 3x3 pixels that allows limiting the effects of point spread function and geometric accuracy. The in-situ data set was processed according to the guidelines defined by the CEOS/WGCV LPV subgroup (Morisette et al., 2006). The product date closest to the date of ground measurement was considered for each site. The accuracy (RMSD) of version 1 products against the reference data set is 0.7/0.08/0.09 for LAI/FAPAR/FCOVER variables (Camacho et al., 2013). In the recent quality monitoring performed on 2013-2014 products, a slight overestimation of the FCOVER product regarding ground references over cropland sites was found. Mu et al.(2015) reported an overestimation of the V1 FCOVER up 0.2 for agricultural sites in China. The magnitude of these differences cannot be explained by other reasons that the calibration of the V1 FCOVER algorithm (Mu et al., 2015). Ding et al., (2015) reported a good overall accuracy of V1 FCOVER over Australian continent, with however overestimation over biomes types with high vegetation density (i.e., broadleaved deciduous forest and closed shrublands), and underestimation for sparsely vegetated areas.

- **PROBA-V Collection 1km Version 2 (PROBA-V V2)**

The Version 2 of algorithm (Verger et al., 2014) initially defined for the estimation of LAI, FAPAR and FCOVER products from the SPOT/VEGETATION series of observations, has been applied to daily top-of-canopy reflectance provided by the PROBA-V sensor. Two specific adaptations are applied 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 methods, the Version 2 of algorithm 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. The details of the Version 2 algorithm are given in the ATBD [CGLOPS1_ATBD_LAI1km-V2]. A summary of validation results is written in section 3.2.

- **SPOT/VGT Collection 1km Version 2 (SPOT/VGT V2)**

The Version 2 of algorithm was developed for SPOT/VEGETATION observations. SPOT/VGT V2 uses as input daily top-of-canopy data. The algorithm principles, product outputs, including quality flags are the same as describe above (PROBA-V V2). The main differences with PROBA-V V2 is that the spectral conversion (PV to VGT), the scaling of the NNT outputs PV to VGT, and the near real time processing do not apply here. SPOT/VGT V2 products are generated in off-line mode [CGLOPS1_ATBD_LAI1km-V2].

The validation results of the SPOT/VGT V2 products [GIOGL1_QAR_LAI1km-VGT-V2] show an overall quite good spatial and temporal consistency with the SPOT/VGT V1 products. However, a negative bias (lower V2 FAPAR values) was detected for low and medium FAPAR values at global scale. All the criteria evaluated, including precision and accuracy assessment, showed good results. The main improvement of the V2 product as compared to V1 is completeness of the product (no missing values) and precision of the products. V2 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 RMSD of 0.83 for LAI with 73% of samples (N=49) within GCOS requirements, similar to SPOT/VGT V1 LAI products (RMSD=0.95). For FAPAR, SPOT/VGT V2 showed an RMSD=0.12 with a slight negative bias (-0.04) mainly over grassland (non-concomitant) sites (whereas SPOT/VGT V1 FAPAR displayed no mean bias). Finally, for the FCOVER, SPOT/VGT V2 showed an RMSD=0.11 and a slight positive mean bias of 0.023, similar to SPOT/VGT V1.

- **NASA MODIS MCD15A2H Collection 6**

Terra and Aqua MODIS LAI/FAPAR (MCD15A2H) collection 6, available since July 2002 from https://lpdaac.usgs.gov/products/ is produced at 500 m spatial resolution and 8 days step over a sinusoidal grid (Yang et al., 2006). The algorithm chooses the “best” pixel available from all the acquisitions of both MODIS sensors located on NASA’s Terra and Aqua satellites from within the 8-day period. The main algorithm is based on Look Up Tables (LUTs) simulated from a three-dimensional radiative transfer model (Knyazikhin et al., 1998). The MODIS red and NIR atmospherically corrected reflectances (Vermote et al., 1997) and the corresponding illumination-view geometries 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 main changes from previous versions are:

- The version 6 product uses the daily L2G-lite surface reflectance (MOD09GA) as input as opposed to MODAGAGG used in C5. MOD09GA is a MODIS daily surface reflectance product which provides daily atmospherically corrected surface reflectance at 500 m resolution in seven spectral bands. MODAGAGG is a MODIS daily aggregated surface reflectance product which provides daily atmospherically corrected surface reflectance at 1 km resolution in seven spectral bands.
- Products are generated at native resolution of 500 meters rather than the 1000 meters of the version 5.
- Version 6 uses an improved multi-year land cover product.

The consistency between C5 and C6 was analyzed (Yan et al., 2016a, Nestola et al., 2017) without finding spatial differences due to resolution changes with an RMSD between both versions of 0.091 for FAPAR (Yan et al., 2016a). The accuracy assessment performed over 45 FAPAR ground measurements showed an overestimation of both C5 and C6 FAPAR products over sparsely-vegetated areas (Yan et al., 2016b). Comparisons with V1 products showed similar spatial distributions at a global scale (Yan et al., 2016b), and temporal comparisons for the 2001–2004 period showed that the products properly captured the seasonality of different biomes, except in evergreen broadleaf forests.

4.3 IN-SITU REFERENCE PRODUCTS

The accuracy assessment of PROBA-V V1 and V2 satellite products was performed against ground-based maps coming from the Ground-Based Observations for Validation (GBOV) service (https://land.copernicus.eu/global/gbov). GBOV, as part of the Copernicus Global Land Service, aims at facilitating the use of observations from operational ground-based monitoring networks and their comparison to Earth Observation products.

In case of LAI, FAPAR and FCOVER products, GBOV service performs the implementation and maintenance of a database for the distribution of reference measurements (RMs) and the corresponding Land Products (LPs). The ATBD [GBOV-ATBD-LP3-LP4-LP5] describes the algorithm used to derive the LP3, LP4 and LP5, corresponding with LAI, FAPAR and FCOVER products. LPs are derived using upscaling techniques, which are endorsed by the Land Product Validation (LPV) sub-group of the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) and are often referred to as the 'two stage' or 'bottom up' approach (Morisette et al., 2006; Baret et al., 2005).

RMs are coming from NEON stations. At each of the selected NEON sites, only three ESUs are routinely sampled every two weeks within the growing season, whereas between twenty and fifty ESUs are typically recommended for the derivation of an empirical transfer function (Morisette et al., 2006; Fernandes et al., 2014). As a result, it is not possible to establish a robust transfer function for each near-coincident high spatial resolution image that is acquired. To overcome this issue, the small number of ESUs is compensated for by regular sampling, and the required range in RM values is built up by substituting spatial variation with temporal variation. This upscaling approach based on temporal variations, but limited spatial sampling, has not been validated by independent experts and, as such, the upscaled LPs must be used with caution for accuracy assessment. For instance, temporal variations along the year introduce important changes in the illumination condition of the vegetation canopy which is a source of uncertainty due to the anisotropy of surface reflectance.

The output of the algorithm consists of a 3 km x 3 km map of each LP. Along with the LP value, per-pixel quality indicators and uncertainty estimates are provided. LPs are provided in the native spatial high resolution and projection of the imagery used for upscaling, in addition to a reduced spatial resolution of 300 m, both in the native projection and reprojected to the World Geodetic

System 1984 (WGS84) coordinate system (as used by the Copernicus Global Land Service products).

Figure 5 displays an example of the FAPAR LP product for the Blandy Experimental Farm (BLAN) site at 10th August 2016 at the native spatial high resolution of 20m (left side), and at the reduced spatial resolution of 300m at the CGLS coordinate system (right side), which is finally used to validated CGLS products (i.e., average values of 3x3 pixels of GBOV 300m LPs are equivalent to 1 pixel of CGLS products).

Figure 6 show the example of the quality indicators and uncertainty associated to the LP values for FAPAR in for BLAN site at 10th August 2016. In addition to the LP values themselves, per-pixel quality indicators are provided to identify pixels where LP values are computed by extrapolating beyond the range of the dataset used to establish the transfer function (i.e. the input or output is out of range, see Figure 6-bottom). Additionally, per-pixel estimates of LP uncertainty are also provided, corresponding to the 95% confidence interval associated with the transfer function used to derive each LP value (Figure 6, top-left). The number of valid high-resolution pixels to derive the degraded 300m resolution maps is also provided as ancillary layer in LPs (Figure 6, top-right).

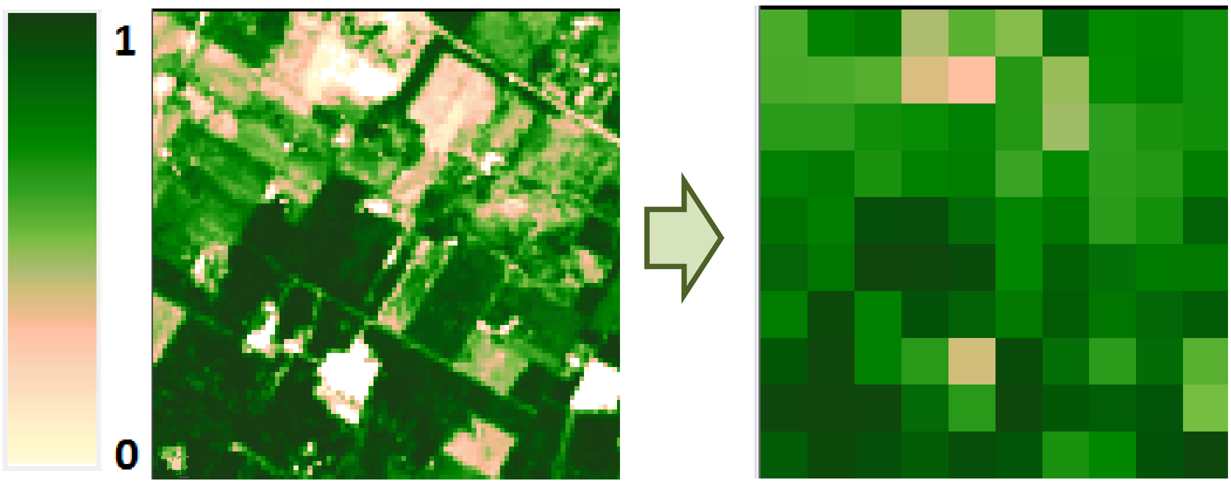


Figure 5: Example of map for FAPAR in BLAN site at 10th August 2016 at native high spatial resolution of 20m (left) and at reduced 300m spatial resolution (right).

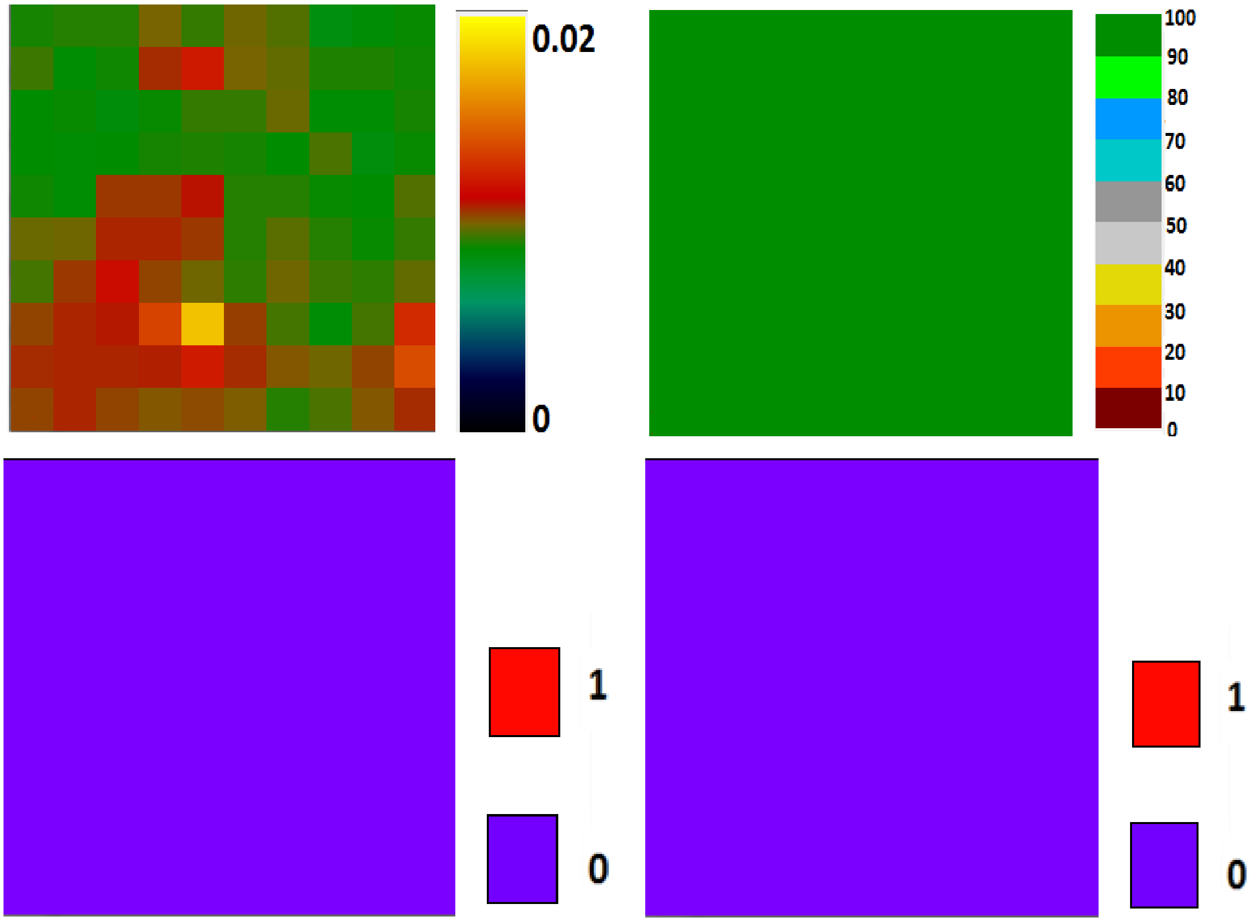


Figure 6: Quality Control indicators in BLAN site (2016.08.10) at 300m resolution. Top-left: Uncertainty corresponding to the 95% confidence interval. Top-right: Valid native spatial resolution pixels used in aggregation (%). Bottom-left: Input out of range flag (0 = “in range”, 1 = “out of range”). Bottom-right: Output out of range flag (0 =” in range”, 1 = “out of range”).

The quality indicators of the empirical high-resolution maps were considered for the accuracy assessment of the different satellite products: only those GBOV pixels in which more than 70% of the corresponding high-resolution pixels the transfer function behaves as interpolator were used. Additionally, only GBOV pixels with input and output ‘in range’ were considered in the analysis while those ‘out of range’ were discarded.

In addition, auxiliary information for each site can be found in a ‘readme’ txt file, where the minimum (DOY_{min}) and maximum (DOY_{max}) date of ground data acquisition is provided. The GBOV LPs produced outside of the minimum and maximum DOY of each site have been discarded in order to prevent extrapolation beyond the season used to develop the transfer function.

Table 14 summarizes the information of the 20 GBOV sites where LAI, FAPAR and FCOVER LPs are available during the 2014-2017 period with a temporal frequency typically of 10 days during the leaf-on season of each site.

Table 14: GBOV sites with availability of LAI, FAPAR and FCOVER LPs during the 2014-2017 period.

#	Site ID	Name	Lat (°)	Long (°)	Land cover type	DOY_{min} - DOY_{max}
1	BART	Bartlett Experimental Forest	44.0639	-71.2873	Mixed Forest	128 - 229
2	BLAN	Blandy Experimental Farm	39.0603	-78.0716	Croplands	110 – 264
3	CPER	Central Plains Experimental Range	40.8155	-104.7460	Grasslands	69 – 340
4	DSNY	Disney Wilderness Preserve	28.1250	-81.4362	Woody Savannas	69 - 340
5	GUAN	Guanica Forest	17.9695	-66.8687	Evergreen Broadleaved Forest	35 – 349
6	HARV	Harvard Forest	42.5378	-72.1715	Mixed Forest	131 – 300
7	JERC	Jones Ecological Research Center	31.1948	-84.4686	Croplands	101 – 301
8	JORN	Jornada	32.5907	-106.8430	Shrublands	16 - 300
9	MOAB	Moab	38.2483	-109.3880	Grasslands	16 – 300
10	NIWO	Niwot Ridge Mountain Research Station	40.0542	-105.5820	Evergreen Needle-leaf Forest	16 – 300
11	STER	North Sterling	40.4619	-103.0290	Grasslands	91 – 288
12	ORNL	Oak Ridge	35.9641	-84.2826	Croplands	131 – 311
13	ONAQ	Onaqui Ault	40.1776	-112.4520	Grasslands	131 - 311
14	OSBS	Ordway Swisher Biological Station	29.6765	-82.0091	Woody Savannas	43 – 316
15	SCBI	Smithsonian Conservation Biology Institute	38.8929	-78.1395	Deciduous Broadleaved Forest	107 – 288
16	SERC	Smithsonian Environmental Research Center	38.8901	-76.5600	Croplands	107 – 288
17	STEI	Steigerwaldt Land Services	45.5089	-89.5864	Mixed Forest	124 – 276
18	TALL	Talladega National Forest	32.9505	-87.3933	Mixed Forest	43 – 316
19	UNDE	Underc	46.2339	-89.5372	Mixed Forest	120 – 285
20	WOOD	Woodworth	47.1282	-99.2414	Croplands	69 - 340

5 RESULTS

5.1 GLOBAL ANALYSIS

5.1.1 Product Completeness

The product completeness was analysed for the period from January to December 2018. Figure 7 and Figure 8 show the percentage of missing values in case of PROBA-V 1km V1, and the percentage of filled land pixels in case of PROBA-V 1km V2 during the period under study.

These results show that:

- The percentages of missing values for V1 and filled land pixels for V2 are, as expected, very similar. Some differences were found over equatorial regions and northern latitudes. Larger fraction of filled values was found for V2 compared to missing V1 data over equatorial areas, and the opposite trend was for over northern latitudes.
- For both versions, the lack of satellite observations goes up to 80% over larger regions in northern latitudes (up to 100% in Greenland) mainly due to persistent snow cover or cloudiness. The percentages of missing data and filled values go up to 100% over equatorial regions with persistent clouds. These results are consistent with that found in previous validation results [CGLOPS1_SQE2017_LAI1km-V1&V2 and CGLOPS1_QAR_LAI1km-PROBAV-V2].

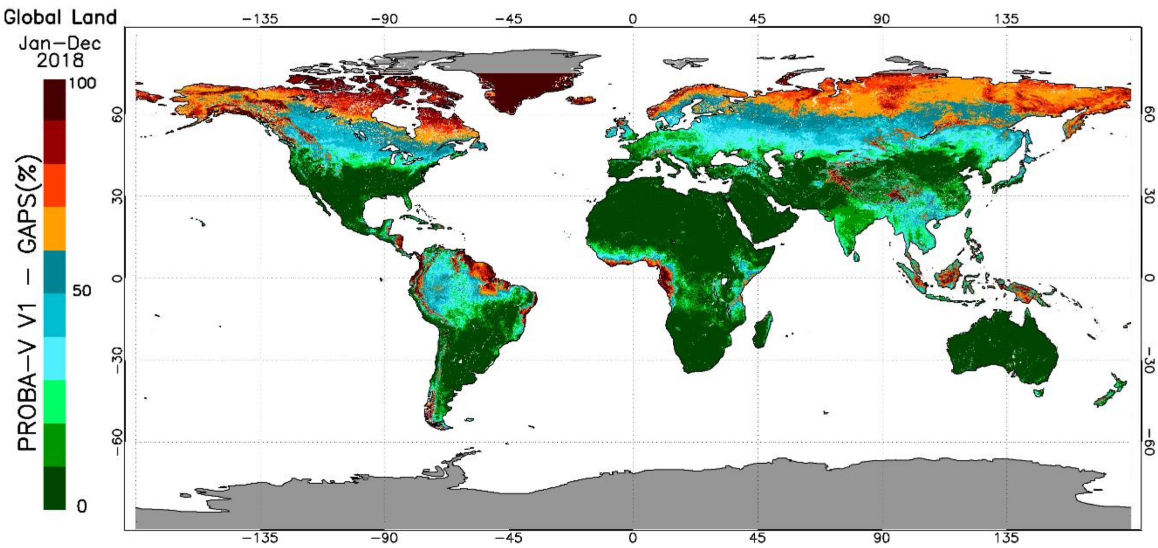


Figure 7: Percentage of missing values during the 2018 year for PROBA-V 1 km V1 products. Grey values represent areas not covered by CGLS PROBA-V products.

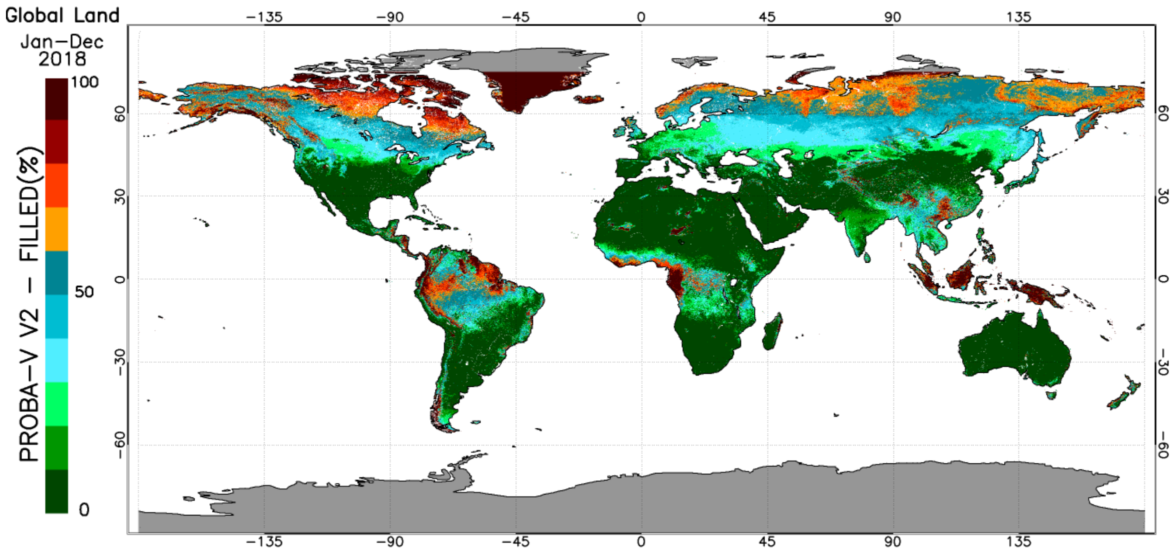


Figure 8: Percentage of filled land pixels during the 2018 year for PROBA-V 1 km V2 products. Grey values represent areas not covered by CGLS PROBA-V products.

Figure 9 to Figure 12 show the temporal variations of missing PROBA-V 1km V1 values or filled PROBA-V 1km V2 land pixels per biomes type and continents during the 2018 year.

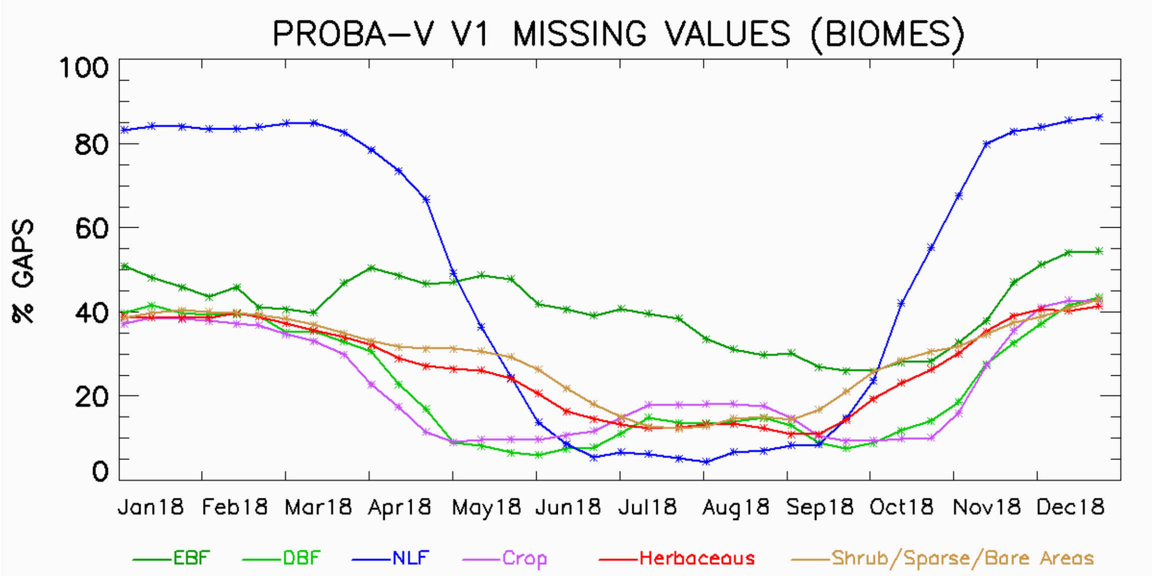


Figure 9: Temporal variations of PROBA-V 1 km V1 missing values per biomes for the 2018 year.

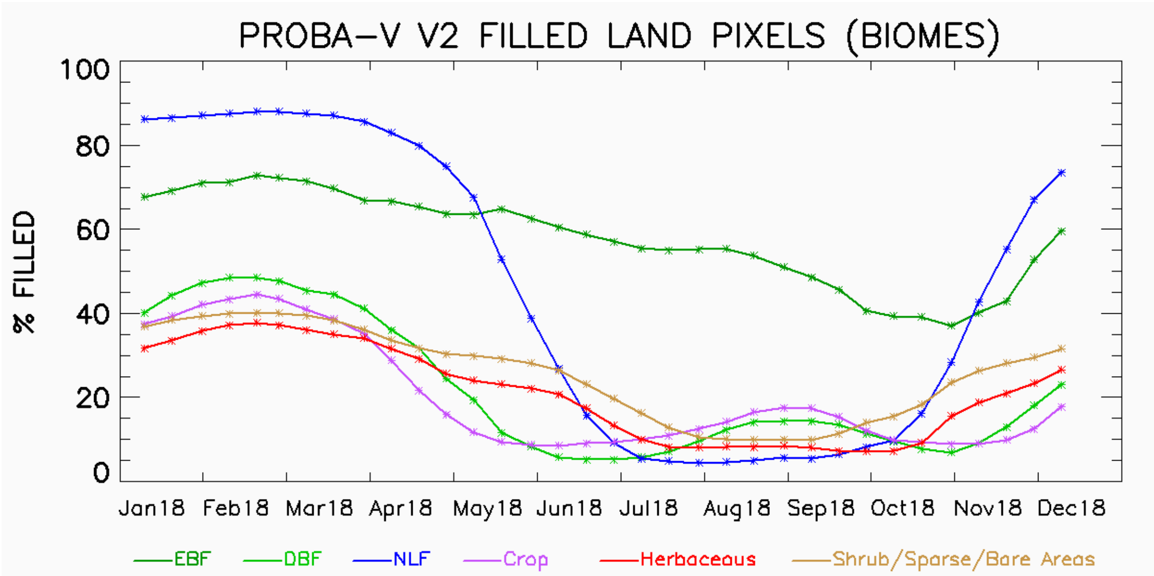


Figure 10: Temporal variations of PROBA-V 1 km V2 filled land pixels per biomes for the 2018 year.

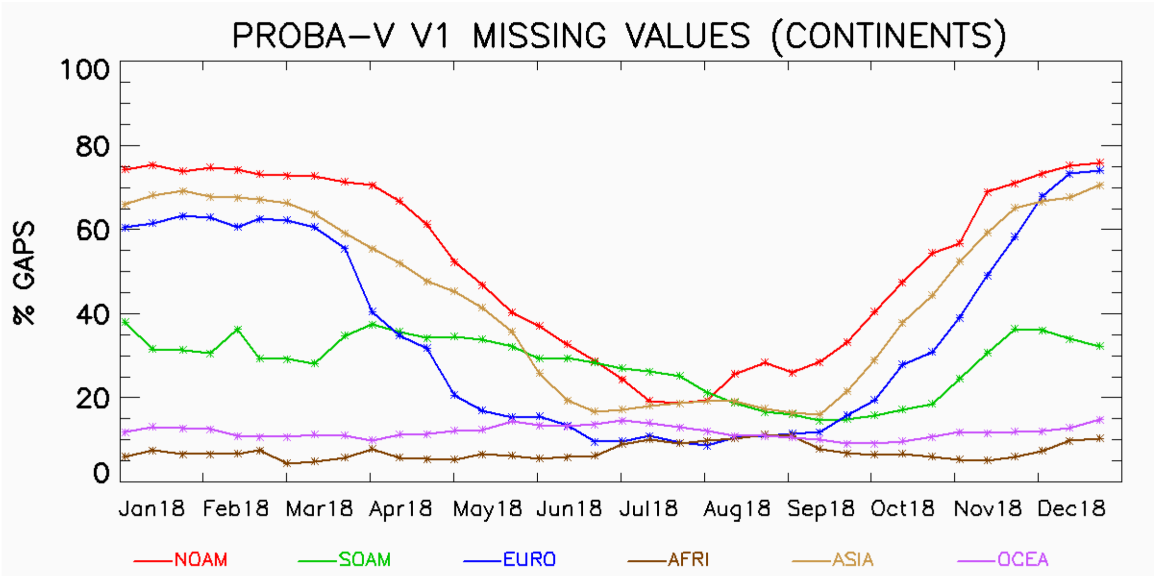


Figure 11: Temporal variations of PROBA-V 1 km V1 missing values per continents for the 2018 year.

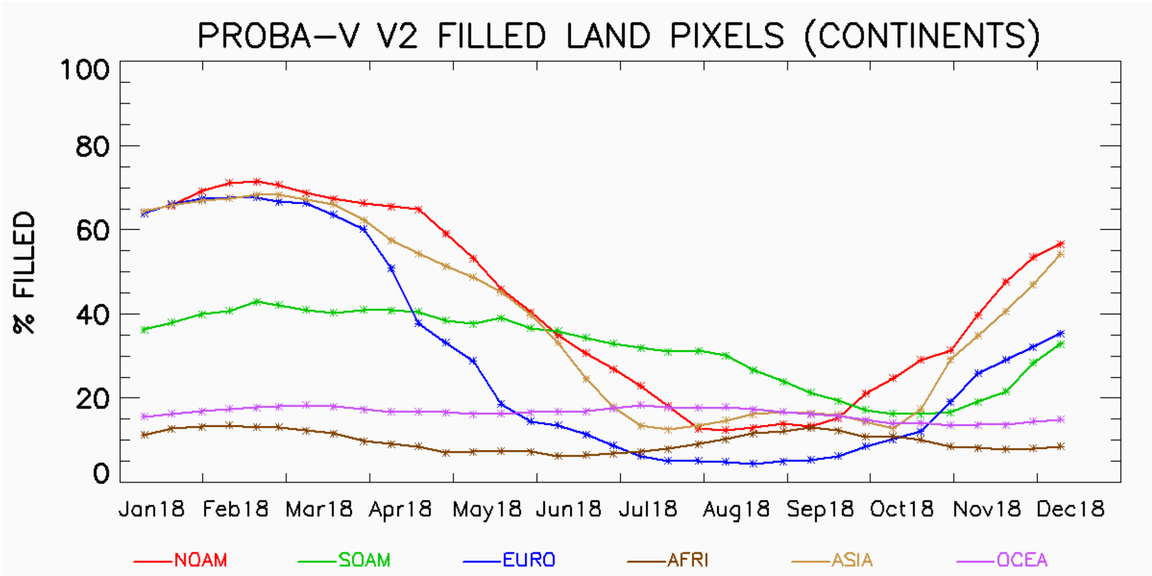


Figure 12: Temporal variations of PROBA-V 1 km V2 filled land pixels per continents for the 2018 year.

These results indicate that:

- The distribution of missing values for V1 and filled land pixels for V2 per biome type and per continent follows the same trend as in 2014 [see validation report, CGLOPS1_QAR_LAI1km-PROBAV-V2] and 2017 years [see SQE of 2017 year,CGLOPS1_SQE2017_LAI1km-V1&V2], showing the largest percentage of missing values or filled land pixels in winter time and the lowest in summer time in northern hemisphere (Figure 10 and Figure 12).
- The largest percentage of missing data was mainly observed over northern regions (EURO, ASIA and NOAM), and Needle-leaf forest types (typically located over northern latitudes), with up to 80% of missing values or filled land pixels during winter time, due to the largest impact of snow and cloud coverage.
- Low seasonality of the missing observations was found over EBF was due to persistent cloud coverage.
- Per continental region, the lowest fraction of missing data was found over AFRI and OCEA along the whole year, and over EURO and ASIA during summer time.
- Over the European region of interest (EURO, blue line in Figure 11 and Figure 12), around 65% and 5% missing data was found during winter and summer time, respectively.

The distribution of the temporal length of the gaps or filled gaps was also evaluated to better understand the impact of the missing values for monitoring the temporal variations. Figure 13 shows the temporal length of gaps (PROBA-V 1km V1) and filled gaps (PROBA-V 1km V2) evaluated over LANDVAL sites during January to December period.

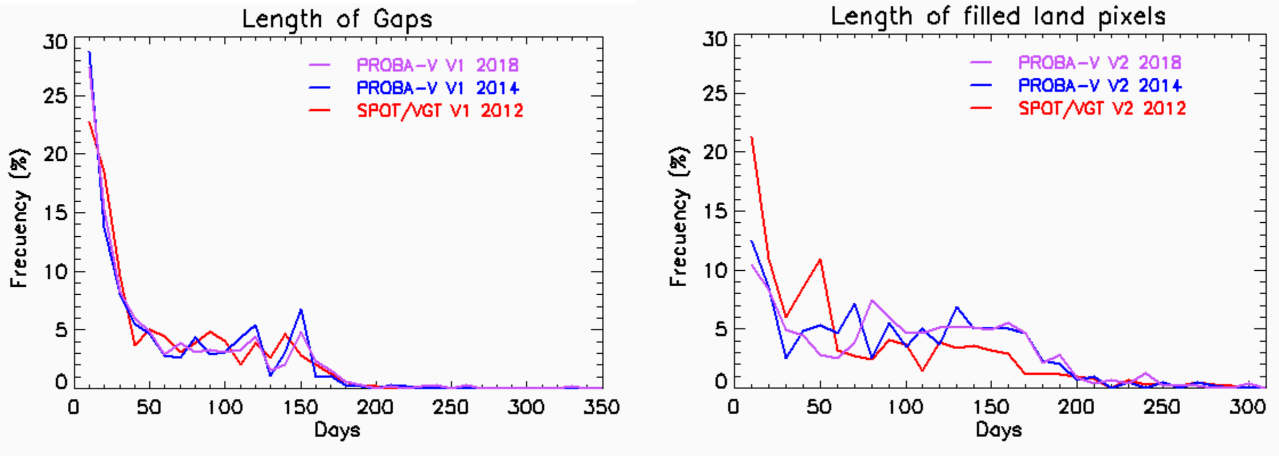


Figure 13: Distribution of the temporal length of the missing 1km V1 values (Left) and filled gaps in 1km V2 products (Right) over LANDVAL sites during the period from January to December of 2014 and 2018 years (PROBA-V) and 2012 year (SPOT/VGT).

These results show:

- Very similar distributions of the length of gaps were found for PROBA-V V1 (years 2014 and 2018) and SPOT/VGT V1 (year 2012) products, with around 55% of gaps shorter than 30 days.
- In case of the distributions of filled gaps, PROBA-V V2 (years 2014 and 2018) showed around 25% of filled gaps shorter than 30 days, slightly different to that in case of SPOT/VGT (year 2012) V2 products with around 40% of filled gaps shorter than 30 days.

5.1.2 Spatial Consistency

5.1.2.1 Distribution of retrievals and residuals per Biome Type

The distribution of retrievals and residuals was computed over LANDVAL sites for the period from 1th January to 31th of December. Recent PROBA-V products (year 2018) have been evaluated as compared with PROBA-V (year 2014) and the SPOT/VGT (year 2012) for both versions (V1 and V2). Figure 14, Figure 15 and Figure 16 show the PDFs of retrievals and histograms of residuals per biome type for LAI, FAPAR and FCOVER, respectively, for 1km V1 products, while the equivalent figures for 1km V2 products are displayed in Figure 17, Figure 18 and Figure 19.

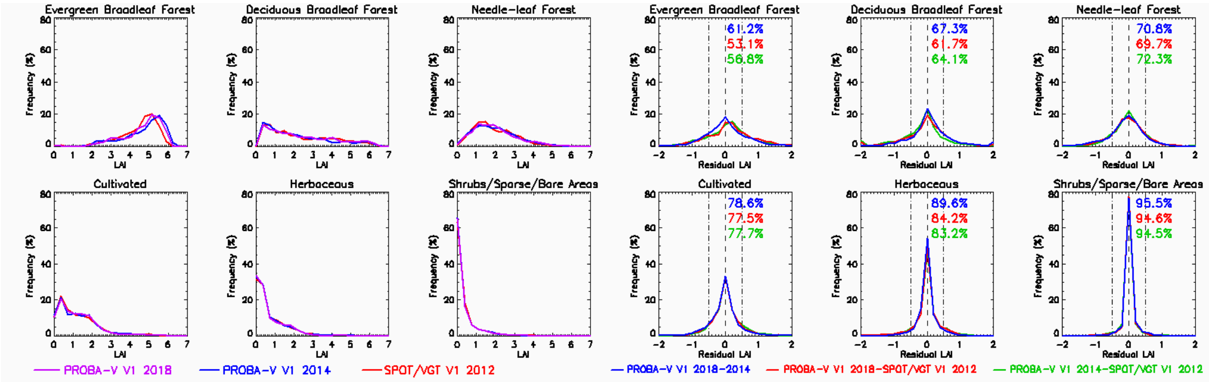


Figure 14: Distribution of LAI values (left panel) and residuals (right panel) for 1km V1 products over the LANDVAL sites during the period of January to December for each biome type. Percentages of residuals between ± 0.5 LAI values are displayed.

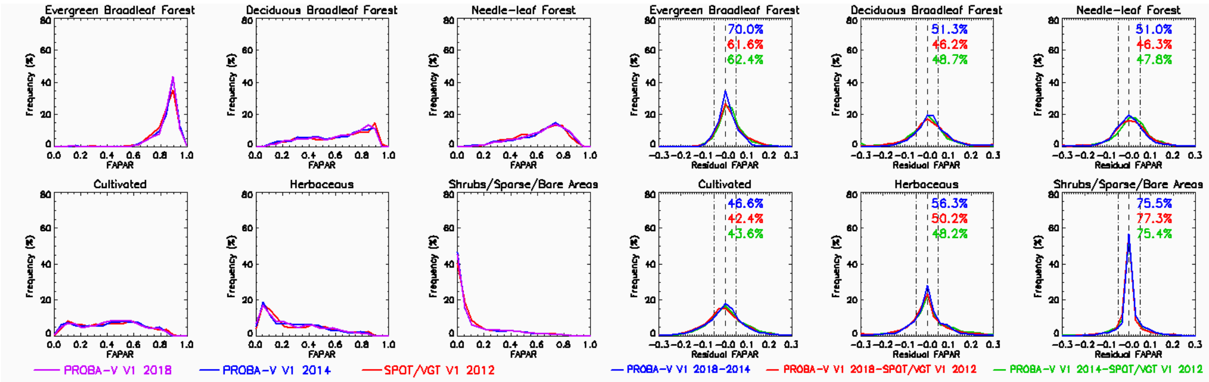


Figure 15: Distribution of FAPAR values (left panel) and residuals (right panel) for 1km V1 products over the LANDVAL sites during the period of January to December for each biome type. Percentages of residuals between ± 0.05 FAPAR values are displayed.

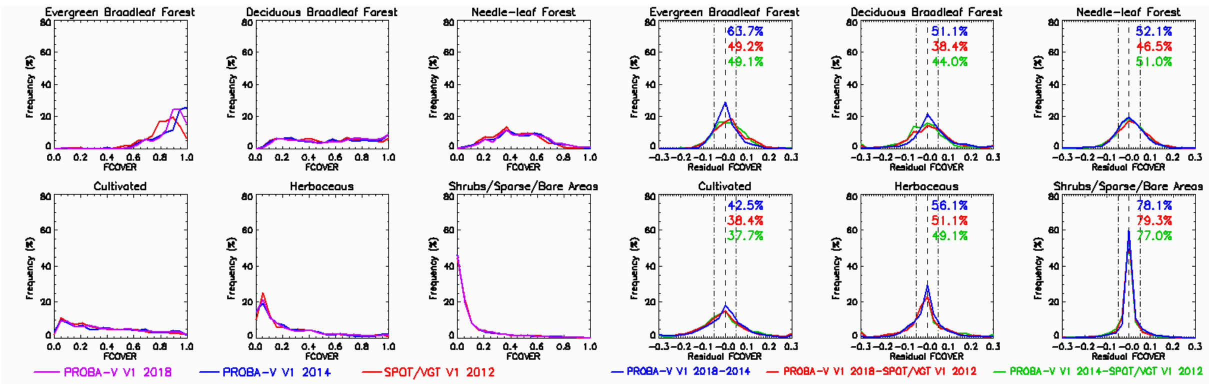


Figure 16: Distribution of FCOVER values (left panel) and residuals (right panel) for 1km V1 products over the LANDVAL sites during the period of January to December for each biome type. Percentages of residuals between ± 0.05 FCOVER values are displayed.

For PROBA-V 1km V1 products the main findings are:

- Very similar distribution of LAI retrievals (Figure 14) were found for recent PROBA-V products (2018) as compared to PROBA-V V1 (2014) and SPOT/VGT V1 (2012) reference products for almost all biome types. The exception was the EBF biome, where values for PROBA-V V1 LAI products (2018 and 2014 years) are slightly larger than for SPOT/VGT V1 (2012). The PDFs of residuals between recent and reference products are centered around zero for all biome types with around 60% (or more) of samples within the LAI threshold (± 0.5), except in EBF when comparing PROBA-V V1 and SPOT/VGT V1 products (slight positive bias: PROBA-V > SPOT/VGT). Noteworthy good results were found for Shrubs/Sparse/Bare Areas with more than 94% of residuals within ±0.5.
- Similar distribution of FAPAR retrievals (Figure 15) was found between recent products compared to PROBA-V V1 (2014) and SPOT/VGT V1 (2012) for almost all biomes types. Slight different distributions were observed for DBF and Herbaceous in the comparison between PROBA-V V1 and SPOT/VGT V1. Histograms of residuals between recent and validated V1 products are centered around zero for all biomes types. Percentages of residuals within the FAPAR threshold (± 0.05) are typically higher than 50% for all biomes except for NLF, DBF and Cultivated (>40%).
- In the case of FCOVER V1 products (Figure 16), similar PDFs of retrievals was generally found for most of biome types, except for EBF (0.8-1 FCOVER range) and for Herbaceous (0-0.1 range) in the comparison between PROBA-V V1 and SPOT/VGT V1 products. The PDFs of residuals are centered around zero for all biome types except in EBF and DBF (slight positive and negative sign, respectively) when comparing PROBA-V V1 and SPOT/VGT V1 products. It can be observed that the percentages of samples within the FCOVER threshold (±0.05) are typically higher than 50% when comparing PROBA-V periods and typically higher than 40% when comparing PROBA-V with SPOT/VGT period. The exception was the cultivated biome type, as expected, due to the non-natural variability of this biome.

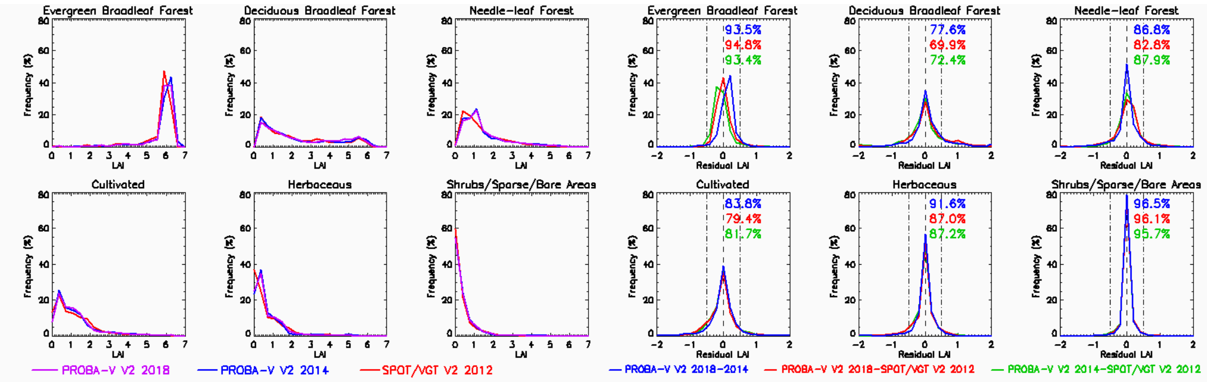


Figure 17: Distribution of LAI values (left panel) and residuals (right panel) for 1 km V2 products over the LANDVAL sites during the period of January to December for each biome type. Percentages of residuals between ± 0.5 LAI values are displayed.

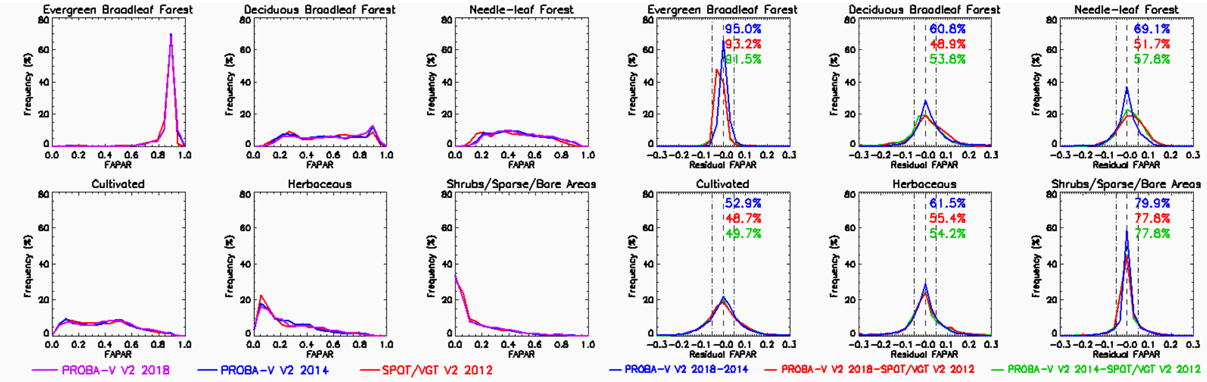


Figure 18: Distribution of FAPAR values (left panel) and residuals (right panel) for 1 km V2 products over the LANDVAL sites during the period of January to December for each biome type. Percentages of residuals between ± 0.05 FAPAR values are displayed.

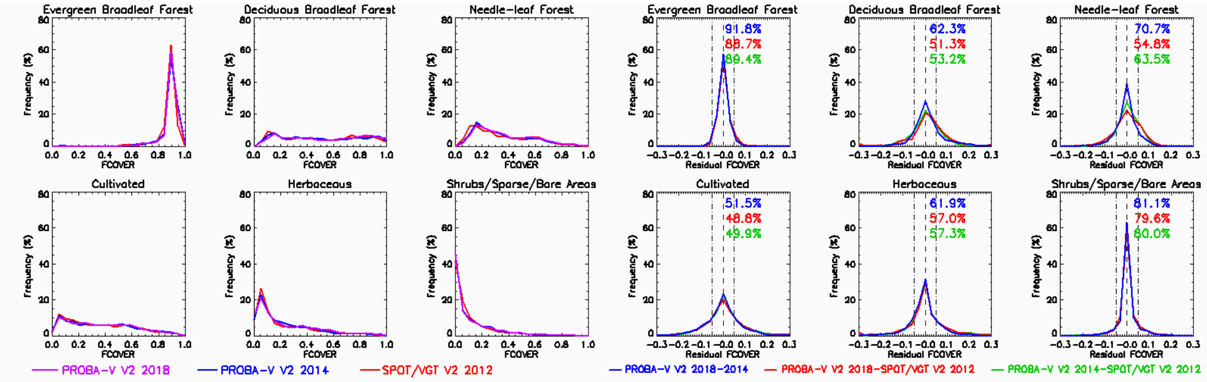


Figure 19: Distribution of FCOVER values (left panel) and residuals (right panel) for V2 products over the LANDVAL sites during the period of January to December for each biome type. Percentages of residuals between ± 0.05 FCOVER values are displayed.

For PROBA-V 1km V2 products the main findings are:

- Similar distribution of LAI retrievals (Figure 17) was found between recent PROBA-V V2 products (2018) as compared to PROBA-V V2 (2014) and SPOT/VGT V2 (2012) reference products for most of biomes. The exceptions were EBF, NLF and Herbaceous where PROBA-V V2 LAI retrievals (2018 and 2014 years) are slightly larger than for SPOT/VGT V2 (2012) retrievals. The PDFs of residuals between recent and reference V2 products are centered around zero for all biomes with typically more than 70% of samples within ±0.5 (a little lower for DBF). The exception of PDFs of residuals centered at zero was the EBF biome when comparing PROBA-V V2 (2018 and 2014 years, positive sign), and when comparing PROBA-V V2 2014 and SPOT/VGT V2 products (slight negative sign). Remarkably good results can be noted for Shrubs/Sparse/Bare Areas with a percentage of residuals higher than 95% within the ±0.5 threshold.
- In case of FAPAR V2 products (Figure 18), similar distribution of retrievals was found between recent and validated products for all biome types, with very slight differences for

NLF and Herbaceous when comparing PROBA-V V2 and SPOT/VGT V2. The PDFs of residuals are centered around zero for all biome types, except in EBF and DBF in case of PROBA-V V2 versus SPOT/VGT V2, with a tendency towards negative. It can be observed that the percentages of FAPAR residuals within ±0.05 threshold are typically higher than 50% for all biomes, with slight lower percentages in Cultivated when comparing PROBA-V and SPOT/VGT.

- Similar performance was found for FCOVER V2 products (Figure 19), showing similar distribution of retrievals between recent and validated products for all biome types, and slight differences in NLF and Herbaceous when comparing PROBA-V V2 and SPOT/VGT V2. Histograms of residuals showed maximum peaks around zero for all biomes. It can be noted that the percentages of FCOVER residuals within ±0.05 are very similar to that found in FAPAR for all biomes.

5.1.3 Temporal Consistency Analysis

5.1.3.1 Cross-Correlation Distributions

Cross-correlation distributions of temporal variations between recent PROBA-V 1km V1 and V2 (2018), validated PROBA-V 1km V1 and V2 (2014), and the reference SPOT/VGT 1km V1 and V2 (2012) products were assessed per biome type for LANDVAL sites during the January to December period (Figure 20 to Figure 22).

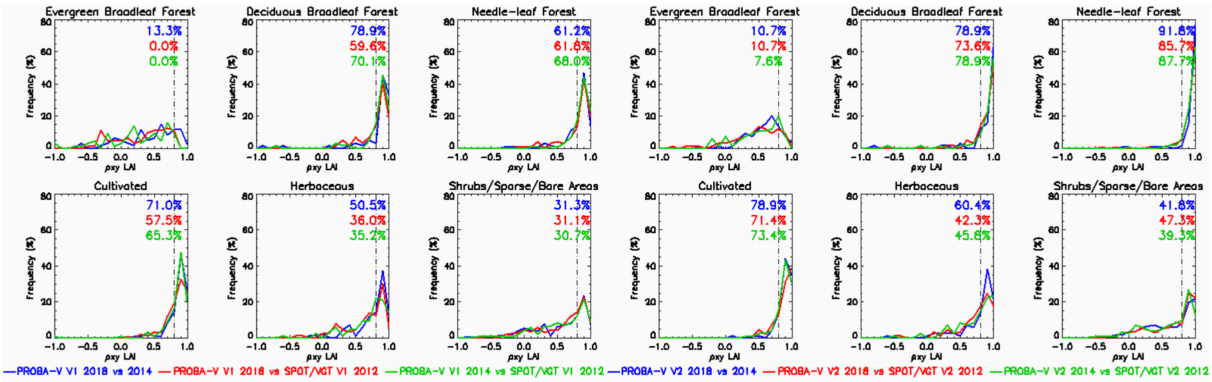


Figure 20: LAI histograms of cross-correlation distributions (ρ_{xy}) between PROBA-V 2018, PROBA-V 2014 and SPOT/VGT 2012 for 1km V1 (left) and 1km V2 (right) over LANDVAL sites during the period of January to December for each biome type. Percentage values showed in each plot correspond to cases with correlation values higher than 0.8.

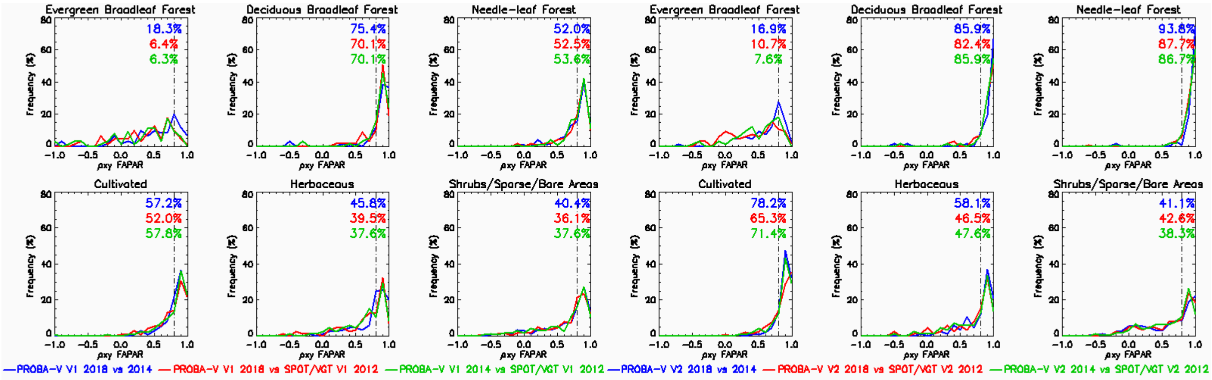


Figure 21: Same as Figure 20 but for FAPAR.

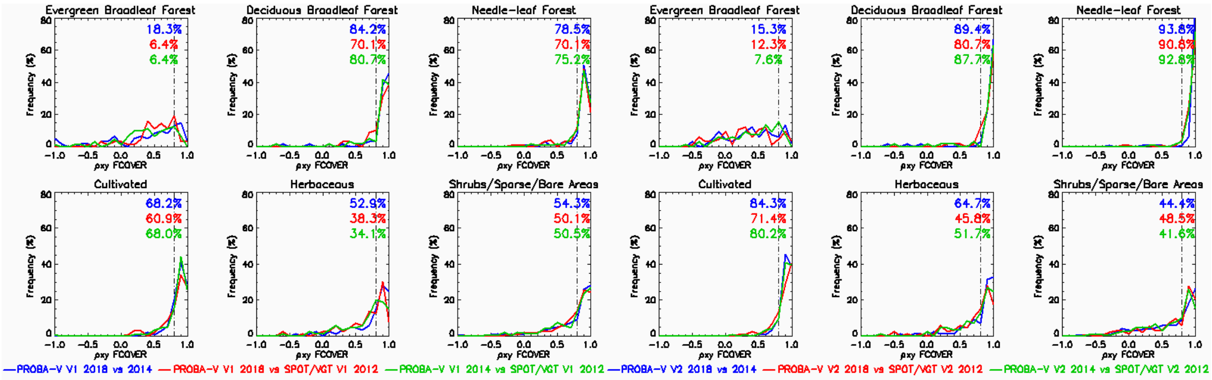


Figure 22: Same as Figure 20 but for FCOVER.

Figure 20 to Figure 22 show:

- Very similar histograms of cross correlations were found when version 1 and version 2 are evaluated. However, version 2 products present higher correlations in all cases, as expected due to gap filling and temporal smoothing methods.
- Cross-correlations of LAI V1 and V2 products between recent PROBA-V 2018 year and references PROBA-V 2014 and SPOT/VGT 2012 equivalent periods (Figure 20) were higher for Deciduous Broadleaved Forest, Needle-leaf Forest and Cultivated than for the rest of biome types (for V1 correlations higher than 0.8 in more than 60% of cases, and for V2 in more than 70% of cases). Herbaceous and Shrubs/Sparse/Bare Areas histograms show slightly lower but satisfactory percentages, explained in the typically low retrievals and amplitudes. On the other hand, for Evergreen Broadleaf Forest, the cross-correlation histograms showed non-satisfactory results, with less than 15% of cross-correlation values higher than 0.8 for V1 and for V2, as this biome displays more erratic variations due to the cloud contamination in V1 and flat temporal profiles in V2 due to gap filling.
- Similar results were found for FAPAR and FCOVER (Figure 21 and Figure 22), showing also the best performances for Deciduous Broadleaf Forest, Needle-leaf Forest and

Cultivated, and lower correlations for Herbaceous, Shrubs/Sparse/Bare Areas and Evergreen Broadleaf Forest, especially lower for this last one.

5.1.4 Inter-Annual Precision

Box-plots per bin value of absolute inter-annual anomalies of PROBA-V 1km recent products (2018) as compared to PROBA-V 1km validated (2014) and to SPOT/VGT 1km (2012) products, computed using the upper 95th and lower 5th percentiles over LANDVAL sites, are analyzed for V1 (Figure 23, Figure 24 and Figure 25) and for V2 (Figure 26, Figure 27 and Figure 28). The median of the absolute anomaly is proposed as overall indicator of inter-annual precision (Fernandes et al., 2014).

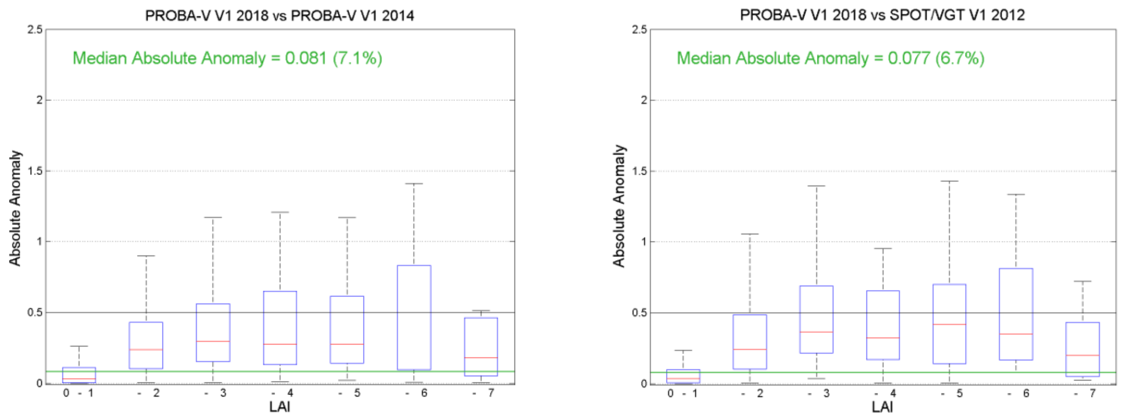


Figure 23: Box-plots of inter-annual absolute anomalies of PROBA-V 1km V1 (year 2018 versus year 2014, left side) and PROBA-V 1km V1 (year 2018) versus SPOT/VGT 1km V1 (year 2012) per bin LAI value. Red bars indicate median values, green line corresponds to the median absolute anomaly including all LAI ranges and black line indicates the 0.5 LAI value.

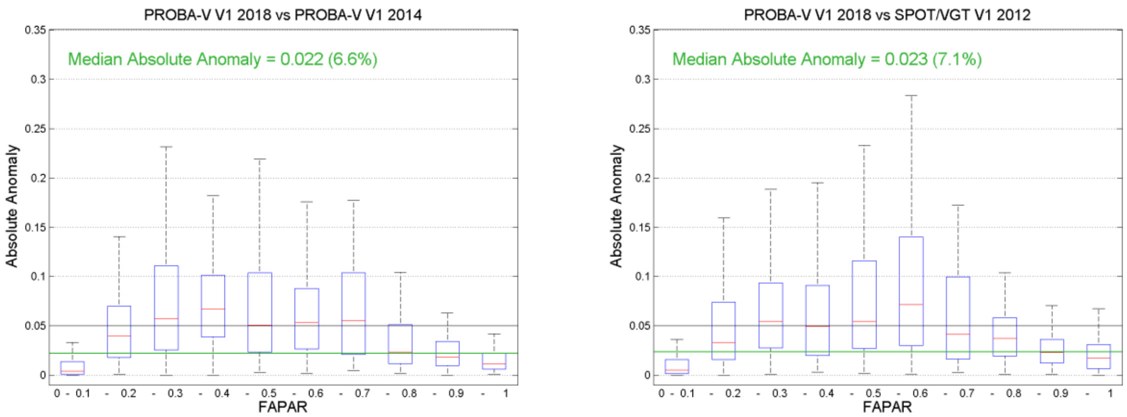


Figure 24: As in Figure 23 for FAPAR. Black line indicates the 0.05 FAPAR value.

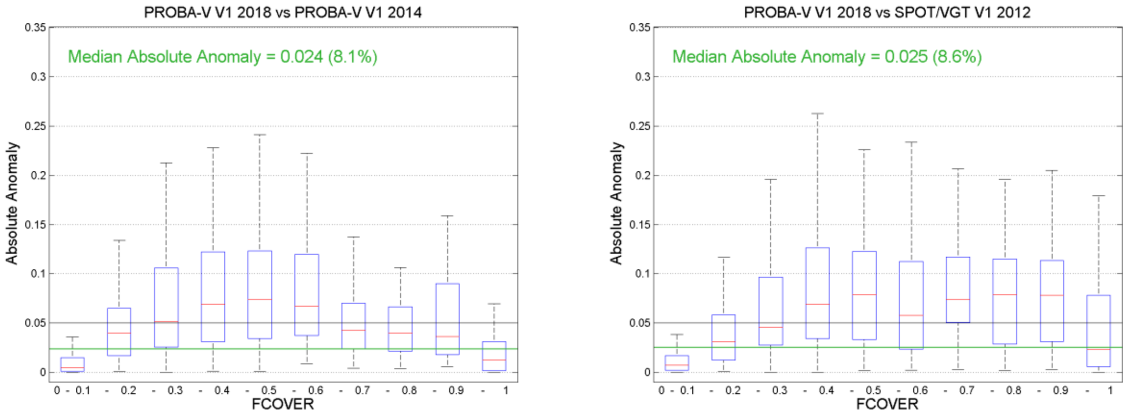


Figure 25: As in Figure 23 for FCOVER. Black line indicates the 0.05 FCOVER value.

The main results of PROBA-V 1km V1 products are:

- For LAI V1 product (Figure 23), more than 50% of absolute anomalies are lower than 1 for all LAI ranges, with median absolute anomalies per bin lower than 0.5 in all cases. The median absolute anomaly achieves the GCOS requirements in terms of stability (Max [10%; 0.25]), when comparing PROBA-V 2018 versus 2014 (7.1%, 0.081) (Figure 23, left), and when comparing PROBA-V 2018 versus SPOT/VGT 2012 (6.7%, 0.077) (Figure 23, right).
- In case of PROBA-V FAPAR V1 products (Figure 24), the median absolute deviation of anomalies for recent FAPAR was 0.022 (6.6%) as compared to PROBA-V V1 (2014) and slightly higher of 0.023 (7.1%) as compared to SPOT/VGT V1 (2012). Both of these results are not within GCOS requirements in terms of stability (Max [3%; 0.02]), but very close.
- Finally, for FCOVER (Figure 25), median inter-annual anomalies of 0.024 (8.1%) between PROBA-V V1 2018 vs 2014 years and 0.025 (8.6%) when compared PROBA-V V1 2018 to SPOT/VGT V1 2012 year were found.
- Very similar results as compared to the equivalent exercise performed during the previous 2017 year [CGLOPS1_SQE2017_LAI1km-V1&V2].

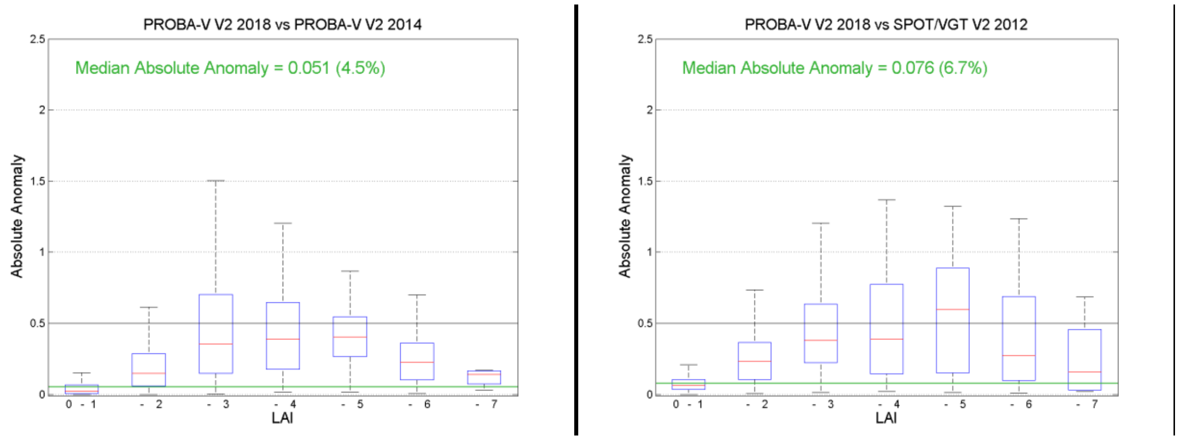


Figure 26: Box-plots of inter-annual absolute anomalies of PROBA-V 1km V2 (year 2018 versus year 2014, left side) and PROBA-V 1km V2 (year 2018) versus SPOT/VGT V2 (year 2012) per bin LAI value. Red bars indicate median values and green line corresponds to the median absolute anomaly including all LAI ranges.

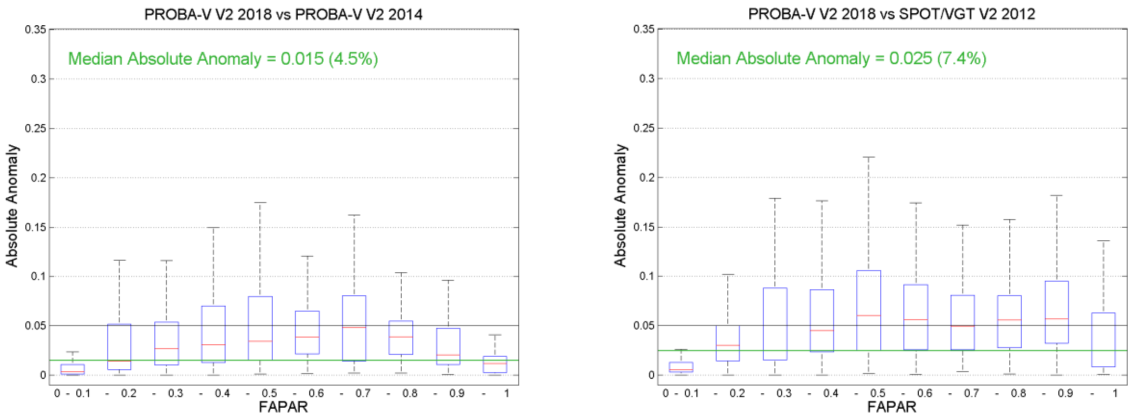


Figure 27: As in Figure 26 for FAPAR.

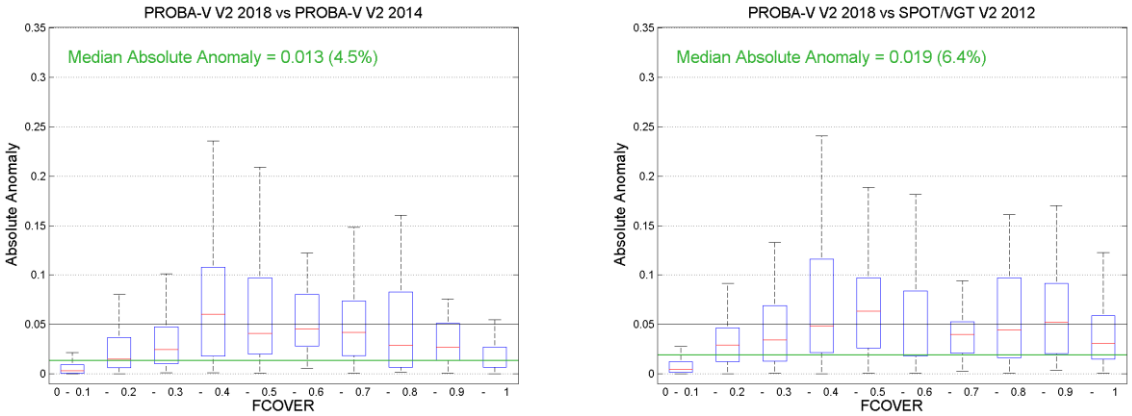


Figure 28: As in Figure 26 for FCOVER.

The main results of PROBA-V 1km V2 products are:

- For PROBA-V LAI V2 product (Figure 26), the median absolute deviation of anomalies for the whole LAI dataset was 0.051 (4.5%) compared to PROBA-V 2014, and slightly higher as compared to SPOT/VGT 2012, with a median of 0.076 (6.7%), but matching the GCOS requirements in terms of stability (Max [10%; 0.25]) in both cases.
- For FAPAR V2 products (Figure 27), the median absolute deviation of anomalies for recent FAPAR was of 0.015 (4.5%) as compared to PROBA-V V2 (2014) and 0.025 (7.4%) as compared to SPOT/VGT V2 (2012), within the GCOS requirements in terms of stability (Max [3%; 0.02]) for the former comparison and very close for the latter.
- In the case of FCOVER (Figure 28), median inter-annual anomalies of 0.013 (4.5%) and 0.019 (6.4%) were found in each comparison (PROBA-V V2 2018 versus 2014, and PROBA-V V2 2018 versus SPOT/VGT V2 2012, respectively).
- Better results in terms of inter-annual precision were found for V2 compared to V1 for the same sensor (PROBA-V) in line with previous validation results [GIOGL1_QAR_LAI1km-VGT-V2]. However, the inter-annual precision between PROBA-V (2018) and SPOT/VGT (2012) is worse in V2 than in V1 for LAI and FAPAR, and better in V2 than V1 for FCOVER. Same conclusion was found during the validation of 2017 year [CGLOPS1_SQE2017_LAI1km-V1&V2].

5.1.5 Intra-Annual Precision (Smoothness)

Figure 29 (V1) and Figure 30 (V2) show the cumulative histograms of the smoothness, δLAI, δFAPAR and δFCOVER, for PROBA-V 2018 products (purple) as compared with the PROBA-V 2014 (blue) and SPOT/VGT 2012 (red) reference products for both versions (V1 and V2) at 1 km resolution.

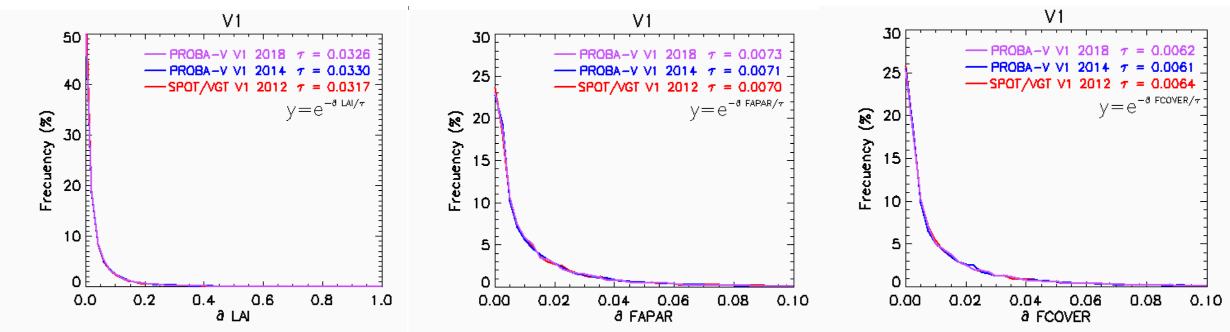


Figure 29: Histograms of the delta function (smoothness) for LAI, FAPAR and FCOVER 1km V1 products for LANDVAL sites during the January-December period. The curves are adjusted to an exponential function and the exponential decay constant is presented in the figure.

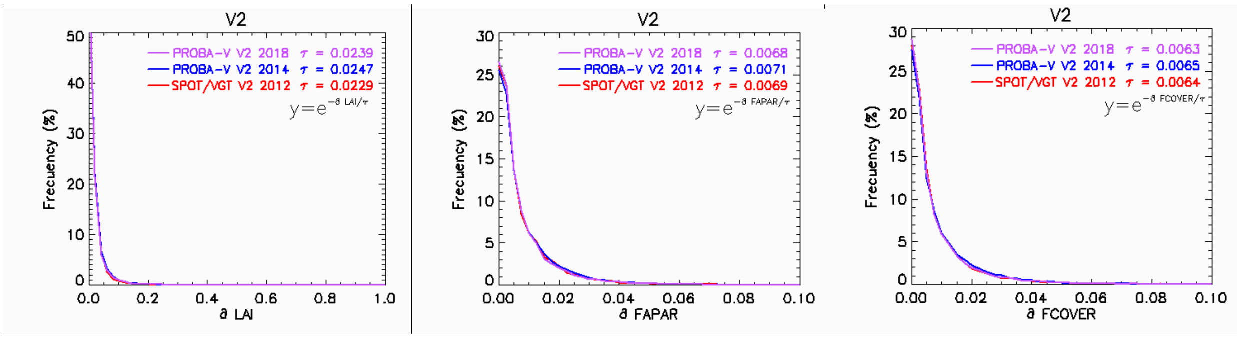


Figure 30: Histograms of the delta function (smoothness) for LAI, FAPAR and FCOVER 1 km V2 products for LANDVAL sites during the January-December period. The curves are adjusted to an exponential function and the exponential decay constant is presented in the figure.

The conclusions are:

- Almost identical distributions of delta values were found for the different years, showing all of delta values below 0.1 for LAI and below 0.01 for FAPAR and FCOVER, which indicates that the precision at short time scale of the recent V1 and V2 products is preserved. Note that the cumulative histograms fit a negative exponential function with a very similar decay constant (τ).
- Better results were found in case of V2 products compared to V1, with typically lower decay constant (τ), except for FCOVER. It indicates the high stability at short time scale for V2 products, as expected due to the smoothing and gap filled methods applied in V2.

5.1.6 Overall Statistical Consistency

To evaluate the overall performance of the recent PROBA-V LAI, FAPAR and FCOVER 1 km products, scatter-plots and relevant statistics were evaluated as compared with validated PROBA-V (year 2014) and SPOT/VGT (year 2012) products for V1 and V2.

- **Global scatter-plots V1**

Figure 31 and Figure 32 show the scatter-plots and associated metrics for V1 in the comparisons of 2018 versus 2014 and 2018 versus 2012 respectively. Pixels flagged as 'low quality' according to Table 10 were removed from the computation. Performance statistics are presented in Table 15 and Table 16.

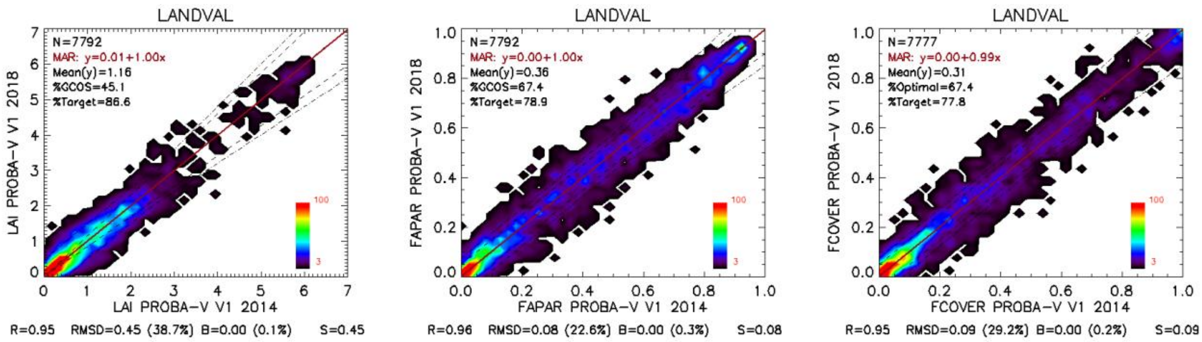


Figure 31: PROBA-V V1 LAI/FAPAR/FCOVER recent products versus PROBA-V 1 km V1 reference product (year 2014) scatter-plots over LANDVAL sites for the January-December period. The term B and S represent the mean and the standard deviation of the difference between the recent products (y axis) and the reference products (x axis). Dashed lines correspond to the 1:1 line, optimal (GCOS) and target requirements.

Table 15: Main statistics between PROBA-V V1 LAI/FAPAR/FCOVER recent products versus PROBA-V 1 km V1 reference product (year 2014) over LANDVAL sites for the period of January-December. p-value corresponds to the test on whether the slope is significantly different to 1. Percentage of samples lying within the uncertainty levels of optimal, target and threshold are displayed.

	PROBA-V V1 (2018) vs PROBA-V V1 (2014)		
	LAI	FAPAR	FCOVER
Correlation	0.95	0.96	0.95
Bias	<0.005 (0.1%)	<0.005 (0.3%)	<0.005 (0.2%)
RMSD	0.45	0.08	0.09
Offset	0.01	0.00	0.00
Slope	1.00	1.00	0.99
p-value	0.536	0.025	0.086
%optimal	45.1	67.4	67.4
%target	86.6	78.9	77.8
%threshold	92.5	86.5	84.9

For PROBA-V 1 km V1 2018 vs PROBA-V 1km V1 2014 (Figure 31 and Table 15):

- The scatter plots show correlations larger than 0.95, with mean bias almost zero (percentages lower than 0.3%) and root mean square deviations (RMSD) of 0.45, 0.08 and 0.09 for LAI, FAPAR and FCOVER, respectively. Optimal lineal MAR relationships were found with offset ~0 and slope of ~1.0, which indicates the good overall consistency of recent period as compared to the validated period.
- More than 45% of LAI pixels are within the optimal consistency level (i.e, GCOS requirements), and 67% for FAPAR/FCOVER. These percentages are higher than 86% for LAI and close to 80% for FAPAR/FCOVER when the target level is considered.

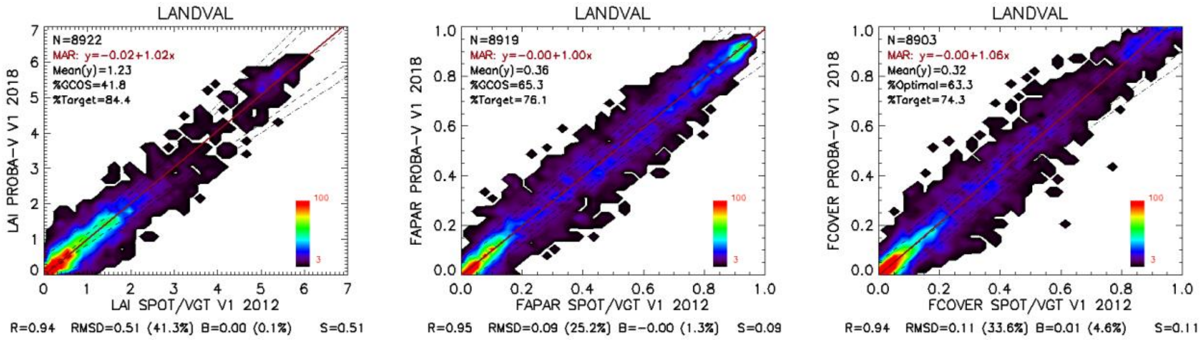


Figure 32: As in Figure 31 between PROBA-V V1 (2018) versus SPOT/VGT 1 km V1 (year 2012).

Table 16: As in Table 15 between PROBA-V 1 km V1 LAI/FAPAR/FCOVER recent products (2018) versus SPOT/VGT 1 km V1 reference (2012) products.

	PROBA-V V1 (2018) vs SPOT/VGT V1 (2012)		
	LAI	FAPAR	FCOVER
Correlation	0.94	0.95	0.94
Bias	<0.005 (0.1%)	<0.005 (-1.3%)	0.01 (4.6%)
RMSD	0.51	0.09	0.11
Offset	-0.02	0.00	0.00
Slope	1.02	1.00	1.06
p-value	0.001	0.047	<0.001
%optimal	41.8	65.3	63.3
%target	84.4	76.1	74.3
%threshold	91.0	83.0	81.8

For PROBA-V 1 km V1 2018 vs SPOT/VGT 1 km V1 2012 (Figure 32 and Table 16):

- Correlation of higher than 0.94 were found, with root mean square deviation values (RMSD) of 0.51, 0.09 and 0.11 for LAI, FAPAR and FCOVER respectively.
- The mean bias showed values close to zero for LAI (0.1%), -1.3% for FAPAR. Large positive bias (4.6%) was found for FCOVER, in line to that found during the validation report [GIOGL1_QAR_LAI1km-V1] and previous 2017 year [CGLOPS1_SQE2017_LAI1km-V1&V2]. Then, we can conclude that the change of the sensor could introduce a systematic positive bias in the FCOVER V1 algorithm over global conditions. This impact could be higher locally.
- It can be observed that more than 40% of pixels are matching the GCOS accuracy requirement for LAI and around 85% are within the target level of uncertainty. For FAPAR and FCOVER around 65% of pixels are in optimal range of consistency, and around 75% considering target level.

- **Global scatter-plots V2**

Figure 33 and Figure 34 show the scatter-plots and associated metrics of PROBA-V 1km V2 LAI, FAPAR and FCOVER products. Here two results were displayed: on the top of figures all pixels where considered whereas on the bottom of figures pixels flagged as 'low quality' according to Table 10 and filled pixels were removed from the computation. The performance statistics are presented in Table 17 to Table 18.

Similar results have been obtained for all pixels and best quality pixels, so for the sake of brevity the discussion was focused of best quality results. Just note that worse performances in terms of GCOS requirements are obtained for “best-quality pixels” case due to the removal of filled pixels.

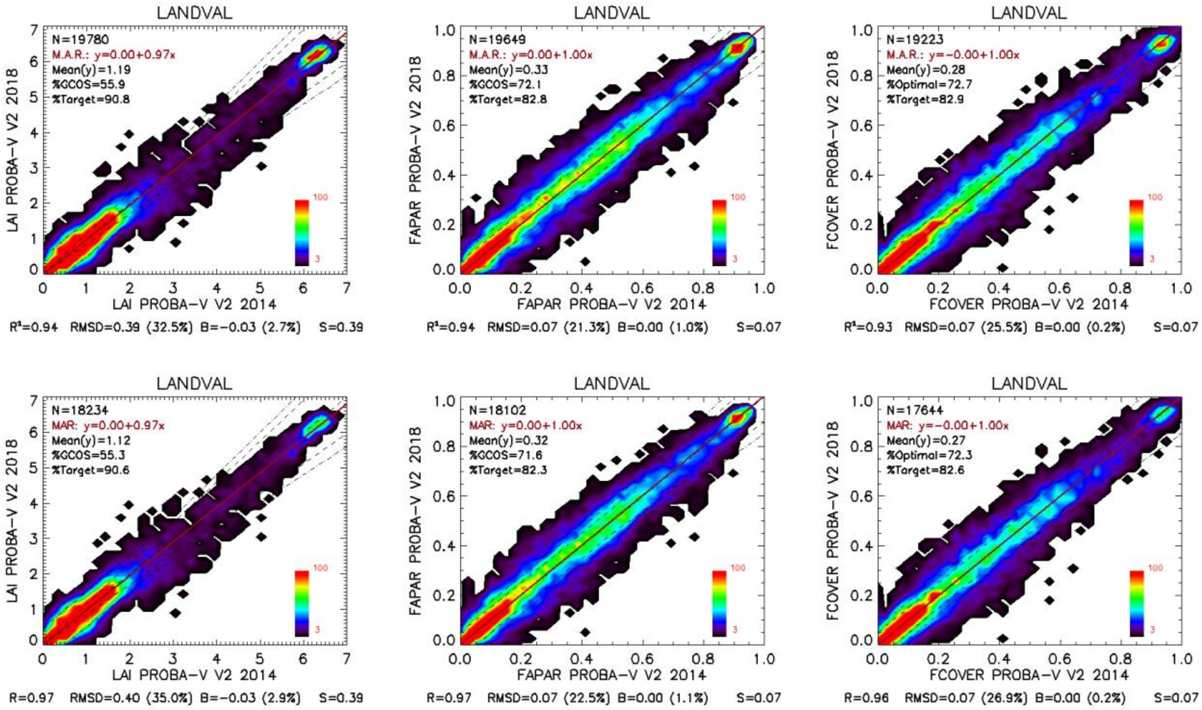


Figure 33: As in Figure 31 between PROBA-V 1km V2 (2018) versus PROBA-V 1km V2 (year 2014). Top: All pixels are considered. Bottom: Best quality pixels (V2 filled values and ‘low-quality’ pixels are removed).

For PROBA-V 1km V2 2018 vs PROBA-V 1km V2 2014 (

Figure 33 and Table 17):

- The scatter plots show correlations of about 0.96-0.97, mean bias of 2.9%, 1.1% and 0.2% and root mean square deviation values (RMSD) of 0.40, 0.07 and 0.07 for LAI, FAPAR and FCOVER, respectively.
- Remarkably good is the linear fit between both datasets for each variable under study, which shows the optimal consistency between recent and validated PROBA-V 1km V2 products. FAPAR and FCOVER display MAR relationships over the 1:1 line (offset almost

zero, slope almost 1) and LAI very close to the 1:1 line (offset almost zero and slope of 0.7). The recent products preserve the quality as compared to the validated period.

- More than 55% of LAI pixels are within the optimal consistency level, and more than 70% for FAPAR/FCOVER. These percentages reach up to 91% for LAI and 82% for FAPAR/FCOVER when the target level is considered.

Table 17: As in Table 15 between PROBA-V 1km V2 LAI/FAPAR/FCOVER recent products (2018) versus PROBA-V 1km V2 reference (2014) products.

	PROBA-V V2 (2018) vs PROBA-V V2 (2014)					
	LAI		FAPAR		FCOVER	
	all pixels	best-quality	all pixels	best-quality	all pixels	best-quality
Correlation	0.94	0.97	0.94	0.97	0.93	0.96
Bias	-0.03 (2.7%)	-0.03 (2.9%)	<0.005 (1%)	<0.005 (1.1%)	<0.005 (0.2%)	<0.005 (0.2%)
RMSD	0.39	0.40	0.07	0.07	0.07	0.07
Offset	0.00	0.00	0.00	0.00	0.00	0.00
Slope	0.97	0.97	1.00	1.00	1.00	1.00
p-value	<0.001	<0.001	0.397	0.908	0.079	0.167
%optimal	55.9	55.3	72.1	71.6	72.7	72.3
%target	90.8	90.6	82.8	82.3	82.9	82.6
%threshold	94.9	94.8	89.1	88.7	88.7	88.5

For PROBA-V 1km V2 2018 vs SPOT/VGT 1km V2 2012 (Figure 34 and Table 18):

- The scatters show correlations higher than 0.93 and root mean square deviation values (RMSD) of 0.43 for LAI and 0.08 for FAPAR and FCOVER.
- The mean bias showed low positive values of 1.7% for LAI, 5.5% for FAPAR, and 1.2% for FCOVER for best quality retrievals, and very similar considering all pixels. This positive bias, mainly for FAPAR, could be partly attributed to the impact of the sensor transition from SPOT/VGT to PROBA-V, in line to that found during the previous exercise, performed for the 2017 year [CGLOPS1_SQE2017_LAI1km-V1&V2].
- It can be noted that around 25% of pixels are matching the GCOS accuracy requirement for LAI and around 88% of pixels are within the target level of uncertainty. For FAPAR and FCOVER around 67% of pixels are in optimal range of consistency, and around 78% considering target level.

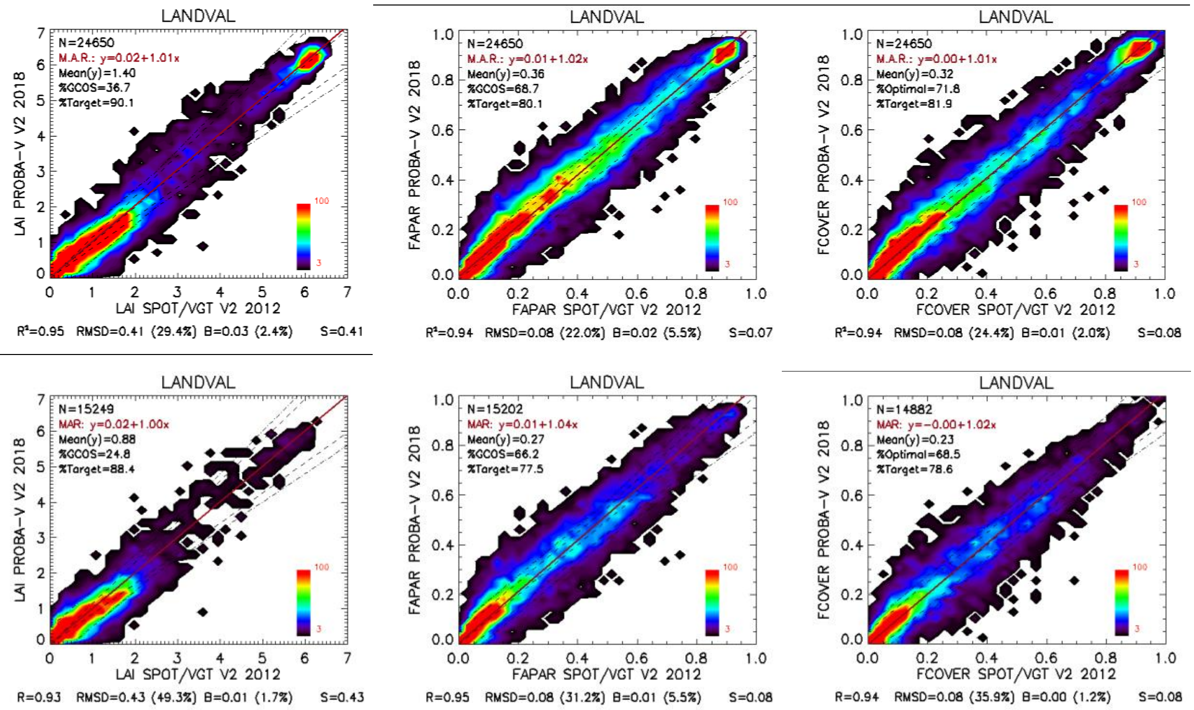


Figure 34: As in Figure 31 between PROBA-V 1km V2 (2018) versus SPOT/VGT 1km V2 (year 2012). Top: All pixels are considered. Bottom: V2 filled values and low quality pixels are removed from the computation.

Table 18: As in Table 15 between PROBA-V 1km V2 LAI/FAPAR/FCOVER recent products (2018) versus SPOT/VGT 1km V2 reference (2012) products.

	PROBA-V V2 (2018) vs SPOT/VGT V2 (2012)					
	LAI		FAPAR		FCOVER	
	all pixels	best quality	all pixels	best-quality	all pixels	best-quality
Correlation	0.95	0.93	0.94	0.95	0.94	0.94
Bias	0.03 (2.4%)	0.01 (1.7%)	0.02 (5.5%)	0.01 (5.5%)	0.01 (2%)	<0.005 (1.2%)
RMSD	0.41	0.43	0.08	0.08	0.08	0.08
Offset	0.02	0.02	0.01	0.01	0.00	0.00
Slope	1.01	1.00	1.02	1.04	1.01	1.02
p-value	0.001	0.968	<0.001	<0.001	<0.001	0.001
%optimal	36.7	24.8	68.7	66.2	71.6	68.5
%target	90.1	88.4	80.1	77.5	81.9	78.6
%threshold	94.5	93.8	87.2	84.5	87.9	85.2

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

The analysis of the discrepancies (bias and RMSD) between PROBA-V LAI, FAPAR and FCOVER 1km and reference equivalent products per range of values during January to December period and over LANDVAL network of sites are presented from Figure 35 to Figure 36 for V1 products and from Figure 37 to Figure 38 for V2 products. These results correspond to best quality retrievals (pixels flagged as 'low quality' in Table 10, and filled pixels in case of V2, were removed).

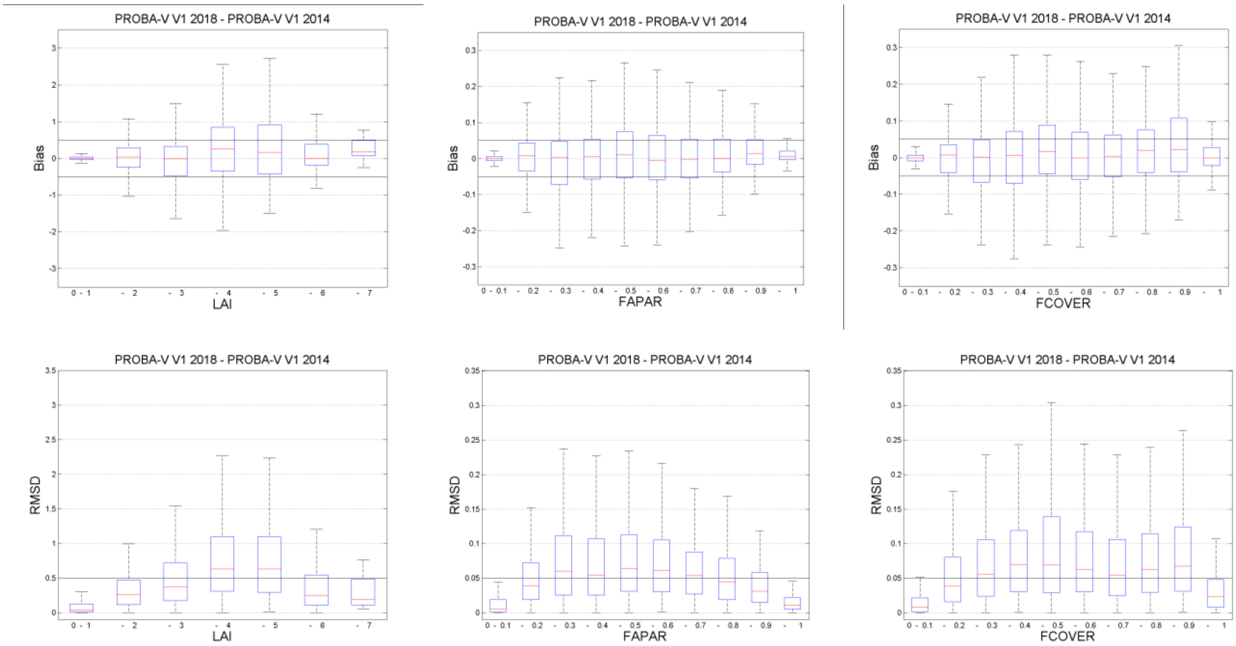


Figure 35: Box-plots of uncertainty statistics between PROBA-V 1km V1 recent (2018) and PROBA-V 1km V1 validated (2014) (Top: bias, bottom: Root Mean Square Deviation (RMSD)) per bin (PROBA-V recent value) for LAI (left), FAPAR (middle) and FCOVER (right) over LANDVAL during January to December period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.

For PROBA-V 1km V1 2018 vs PROBA-V 1km V1 2014 (Figure 35):

- Box-plots of uncertainty metrics show median bias values close to zero for all products, with the 50% of values with differences typically lower than 0.5 for LAI, 0.05 for FAPAR and 0.1 for FCOVER. For FCOVER slightly greater differences are found. These results confirm the good consistency of recent products as compared to validated PROBA-V references.
- In case of RMSD, for LAI product, median values are lower than 0.5 except for LAI values between 3 and 5 that are slightly higher than 0.5, with more than 50% of data typically below 1. For FAPAR and FCOVER median values are typically around 0.05 with the 50% of data below or around 0.1, showing FCOVER slightly higher differences.

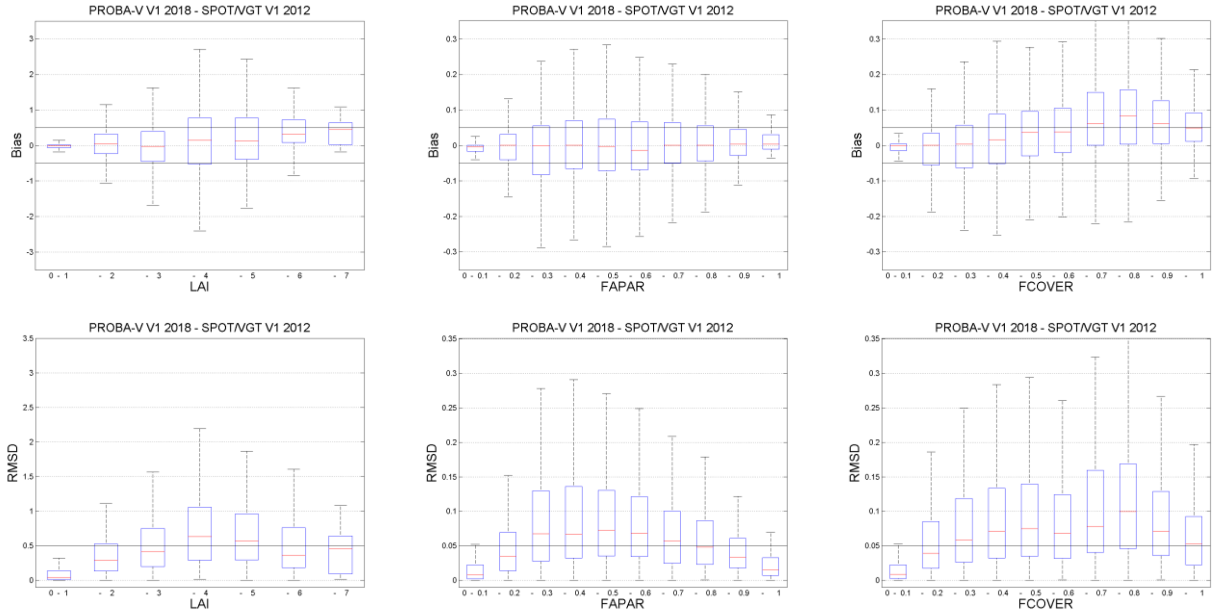


Figure 36: Box-plots of uncertainty statistics between PROBA-V 1km V1 recent (2018) and SPOT/VGT 1km V1 reference (2012) (Top: bias, bottom: Root Mean Square Deviation (RMSD)) per bin (PROBA-V recent value) for LAI (left), FAPAR (middle) and FCOVER (right) over LANDVAL during January to December period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.

For PROBA-V 1km V1 2018 vs SPOT/VGT 1km V1 2012 (Figure 36):

- Median bias close to 0 was found for all LAI ranges, except from 5 to 7, in which positive median bias close to 0.5 was found. For FAPAR, median bias close to zero was found for all ranges, with 50% of the differences typically lower or close than 0.05. However, for FCOVER a positive bias (median bias around 0.05) was found for values greater than 0.4. These results are consistent with those found in previous analysis [GIOGL1_QAR_LAI1km-V1] where positive bias was observed between PROBA-V V1 and SPOT/VGT V1 for the FCOVER, mainly for the higher FCOVER ranges.
- In case of RMSD, median LAI values are lower than 0.5 except for LAI ranges between 3 and 5 (slightly higher than 0.5), with typically more than 50% of data typically below 1. FAPAR median RMSD values are typically lower than 0.07, whereas for FCOVER larger discrepancies were found, showing median RMSD values up to 0.1.

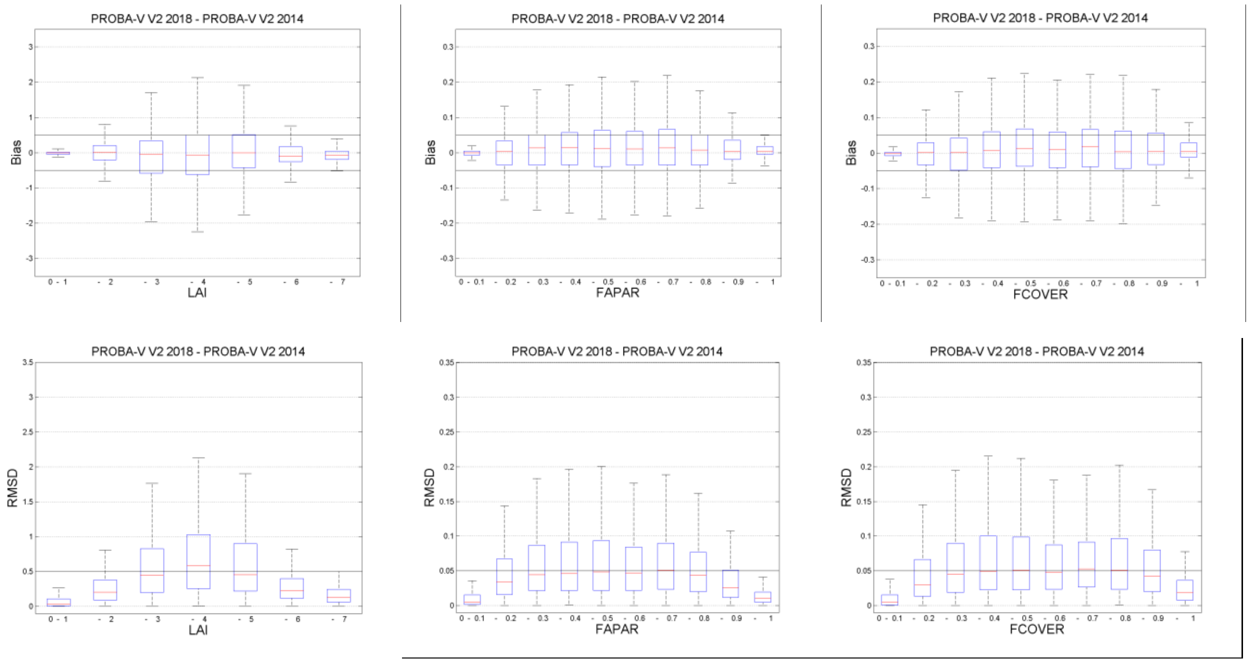


Figure 37: Box-plots of uncertainty statistics between PROBA-V 1km V2 recent (2018) and PROBA-V 1km V2 validated (2014) (Top: bias, bottom: Root Mean Square Deviation (RMSD)) per bin (PROBA-V recent value) for LAI (left), FAPAR (middle) and FCOVER (right) over LANDVAL during January to December period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.

For PROBA-V 1km V2 2018 vs PROBA-V 1km V2 2014 (Figure 37):

- Box-plots of uncertainty metrics show median bias values very close to 0 for all products, with typically more than 50% of values with differences below or around 0.5 for LAI and 0.05 for FAPAR and FCOVER. Recent products achieve good consistency compared with validated PROBA-V products for all range values.
- In case of RMSD, all median values are lower than 0.5 for LAI (except the range between 3 and 4), and to 0.05 for FAPAR and FCOVER. Furthermore, almost all RMSD are below 1 for LAI and below 0.1 for FAPAR and FCOVER.

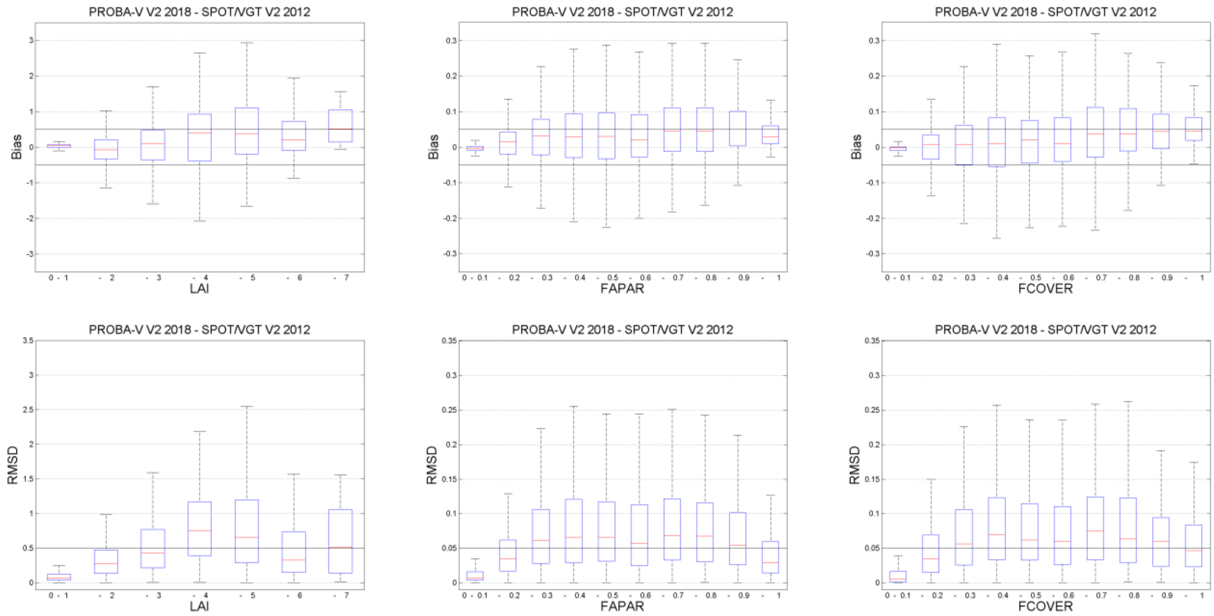


Figure 38: Box-plots of uncertainty statistics between PROBA-V 1km V2 recent (2018) and SPOT/VGT 1km V2 reference (2012) (Top: bias, bottom: Root Mean Square Deviation (RMSD)) per bin (PROBA-V recent value) for LAI (left), FAPAR (middle) and FCOVER (right) over LANDVAL during January to December period. Red bars indicate median values, blue boxes stretch from the 25th percentile to the 75th percentile of the data and whiskers include 99.3% of the coverage data (±2.7 σ). Outliers are not displayed.

For PROBA-V 1km V2 2018 vs SPOT/VGT 1km V2 2012 (Figure 38):

- The analysis of the discrepancies shows median bias close to 0 for LAI values lower than 3, and a positive median bias around 0.5 for LAI values higher than 3. 50% of cases show differences lower than 0.5 for low values, and typically between 0 and 1 for values between 3 and 7. For FAPAR and FCOVER, median bias close to zero was found for the lowest ranges (0-0.1) with slight positive median bias (lower than 0.05) for the rest of ranges (0.1 to 1). The positive bias is higher in the case of FAPAR. This confirms that the change of the input sensor could introduce a systematic bias in the three variables, more important for medium to high values.
- Regarding the RMSD, median LAI RMSD is lower than 0.5 except for LAI values between 3 and 5 (around 0.6-0.7). For FAPAR and FCOVER almost all median values are slightly higher than 0.05 with the 50% of data below or around 0.1.

5.2 Regional analysis

5.2.1 Temporal variations over Europe

Figure 39 and Figure 40 show temporal profiles of mean values for PROBA-V 1km V1 and V2 respectively during the 2018 and 2014 years over cropland areas (see Figure 4) for a selection of countries in Europe: Finland, Germany, Belgium, Denmark, Estonia and Portugal.

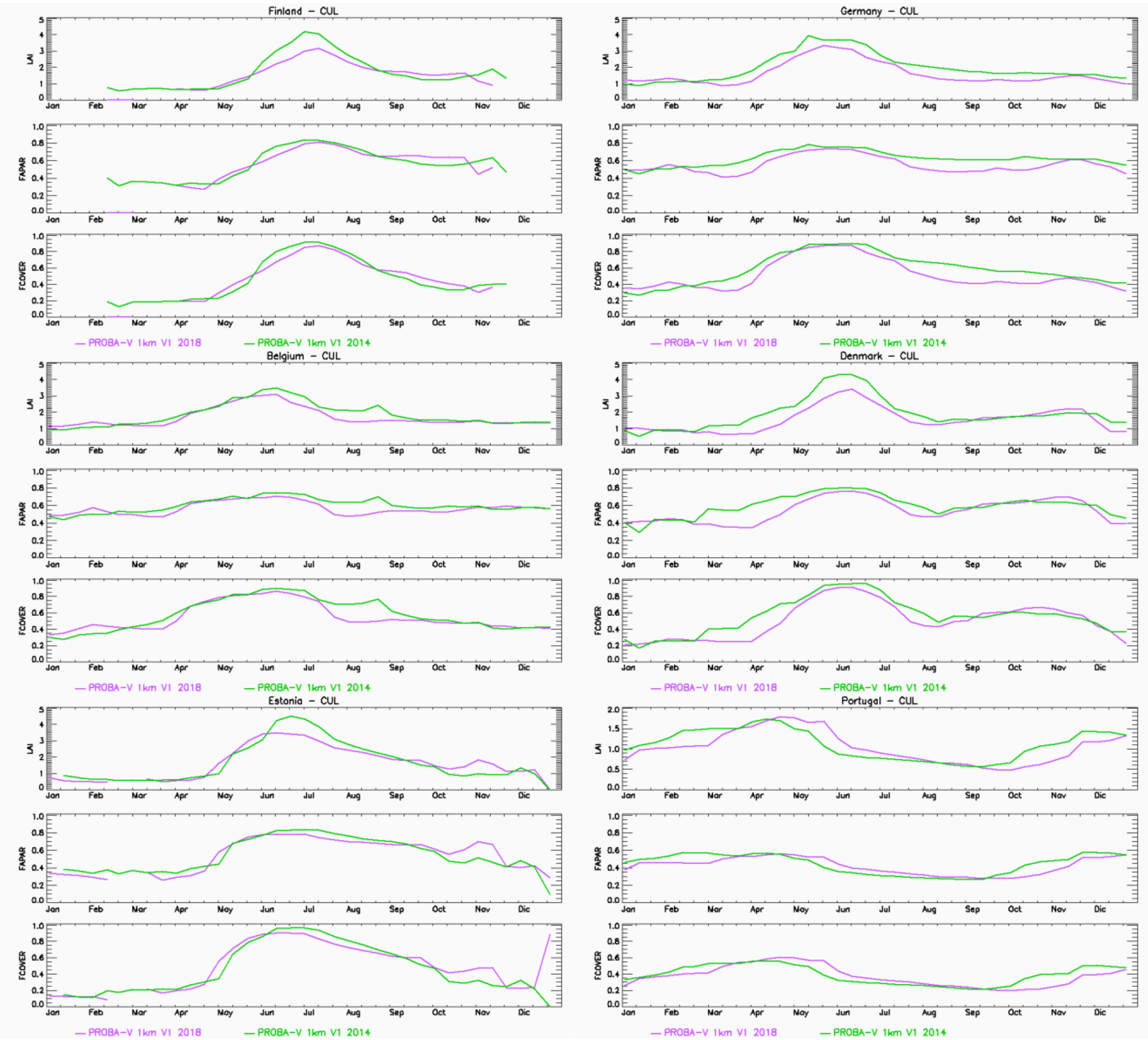


Figure 39: Temporal profiles of PROBA-V 1km V1 2018 year (purple line) and 2014 year (green line) for LAI (top) FAPAR (middle) and FCOVER (bottom) products over cultivated areas in Finland, Germany, Belgium, Denmark, Estonia and Portugal.

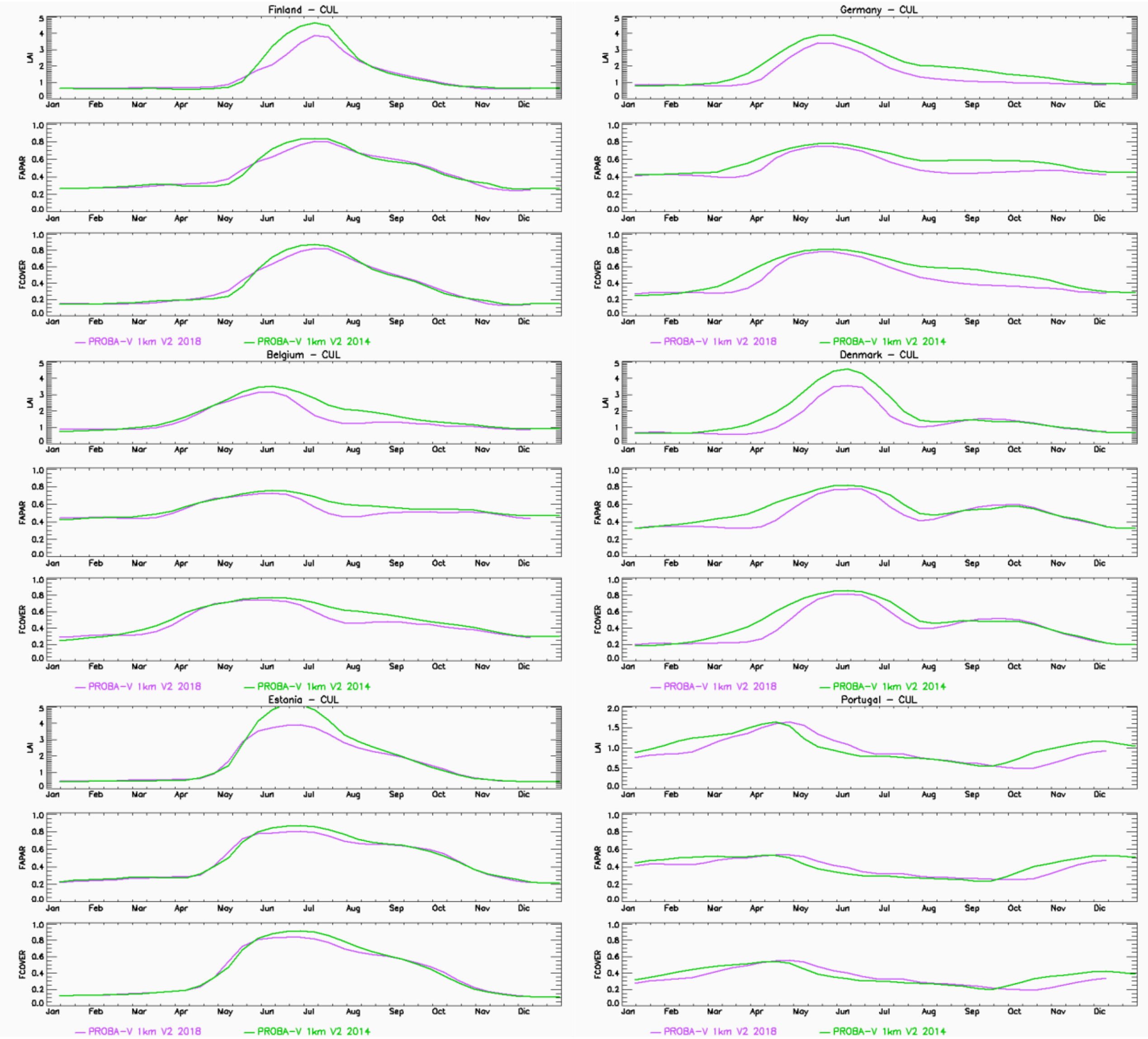


Figure 40: Temporal profiles of PROBA-V 1km V2 2018 year (purple line) and 2014 year (green line) for LAI (top) FAPAR (middle) and FCOVER (bottom) products over cultivated areas in Finland, Germany, Belgium, Denmark, Estonia and Portugal.

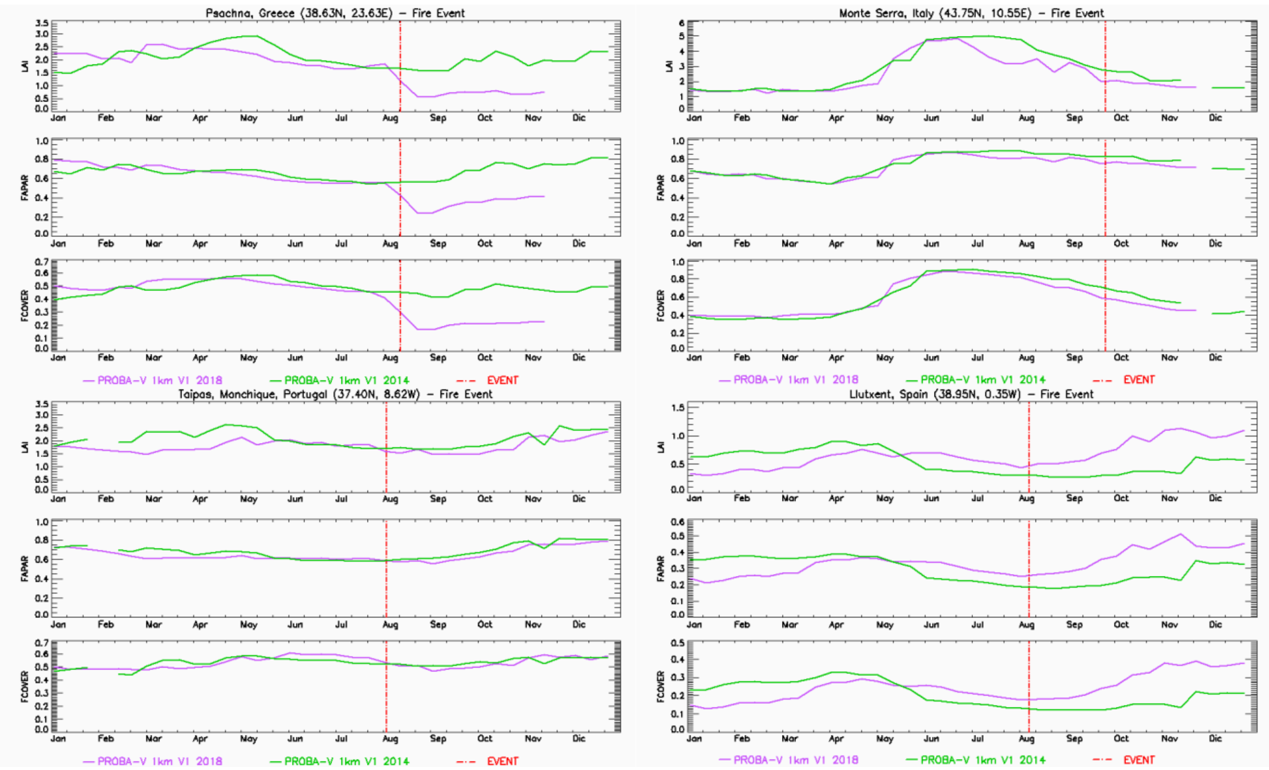
The main conclusions are the same for V1 and V2. The graphs show:

- A delay in the start of the crop season in Finland, Germany, Belgium and Denmark, due to the effect of the drought in the first months of 2018.
- Lower average of LAI, FAPAR and FCOVER values compared to 2014 from June onwards in Finland, Germany, Belgium, Denmark and Estonia, due to the effect of the summer drought.

- Higher LAI, FAPAR and FCOVER average values in 2018 compared to 2014 in Portugal during the period from May to September, because of warm and relatively wet conditions during the growing season.

5.2.2 Temporal variations and realism over specific events

Figure 41 and Figure 42 show temporal profiles of PROBA-V V1 and PROBA-V V2 products over ten selected sites where different types of environmental event took place during the 2018 year (see Table 13). The PROBA-V products are compared separately for each version, and they have been evaluated for 2018 and 2014 (validation year) years. Note that the dates of the events are flagged by the dashed red vertical lines. Temporal profiles of LAI and FAPAR MODIS C6 products were also evaluated, for benchmarking, and presented in ANNEX I. Additionally, maps of PROBA-V V1 and V2 products, at 1º x 1º are presented in ANNEX II with aim to provide the visual inspection over the affected areas.



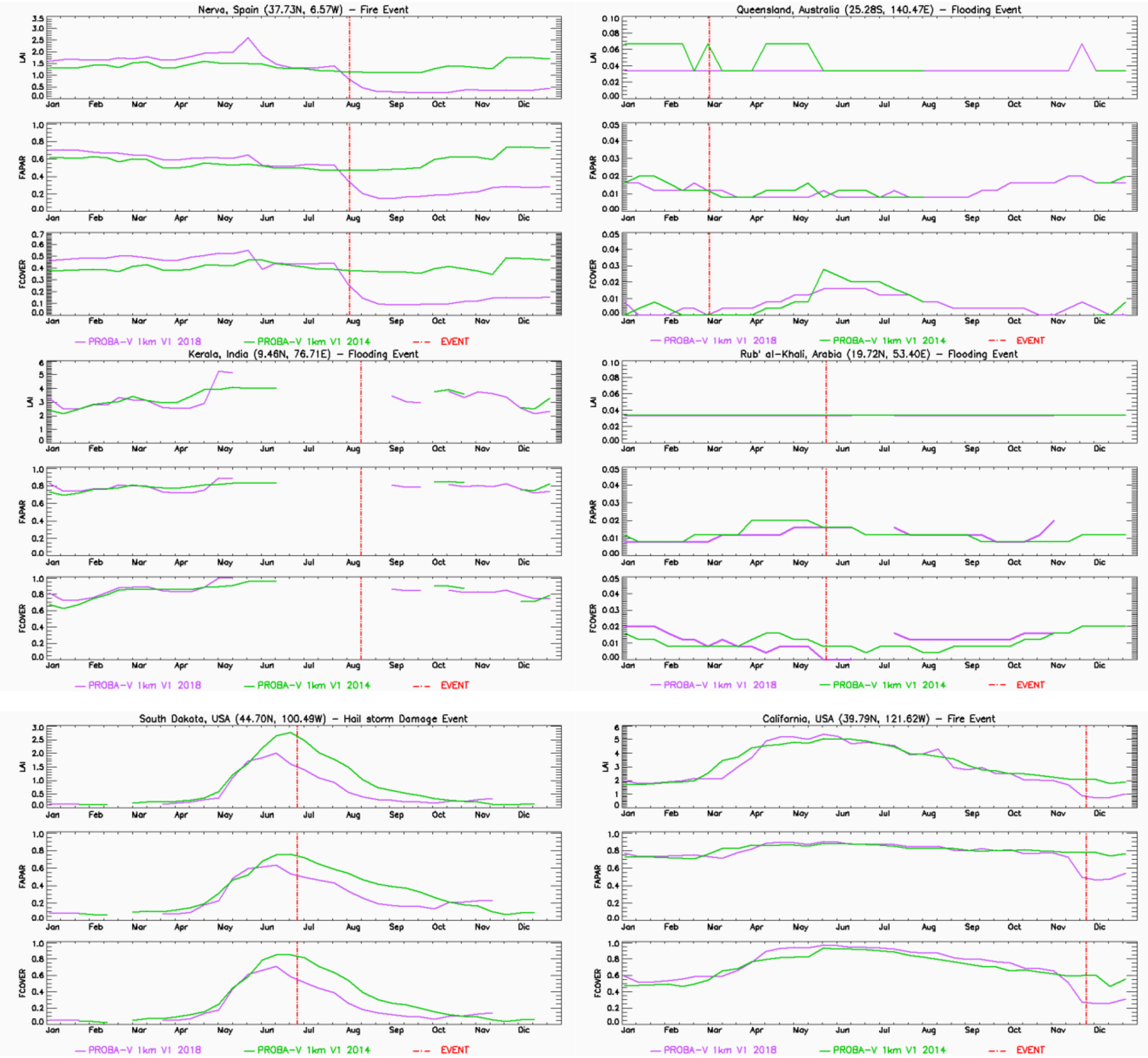
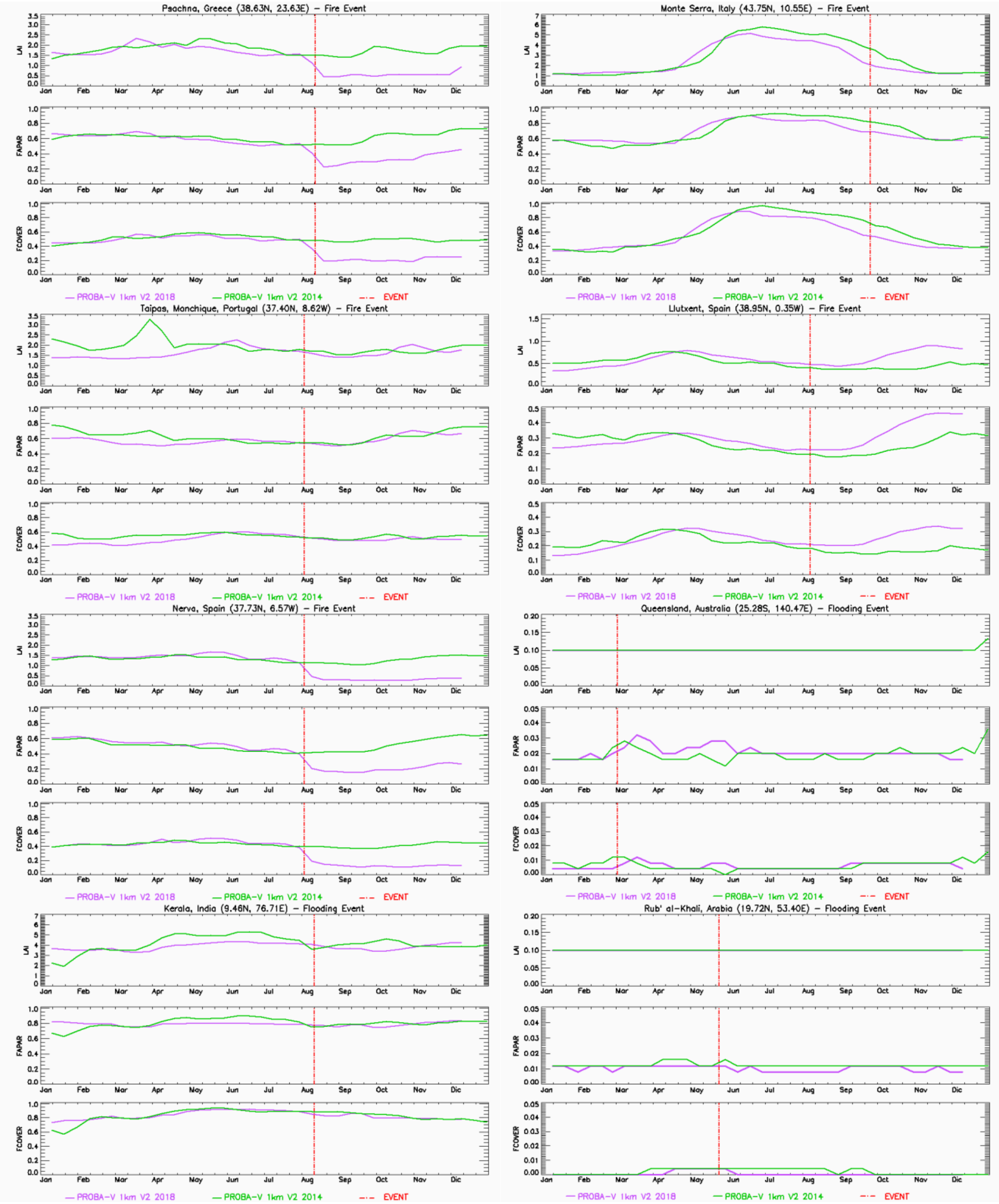


Figure 41: Temporal profiles of PROBA-V 1km V1 2018 (purple line) and 2014 year (green line) LAI (top) FAPAR (middle) and FCOVER (bottom) products over sites with specific events. Red dash-line indicates the event date.


Psachna, Greece (38.63N, 23.63E) – Fire Event
Monte Serra, Italy (43.75N, 10.55E) – Fire Event
Taipas, Monchique, Portugal (37.40N, 8.62W) – Fire Event
Llutxent, Spain (38.95N, 0.35W) – Fire Event
Nerva, Spain (37.73N, 6.57W) – Fire Event
Queensland, Australia (25.28S, 140.47E) – Flooding Event
Kerala, India (9.46N, 76.71E) – Flooding Event
Rub' al-Khali, Arabia (19.72N, 53.40E) – Flooding Event
LAI
FAPAR
FCOVER
PROBA-V 1km V2 2018
PROBA-V 1km V2 2014
EVENT

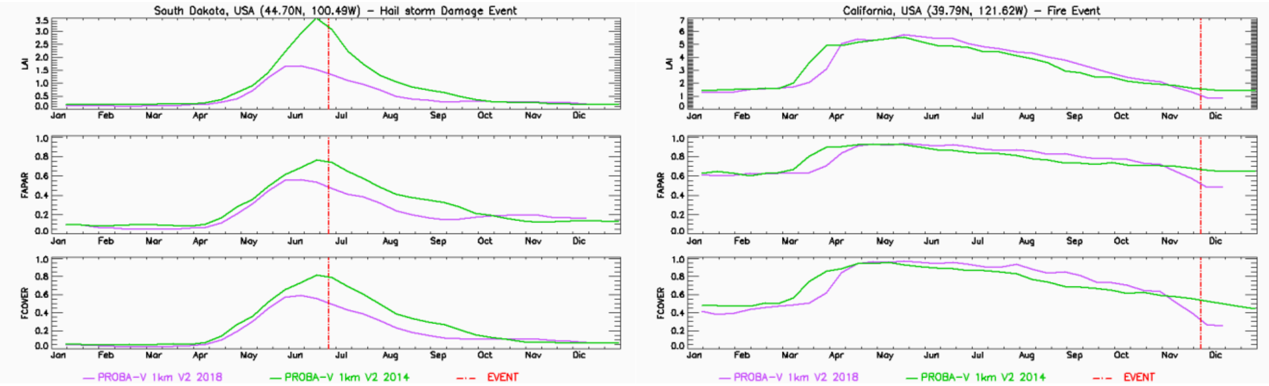


Figure 42: Temporal profiles of PROBA-V 1km V2 2018 (purple line) and 2014 year (green line) LAI (top) FAPAR (middle) and FCOVER (bottom) products over sites with specific events. Red dash-line indicates the event date.

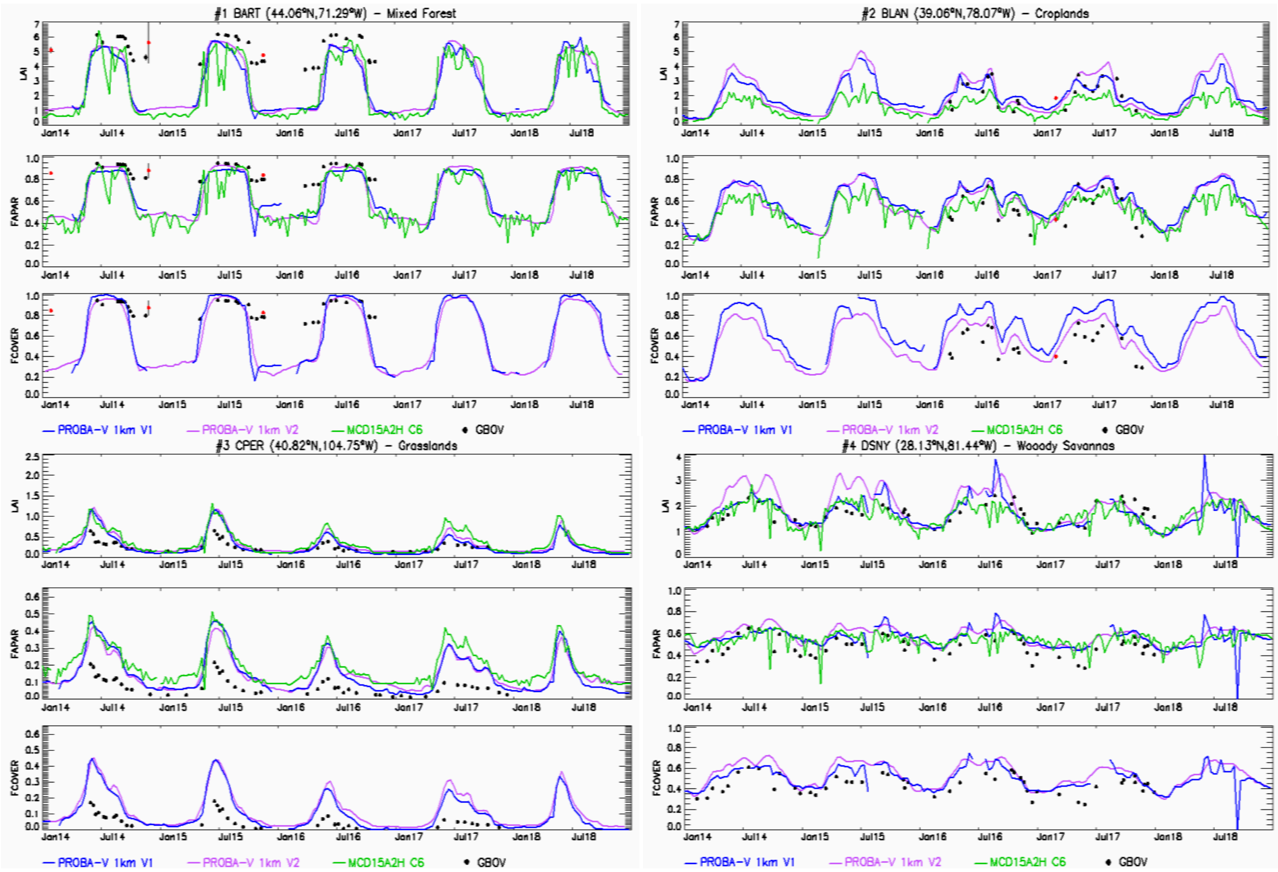
Main conclusions from Figure 41, Figure 42, and from ANNEX I and ANNEX II are:

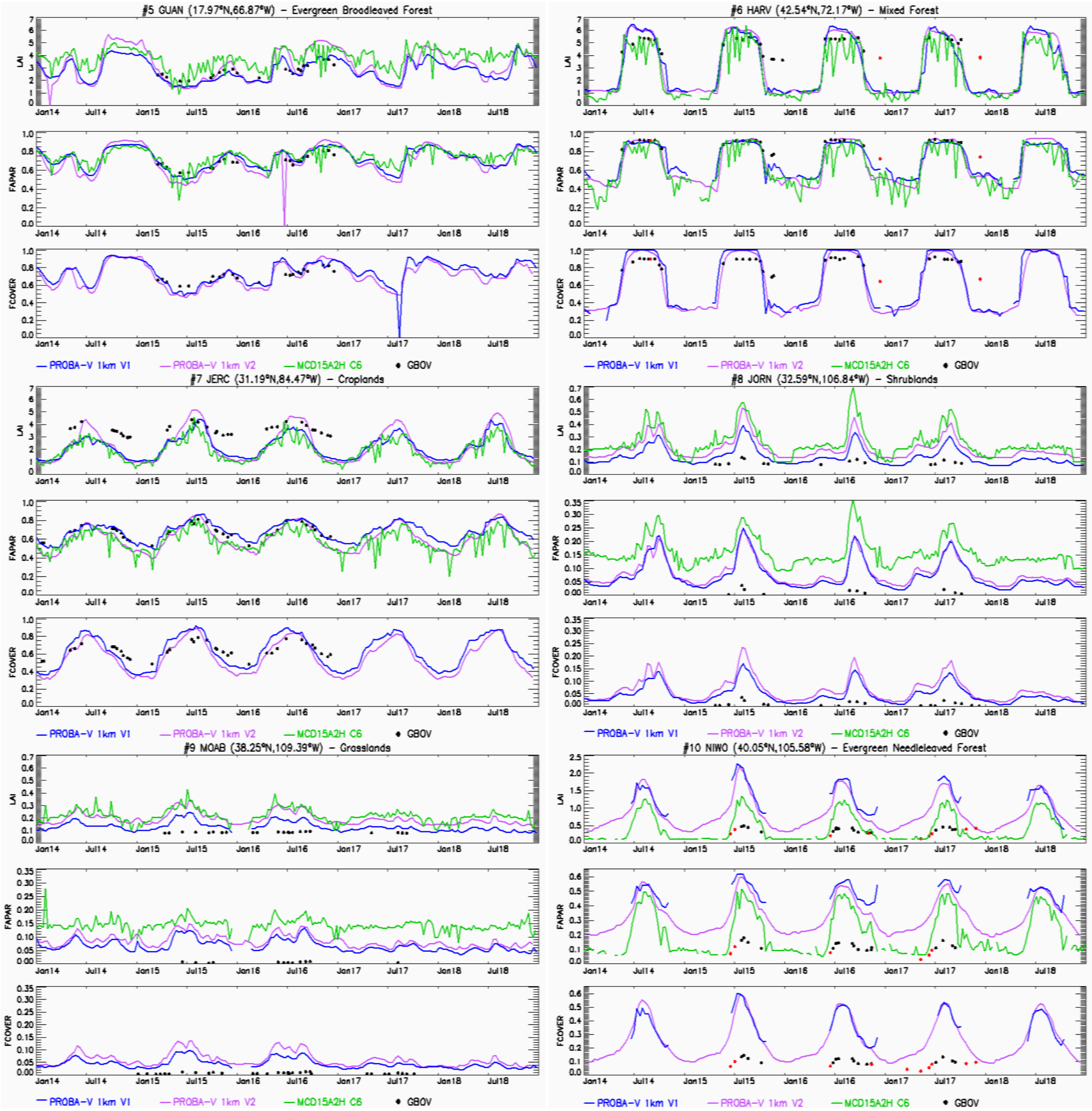
- For *Psachna*, *Nerva* and *California* the fire events were well captured by PROBA-V V1 and V2 (and MODIS C6, see ANNEX I), showing a significant decrease of LAI, FAPAR and FCOVER values since the event date. In *Taipas* and *Monte Serra*, a slight decrease of LAI, FAPAR and FCOVER values was also observed in both PROBA-V V1 and V2 products since the fire event. The effect of these fire events was clearly observed at the maps in ANNEX II.
- However, the PROBA-V V1 and V2 LAI, FAPAR, FCOVER products do not display any decrease in *Llutxent* but, one month after the event, they show an increase reaching values higher than in 2017; what can translate a significant recovery of the vegetation after the fire. MODIS C6 shows the same behavior than PROBA-V products. Note that NDVI 1km V2.2 products show a drop from values of 0.6 to 0.2 [see CGLOPS1_SQE2018_NDVI1km-V2.2]. Then, the fire event is well captured by the PROBA-V input data, and not reproduced by PROBA-V V1 and V2 algorithm.
- The flood events in *Queensland* (#6), *Kerala* (#7) and *Rub'al-Khai* (#8) are hard to visually delineate by PROBA-V V1 and V2 satellite products in the maps in ANNEX II. PROBA-V V1 provides gaps over large areas around the event locations. In case of *Queensland,* a slight increase in the FAPAR and FCOVER PROBA-V V2 retrievals was observed during the dekads after the flood event. A significant increase, six weeks after the flood, in *Queensland* was clearly reproduced by the input PROBA-V data, as showed in the NDVI 1km product [CGLOPS1_SQE2018_NDVI1km-V2.2]; the same increase is also visible on the MODIS products [ANNEX I. Temporal profiles of specific events for MODIS C6]. In case of *Kerala* and *Rub'al-Khai,* no significant changes were observed by PROBA-V V2 retrievals since the flood event dates.
- The effect of the hail storm damage event in *South Dakota*, was observed at the temporal profiles, with a significant decrease of the biophysical PROBA-V V1 and V2 values. The extent of the hail storm scar is clearly visible in the maps in ANNEX II.

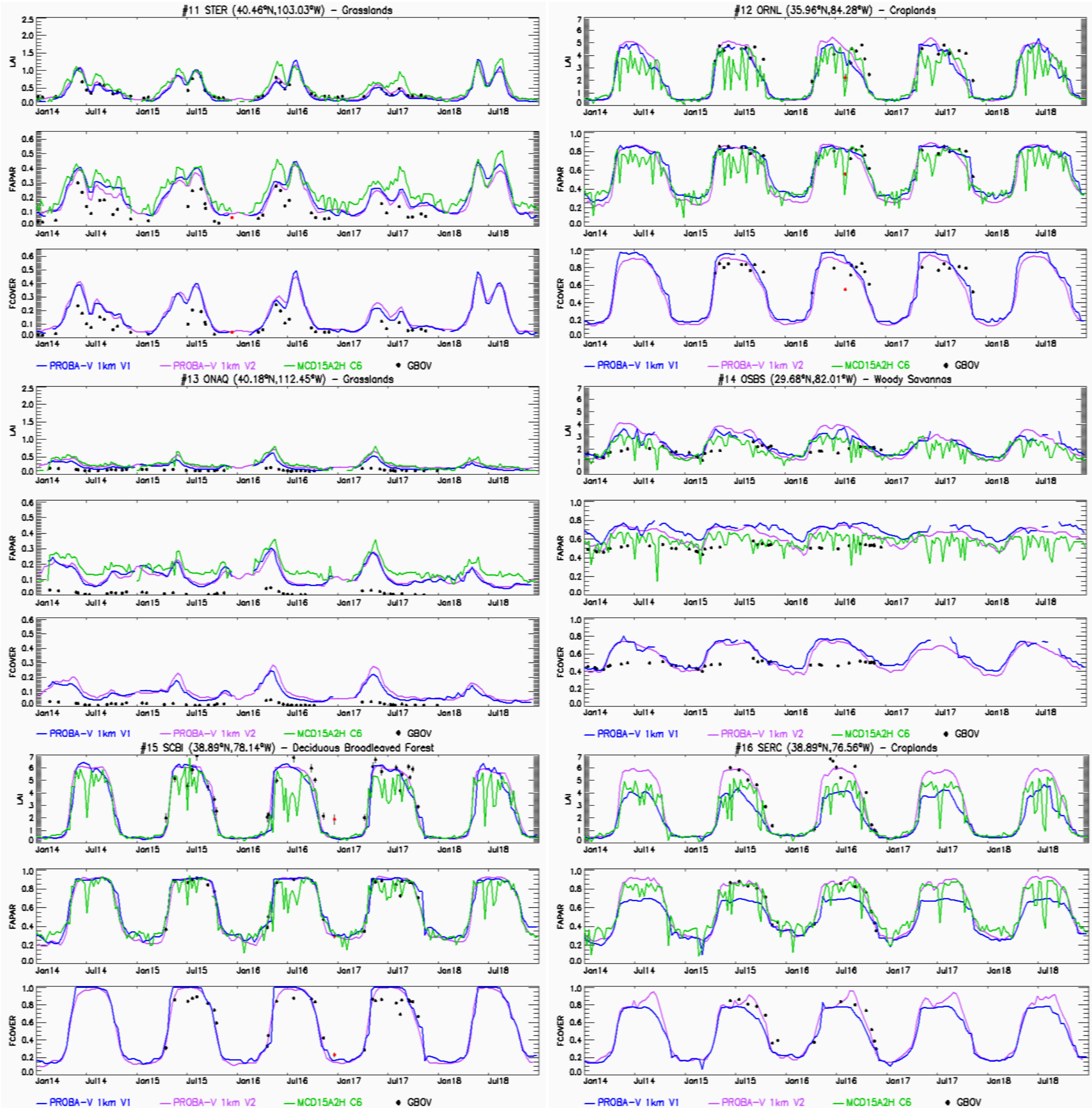
- In summary, similar temporal trends were found for V1 and V2. However, when missing data exists for V1, V2 displays value due to gap-filling algorithm using the climatology, which does not allow capturing the impact of such occasional events. A good example is the flooding in Kerala. This translates a known limitation of the gap-filling method based upon a climatology.

5.2.3 Temporal realism over GBOV sites

The realism of the temporal variations (Figure 43) of PROBA-V Collection 1km V1, V2 and MODIS C6 satellite products was evaluated over the 20 GBOV sites (Table 14) where multi-temporal ground-based maps are available during the 2014-2017 period. Note that the spatial resolution used is 3km x 3km (i.e., average values of 3x3 pixels in case of V1 and V2, 5x5 pixels in case of MODIS C6, and 9x9 pixels in case of GBOV). In case of GBOV, the ancillary quality indicator providing the number of the valid observations at the primary high-resolution (20m) was used, and 300m pixels with less than 70% of valid primary data were flagged in Figure 43 (red dots). Vertical bars correspond to GBOV uncertainties.




#5 GUAN (17.97°N,66.87°W) – Evergreen Broadleaved Forest
#6 HARV (42.54°N,72.17°W) – Mixed Forest
#7 JERC (31.19°N,84.47°W) – Croplands
#8 JORN (32.59°N,106.84°W) – Shrublands
#9 MOAB (38.25°N,109.39°W) – Grasslands
#10 NIWO (40.05°N,105.58°W) – Evergreen Needleleaved Forest
LAI
FAPAR
FCOVER
Jan14
Jul14
Jan15
Jul15
Jan16
Jul16
Jan17
Jul17
Jan18
Jul18
PROBA-V 1km V1
PROBA-V 1km V2
MCD15A2H C6
GBOV


#11 STER (40.46°N,103.03°W) – Grasslands
#12 ORNL (35.96°N,84.28°W) – Croplands
#13 ONAQ (40.18°N,112.45°W) – Grasslands
#14 OSBS (29.68°N,82.01°W) – Woody Savannas
#15 SCBI (38.89°N,78.14°W) – Deciduous Broadleaved Forest
#16 SERC (38.89°N,76.56°W) – Croplands
LAI
FAPAR
FCOVER
Jan14 Jul14 Jan15 Jul15 Jan16 Jul16 Jan17 Jul17 Jan18 Jul18
PROBA-V 1km V1
PROBA-V 1km V2
MCD15A2H C6
GBOV

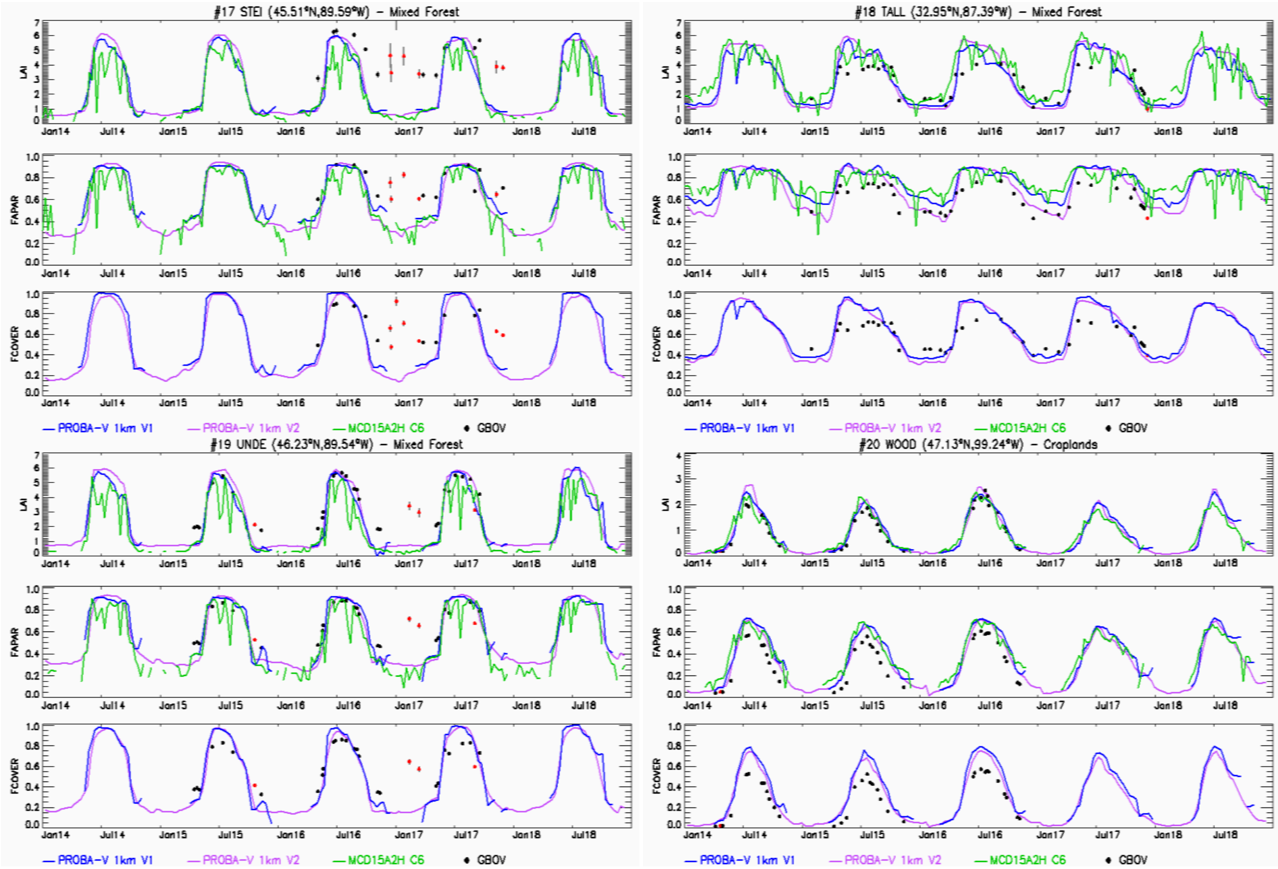


Figure 43: Temporal profiles of PROBA-V 1km V1 (blue), PROBA-V 1km V2 (purple) and MCD15A2H C6 (green) products over the 20 GBOV sits with availability of ground-based maps during the 2014-2018 period at 3km x 3km of spatial resolution. In case of GBOV, black dots correspond with average values with more than 70% of valid pixels at the primary high-resolution, and red dots with less than 70% of valid observations. Vertical bars in GBOV correspond to uncertainties.

Main conclusions from temporal profiles in Figure 43 are:

- PROBA-V 1km V1 and V2 (and MODIS C6) reproduce quite well the temporal variations of GBOV values for most of the sites (i.e. BLAN, CPER, DSNY, GUAN, HARV, JERC, NIWO, STER, ORNL, SCBI, SERC, TALL, UNDE, WOOD). However, in some cases (CPER, NIWO) large discrepancies in magnitude were found between all satellite products and GBOV ground-based values, mainly at the maximum peak of the vegetation cycle.
- Note that the use of the GBOV ancillary layer indicating the number of the valid observations at the primary resolution is strongly recommended to discard unreliable GBOV values as observed in STEI and UNDE forest sites. GBOV values at the degraded 300m resolution with less than 70% of high-resolution observations should be discarded.
- In few cases, such as BART forest site, satellite retrievals disagree with GBOV land products in winter time, probably because the illumination geometry was not considered in the multi-temporal up-scaling approach of GBOV algorithm [GBOV-ATBD-LP3-LP4-LP5].

So, it is also recommended to discard the GBOV LPs produced outside of the minimum and maximum DOY of each site.

- In some few cases (i.e., JORN, MOAB, ONAQ and OSBS) satellite products display some temporal seasonality whereas GBOV observations show almost flat temporal trajectories.
- Very low uncertainty of GBOV values was observed for most of the sites and dates (vertical bars are not visible), so these uncertainties could not be considered as representative. Only in few cases where less than 70% of valid high-resolution observations large uncertainty values were found (see, for instance red dots in BART and STEI).

5.2.4 Accuracy Assessment

Figure 44, Figure 45 and Figure 46 show the scatter-plots between LAI, FAPAR and FCOVER PROBA-V 1km V1, PROBA-V 1km V2 and MODIS C6 satellite products versus ground-based reference maps from GBOV database (https://land.copernicus.eu/global/gbov). The relevant statistics for each satellite product are summarized in Table 19, Table 20 and Table 21. The results per main biome type (Forest, Cultivated and grass/shrubs) are presented in ANNEX III. The direct comparison of the ground-based high-resolution maps and the PROBA-V V1 and V2 product was performed at the spatial resolution of 3x3 Collection 1km pixels that allows limiting the effects of point spread function and geometric accuracy (Morisette et al., 2006). Same spatial resolution (3km x 3km) was used for MODIS C6 products (i.3., 6x6 pixels).

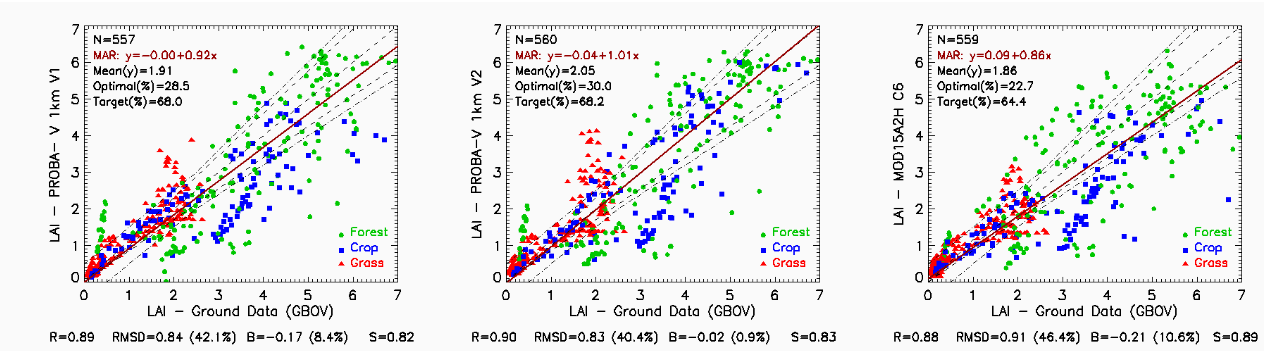


Figure 44: Comparison between satellite LAI products (PROBA-V 1km V1, PROBA-V 1km V2, MODIS C6) versus GBOV LAI ground-based maps for the 2014-2017 period. Forest stands for Broadleaf and Needle-leaf Forests, Crops stands for Cultivated and Grass refers to Herbaceous, Shrubs, and Savanna sites. Dashed lines correspond to the 1:1 line, optimal (GCOS) and target uncertainty levels, and continuous red line to the linear fit using Major Axis Regression (MAR).

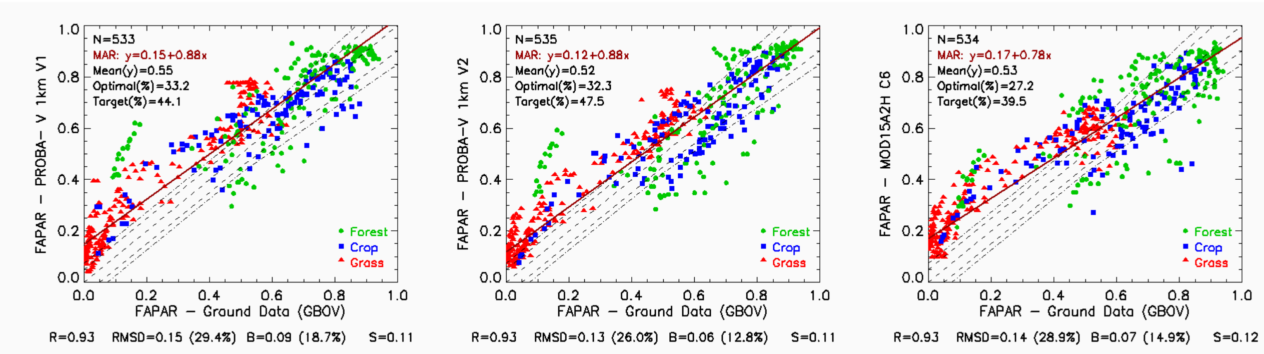


Figure 45: Same as Figure 44 for FAPAR products (PROBA-V 1km V1, PROBA-V 1km V2, MODIS C6) versus GBOV FAPAR ground-based maps for the 2014-2017 period.

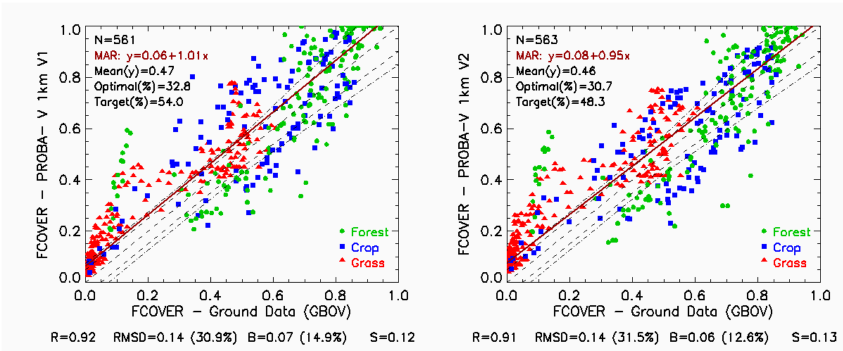


Figure 46: Same as Figure 44 for FCOVER products (PROBA-V 1km V1, PROBA-V 1km V2) versus GBOV FCOVER ground-based maps for the 2014-2017 period.

Table 19: Main statistics for PROBA-V 1km V1 LAI, FAPAR and FCOVER products versus ground-based maps over GBOV sites during the 2014-2017 period. Percentage of samples lying within the uncertainty optimal (GCOS), target and threshold pre-defined levels (Table 6) (blue) as well as the uncertainty levels for FAPAR and FCOVER recommended by the technical user group of Copernicus Global Land (Table 2) (purple) are displayed.

	PROBA-V 1km V1 vs Ground data					
	LAI		FAPAR		FCOVER	
N	557		533		561	
Correlation	0.89		0.93		0.92	
Bias	-0.17		0.09		0.07	
RMSD	0.84		0.15		0.14	
Offset	0.00		0.15		0.06	
Slope	0.92		0.88		1.01	
p-value	0.001		<0.001		0.540	
%optimal	28.5	-	33.2	18.8	32.8	10.5
%target	68.0	-	44.1	30.2	54.0	19.1
%threshold	77.0	-	56.1	43.7	66.5	41.2

Table 20: As in Table 19 for PROBA-V 1km V2 LAI, FAPAR and FCOVER products.

	PROBA-V 1km V2 vs Ground data					
	LAI		FAPAR		FCOVER	
N	560		535		563	
Correlation	0.90		0.93		0.91	
Bias	-0.02		0.06		0.06	
RMSD	0.83		0.13		0.14	
Offset	-0.04		0.12		0.08	
Slope	1.01		0.88		0.95	
p-value	0.578		<0.001		0.001	
%optimal	30.0	-	32.3	16.6	30.7	10.7
%target	68.2	-	47.5	30.1	48.3	22.6
%threshold	76.4	-	65.8	51.1	61.3	38.9

Table 21: As in Table 19 for MOD15A2H C6 LAI and FAPAR products.

	MOD15A2H C6 vs Ground data			
	LAI		FAPAR	
N	559		534	
Correlation	0.88		0.93	
Bias	-0.21		0.07	
RMSD	0.91		0.14	
Offset	0.09		0.17	
Slope	0.86		0.78	
p-value	0.001		<0.001	
%optimal	22.7	-	27.2	15.0
%target	64.4	-	39.5	27.0
%threshold	74.1	-	50.7	46.4

Main findings for LAI are:

- PROBA-V V1 shows an overall accuracy (RMSD) of 0.84 with a tendency to underestimate ground data (mean negative bias of -0.17, 8.4%, slope of the MAR regression of 0.92). 28.5% of the samples are fulfilling optimal consistency (i.e. GCOS requirements), with 68.0% of the samples within target level. Per biome type, PROBA-V V1 tends to underestimate GBOV values for forests (bias=-7.3%) and crops (-25.0%), and to overestimate grassland sites (11.5%).
- PROBA-V V2 shows slight improved overall results than V1 (RMSD=0.83), with almost no mean bias of -0.02 (0.9%) and remarkably good MAR relationship, close to the 1:1 line. Similar to PROBA-V V1, PROBA-V V2 negative bias was found forests (-2.0%) and crops (-13.2%), and positive grassland sites (18.8%).

- MODIS C6 provides the lowest accuracy (RMSD = 0.91), with negative bias of -0.21 (~10%). Large negative bias than PROBA-V was found for forests (-9.6%) and crops (-29.5%). As observed for PROBA-V products, positive bias (11.9%) was found for grassland sites.
- In summary, all satellite products tend to provide higher values than GBOV data for low LAI ranges, where grassland sites are mainly present.
- Comparison with GBOV LPs (RMSD=0.84 for V1 and RMSD=0.83 for V2) gives divergent results than the accuracy assessment exercises [GIOGL1_VR_LAIV1 CGLOPS1_QAR_LAI1km-PROBAV-V2] performed over another limited ground dataset, where RMSD values of 0.52 for V1 (Table 4) and 1.06 for V2 (Table 5) were found.

For FAPAR:

- PROBA-V V1 shows an overall accuracy of RMSD=0.15 and positive bias of 0.09 (~19%). 33.2% of PROBA-V V1 cases fulfilled GCOS requirements. In case of CGLOPS requirements, 18.8%, 30.2% and 43.7% of samples are within optimal, target and threshold levels. Positive bias was found for all biome type, which is lower than 10% for forests and crops and higher (46.1%) for grassland sites.
- As observed for LAI, PROBA-V V2 shows improved accuracy than PROBA-V V1, with RMSD of 0.13, low positive bias of 0.06 (12.8%) and 32.3% of samples within CGOS requirements. 16.6%, 30.1% and 51.1% of samples are within optimal, target and threshold CGLOPS requirement levels. Low mean bias was found for forests (4.3%) and crops (3.0%), whereas large positive bias (37.7%) was found for grassland sites.
- MODIS C6 FAPAR provides slight degraded accuracy than PROBA-V V2 but improved than PROBA-V V1 (RMSD=0.14). Positive mean bias of 0.07 (14.9%), with 27.2% of MODIS C6 cases within GCOS requirements. As observed for PROBA-V V2, low mean bias was found for forests (4.5%) and crops (3.2%), whereas large positive bias (43.8%) was found for grassland sites.
- In summary, all satellite products tend to provide higher values than GBOV data for low FAPAR ranges, where most of GBOV sites correspond with grassland sites and forests during the leaf-off season.
- Larger discrepancies were obtained in the comparison with GBOV LPs (RMSD=0.15 for V1 and RMSD=0.13 for V2) to that found in the accuracy assessment exercises [GIOGL1_VR_LAIV1 CGLOPS1_QAR_LAI1km-PROBAV-V2] performed over another limited ground dataset, where RMSD values of 0.11 for V1 (Table 4) and 0.1 for V2 (Table 5) were found.

Finally, for FCOVER:

- PROBA-V V1 shows an overall accuracy of RMSD=0.14 and positive bias of 0.07 (14.9%). Regarding CGLOPS requirements, 10.5%, 19.1% and 41.2% of samples are within the optimal, target and threshold levels. Positive bias was found for all biome type, which is low for forests (7.3%) and for crops (10.9%) and high (33.9%) for grassland sites.

- PROBA-V V2 shows almost identical results than PROBA-V V1, with RMSD=0.14 and positive bias of 0.06 (12.6%). As observed for FAPAR, low mean bias was found for forests (4.4%) and crops (2.6%), whereas large positive bias (38.7%) was found for grassland sites.
- For V1, similar discrepancies (RMSD=0.14) were found in the comparison with GBOV LPs than in the accuracy assessment exercise performed with another limited ground dataset [GIOGL1_QAR_LAI1km-V1] (Table 4). In case of V2, better agreement was found in the comparison with GBOV LPs (RMSD=0.14) to that found in the accuracy assessment [CGLOPS1_QAR_LAI1km-PROBAV-V2] against another limited ground dataset (RMSD=0.17) (Table 5).

6 CONCLUSIONS

The scientific quality evaluation of the PROBA-V LAI/FAPAR/FCOVER 1km V1 and V2 products during the whole 2018 year was conducted, adapting the procedure from the CEOS LPV best practices for validation of remote sensing LAI products as detailed in the CGLS Service Validation Plan. The main objective was to demonstrate that the recent PROBA-V V1 and V2 products keep the same quality level than the validated PROBA-V V1 and V2 products (2014). In addition, the consistency with SPOT/VGT V1 and V2 products (2012) was assessed. For that, several criteria of performance including completeness, spatial and temporal consistency, smoothness (intra-annual precision) and inter-annual were evaluated. Furthermore, temporal anomalies over cultivated areas in Europe were evaluated, as well as the realism of temporal trajectories over locations with specific events in 2018 (i.e., fire events, floods, hail storms). Finally, the accuracy was evaluated over 20 sites with multi-temporal ground-based maps coming from GBOV database available for the 2014-2017 period (https://land.copernicus.eu/global/gbov).

The main conclusions are summarized below:

- **Product Completeness**

Similar spatial distribution and temporal evolution of missing values in case of V1 and filled land pixels in case of V2 was found for the 2018, consistent with that found for the validated period (2014) and during the evaluation of the previous 2017 year. The main limitation was found over high latitudes and equatorial regions, which can be larger than 80% of missing values or filled land pixels.

The length of gaps was also consistent in the recent V1 products as compared to the validated. For V2 products, the length of filled gaps is very similar to the equivalent validated 2014 year, but some differences were found as compared to SPOT/VGT 2012.

- **Spatial Consistency**

Distribution of retrievals per biome type, evaluated over LANDVAL sites, show similar distribution for recent (PROBA-V V1 and V2 2018) and validated products (PROBA-V V1 and V2 2014 and SPOT/VGT V1 and V2 2012) LAI, FAPAR and FCOVER for all biome types. Histograms of residuals are generally centered at zero with some exceptions when PROBA-V products are compared to SPOT/VGT: EBF in case of LAI, and EBF and DBF in case of FCOVER.

- **Temporal Consistency**

Globally, the cross-correlations between recent PROBA-V V1 and V2 and validated PROBA-V and SPOT/VGT V1 and V2 temporal variations, computed over LANDVAL sites, were higher than 0.8 typically in more than 60% of the sites for V1 and more than 70% for V2 for all biome types with just the exception in EBF and low or non-vegetated biomes (Herbaceous and SBA) where lower correlations were observed.

Temporal trajectories of average values over cropland areas in 2018 compared with 2014 show the effect of the summer drought of 2018 for most of the European countries, with a delay in the start of the crop season and lower average values. Furthermore, the exceptionally warm and relatively wet conditions over some areas (i.e., Portugal) were satisfactory reproduced, with higher biophysical values in 2018 compared with 2014.

Temporal variations of PROBA-V V1 and V2 (and MODIS C6) reproduce quite well the impact of fires showing a decrease of LAI, FAPAR and FCOVER values for most of the events.

PROBA-V V1 and V2 (and MODIS C6) fit properly the GBOV variations in time and magnitude for most of the sites, with the exceptions of few cases where large discrepancies in magnitude were found. In few cases, satellite retrievals and GBOV observations disagree in winter time, probably because the illumination geometry was not considered in the multi-temporal up-scaling approach of GBOV algorithm. In few other cases, PROBA-V and MODIS products display seasonal variations while GBOV database shows flat temporal evolution. GBOV values produced outside of the minimum and maximum DOY of each site and GBOV values obtained at 300m resolution with less than 70% of high-resolution observations should be discarded. Also note that GBOV uncertainties are not relevant, since very low values were found.

- **Inter- Annual Precision**

PROBA-V V1 recent products (2018) versus validated PROBA-V V1 products (2014) show median absolute deviation of anomalies of 0.081 (7.1%), 0.022 (6.6%) and 0.024 (8.1%) for LAI, FAPAR and FCOVER, respectively. For V2 products, PROBA-V V2 2018 versus validated PROBA-V V2 products (2014) show, as expected, better results than V1 with median absolute deviation of anomalies of 0.051 (4.5%), 0.015 (4.5%) and 0.013 (4.5%) for LAI, FAPAR and FCOVER, respectively. For both versions, the results match the GCOS requirements in terms of stability for LAI, and close to GCOS requirements for FAPAR.

As expected, larger median absolute deviations of anomalies were found when comparing PROBA-V (2018) versus SPOT/VGT (2012) due to the additional impact of the change of sensor. The increase of the median absolute deviation for two years with sensor transition was mainly noticed in V2.

- **Intra- Annual Precision**

Recent PROBA-V 1km V1 and V2 product shows that the precision at short time scale is preserved during the 2018 year, with almost identical intra-annual precision (smoothness) than PROBA-V for 2014 and SPOT/VGT for 2012. Note that V2 products display smoother trajectories.

- **Statistical Consistency**

The comparison over the global LANDVAL network of sites of recent PROBA-V V1 and V2 (2018) products with the validated year (2014) shows almost no mean bias (<0.3% for V1, and <3% for V2) and low RMSD values (for V1 RMSD= 0.45/0.08/0.09 for LAI/FAPAR/FCOVER and for V2

RMSD=0.4/0.07/0.07 for LAI/FAPAR/FCOVER). This demonstrates that the quality of the 2018 V1 and V2 products is preserved as compared to the validated (2014) PROBA-V products.

The comparison between the recent PROBA-V V1 and V2 (2018) and the reference SPOT/VGT products (2012) shows good correlations (0.94-0.5 for both versions), and low RMSD values (RMSD of 0.51/0.09/0.11 for LAI/FAPAR/FCOVER V1 and 0.4/0.07/0.07 for LAI/FAPAR/FCOVER V2). For V1, almost no bias was found for LAI (0.1%) and FAPAR (-1.3%) whereas systematic positive bias was found for FCOVER (5%), mainly for medium and high ranges. In case of V2, systematic positive deviations were observed for FAPAR (relative bias 5.5%), and low positive bias for LAI (1.7%) and FCOVER (1.2%).

In summary, the change of sensor from SPOT/VGT to PROBA-V could introduce positive bias (PROBA-V > SPOT/VGT) of around 5% for FCOVER V1 and FAPAR V2.

- **Accuracy Assessment**

Compared with GBOV multi-temporal ground-based maps during the 2014-2017 period, PROBA-V Collection 1km V1 products shows an overall accuracy (RMSD) of 0.84, 0.15 and 0.14 for LAI, FAPAR and FCOVER, respectively. Around 30% of samples achieved GCOS requirements. In case of CGLS requirements, 18.8%/30.2%/43.7% of samples achieved optimal/target/threshold levels for FAPAR and 10.5%/19.1%/41.2% for FCOVER.

PROBA-V Collection 1km V2 shows improved accuracy than V1 with RMSD values of 0.83, 0.13 and 0.14 for LAI, FAPAR and FCOVER. Around 30% of samples achieved GCOS requirements. In case of CGLS requirements, 16.6%/30.1%/51.1% of samples achieved optimal/target/threshold levels for FAPAR and 10.7%/22.6%/38.9% for FCOVER.

The accuracy (RMSD) of MODIS C6 LAI/FAPAR products was 0.91/0.14 compared with GBOV ground-based maps during the 2014-2017 period.

All satellite products tend to provide higher values than GBOV data for low ranges, where the grassland biome type is mainly affected, as well as forests sites during the leaf-off season.

***Note*: the GBOV database has not been yet validated by independent expert and, as such, cannot be considered yet as reliable validation reference dataset.**

Concluding remarks

This Scientific Quality Evaluation demonstrates that the recent PROBA-V Collection 1km V1 and V2 products, evaluated during the 2018 year, keep a similar level of quality than the validated PROBA-V Collection 1km products (2014) and the reference SPOT/VGT (year 2012) products for all variables. However, the transition from SPOT/VGT to PROBA-V seems to introduce systematic discrepancies (around 5% of positive bias) as well as an impact in the inter-annual precision, mainly for FCOVER in V1 and for FAPAR in V2. The regional analysis shows that PROBA-V V1 and V2 2018 products reproduce well the changes due to drought and wet conditions in Europe, as well as the impact of specific environmental events around the globe and multi-temporal ground-based maps coming from GBOV database (20 NEON sites in USA). The accuracy assessment over 20 GBOV sites with availability of multi-temporal ground-based during the 2014-2017 period shows overall discrepancies (RMSD) of 0.84/0.15/0.14 for PROBA-V 1 km V1 LAI/FAPAR/FCOVER. PROBA-V 1 km V2 shows slight improved accuracy than V1 with RMSD values of 0.83/0.13/0.14 for LAI/FAPAR/FCOVER. Table 22 summarizes the main results for V1 and Table 23 for V2 products:

Table 22: Summary of Product Evaluation (PROBA-V V1). The plus (minus) symbol means that the product has a good (poor) performance according to this criterion.

QA Criteria	Performance	Comments
Product Completeness	-	Main limitations over northern latitudes in wintertime and equatorial areas. Highly affected the Needle-leaf forest biome and northern regions.
Spatial Consistency	±	Similar distribution of retrievals between recent and validated Collection 1km Version 1 products for all biome types showing large discrepancies for EBF.
Temporal Consistency	+	Cross-correlations between recent and validated Collection 1km V1 products higher than 0.8 in more than 60% of samples for all biomes except in EBF, Herbaceous and SBA. Specific events and GBOV multi-temporal ground-based maps are temporally well reproduced in most of cases. Similar temporal variations between PROBA-V V2, PROBA-V V1 and MODIS C6.
Intra-Annual Precision	+	Very low short-time variability (smooth temporal profiles) as for 2014.
Inter-Annual Precision	+	Median absolute deviation of anomalies (95^{th} and 5^{th} percentiles) between PROBA-V (2018 vs 2014) is 0.081 (7.1%) for LAI, 0.022 (6.6%) for FAPAR and 0.024 (8.1%) for FCOVER matching the GCOS stability requirements for LAI and close for FAPAR. Slightly degraded performances as compared to SPOT/VGT (2012) reference for LAI (0.077, 6.7%), FAPAR (0.023, 7.1%) and FCOVER (0.025, 8.6%).
Statistical Consistency	±	PROBA-V 2018 vs PROBA-V 2014: •LAI: R=0.95, RMSD=0.45, Bias=0.1%, 45% (87%) optimal (target) •FAPAR: R=0.96, RMSD=0.08, Bias=0.3%, 67% (79%) optimal (target) •FCOVER: R=0.95, RMSD=0.09, Bias=0.2%, 67% (78%) optimal (target) PROBA-V 2018 vs SPOT/VGT 2012: •LAI: R=0.94, RMSD=0.51, Bias=0.1%, 42% (84%) optimal (target) •FAPAR: R=0.95, RMSD=0.09, Bias=-1.3%, 65% (76%) optimal (target) •FCOVER: R=0.94, RMSD=0.11, Bias=4.6%, 63% (74%) optimal (target)
Accuracy	±	20 GBOV sites, 2014-2017 period: •LAI: N=557, R=0.89, RMSD=0.84, Bias=-0.17 (8.4%), 28.5% GCOS. •FAPAR: N=533, R=0.93, RMSD=0.15, Bias=0.09 (18.7%), 33.2% GCOS. 18.8%/30.2%/43.7% CGLOPS optimal/target/threshold. •FCOVER: N=561, R=0.92, RMSD=0.14, Bias=0.07 (14.9%). 10.5%/19.1%/41.0% CGLOPS optimal/target/threshold.

Table 23: Summary of Product Evaluation (PROBA-V 1 km V2). 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 PROBA-V V2 products. The filled land pixels are introduced mainly over northern latitudes in wintertime and equatorial areas. Needle-leaf forest biome and northern regions have the most quantity of filled land pixels.
Spatial Consistency	±	Similar distribution of retrievals between recent and validated Collection 1km Version 2 products for all biome types showing small discrepancies for EBF and NLF.
Temporal Consistency	+	Cross-correlations between recent and validated Collection 1km V2 products higher than 0.8 in more than 70% of samples for all biomes except in EBF, Herbaceous and SBA. Higher correlations than for 1km V1 products for all biomes. Specific events and GBOV multi-temporal ground-based maps are temporally well reproduced in most of cases. Similar temporal variations between PROBA-V V2, PROBA-V V1 and MODIS C6.
Intra-Annual Precision	+	Very low short-time variability (smooth temporal profiles) as for 2014, better than PROBA-V V1.
Inter-Annual Precision	+	Median absolute deviation of anomalies (95th and 5th percentiles) between PROBA-V 2018 vs 2014 of 0.051 (4.5%) for LAI, (0.015, 4.5%) for FAPAR and 0.013 (4.5%) FCOVER matching the GCOS stability requirements. Degraded performances (up to 100% higher) were obtained when comparing with SPOT/VGT (2012) for LAI (0.076, 6.7%), FAPAR (0.025, 7.4%) and FCOVER (0.019, 6.4%).
Statistical Consistency	±	PROBA-V 2018 vs PROBA-V 2014: •LAI: R=0.97, RMSD=0.4, Bias=-2.9%, 55% (91%) optimal (target) •FAPAR: R=0.97, RMSD=0.07, Bias=1.1%, 72% (82%) optimal (target) •FCOVER: R=0.96, RMSD=0.07, Bias=0.2%, 72% (83%) optimal (target) PROBA-V 2018 vs SPOT/VGT 2012: •LAI: R=0.93, RMSD=0.43, Bias=1.7%, 25% (88%) optimal (target) •FAPAR: R=0.95, RMSD=0.08, Bias=5.5%, 66% (78%) optimal (target) •FCOVER: R=0.94, RMSD=0.08, Bias=1.2%, 69% (79%) optimal (target)
Accuracy	±	20 GBOV sites, 2014-2017 period: •LAI: N=560, R=0.90, RMSD=0.83, Bias=-0.02 (0.9%), 30.0% GCOS. •FAPAR: N=535, R=0.93, RMSD=0.13, Bias=0.06 (12.8%), 32.3% GCOS. 16.6%/30.1%/51.1% CGLOPS optimal/target/threshold. •FCOVER: N=563, R=0.91, RMSD=0.14, Bias=0.06 (12.6%). 10.7%/22.6%/38.9% CGLOPS optimal/target/threshold.

7 RECOMMENDATIONS

Based upon these results, it is recommended to upgrade the status of the LAI, FAPAR, FCOVER Collection 1km Version 2 products to "operational" while informing the users that a positive bias, due to the transition between SPOT/VGT and PROBA-V, might contribute to the observed inter-annual variations.

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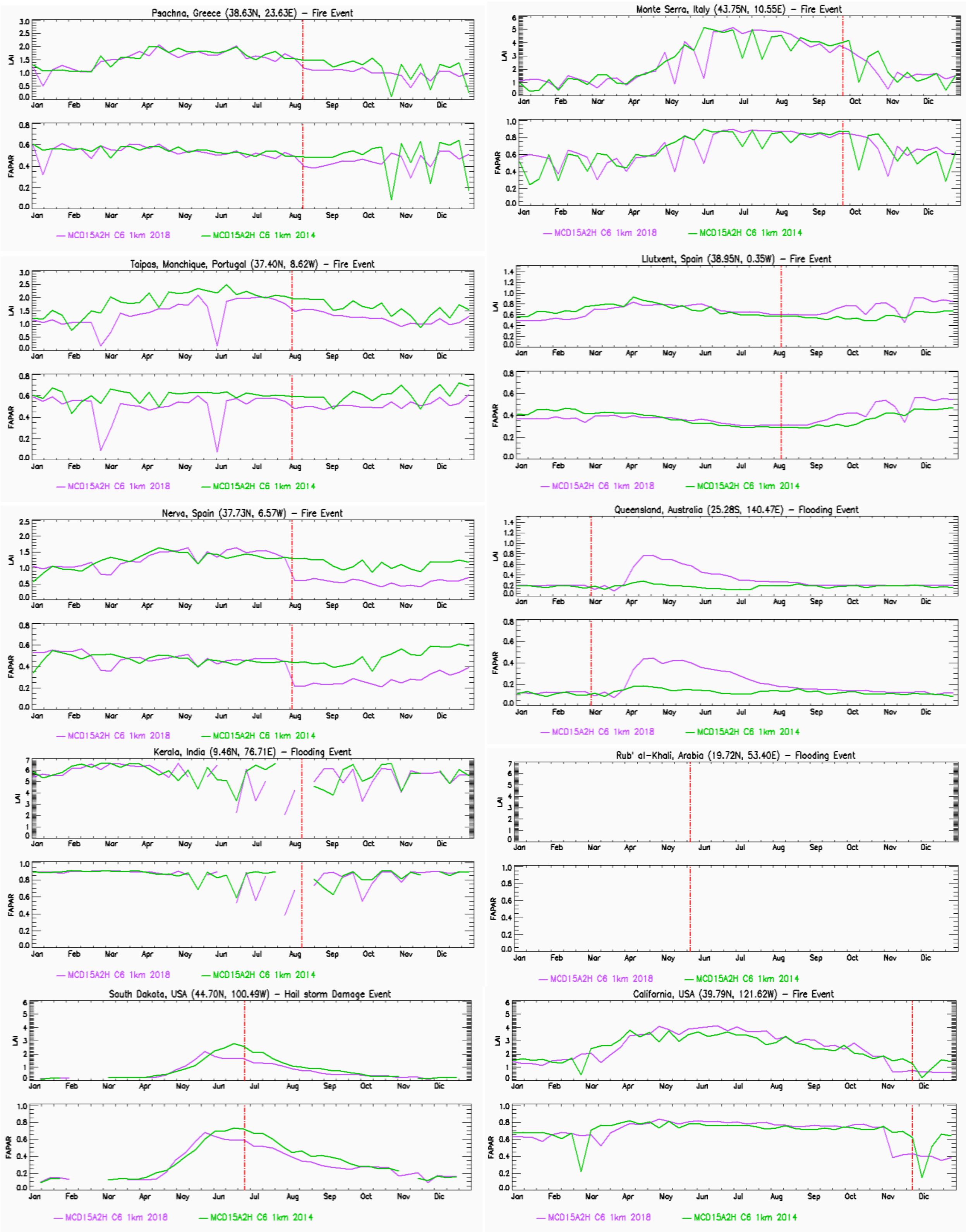
ANNEX I. TEMPORAL PROFILES OF SPECIFIC EVENTS FOR MODIS C6



ANNEX II. MAPS OVER OF PROBA-V 1KM V1 & V2 LAI, FAPAR AND FCOVER PRODUCTS OVER SPECIFIC EVENTS

PROBA-V Collection 1km V1

- LAI

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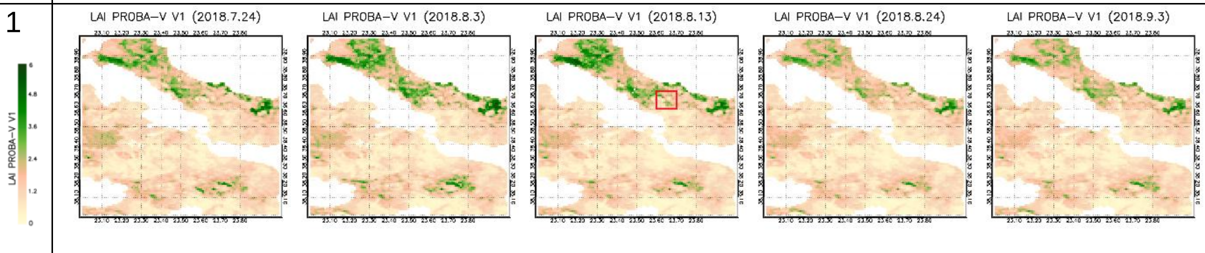
<tr><td>1</td><td colspan="3">
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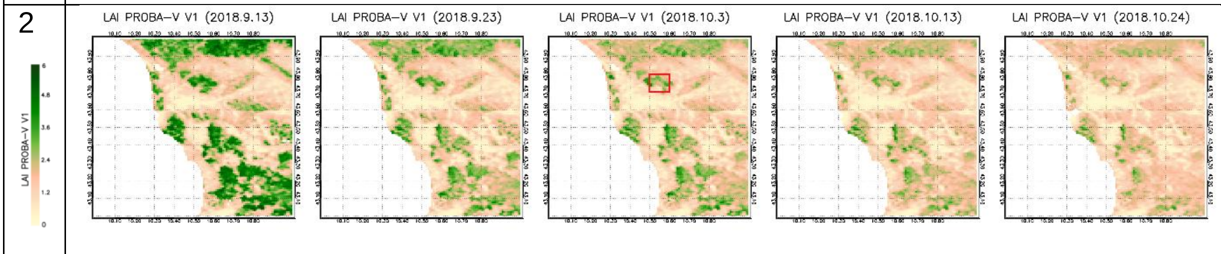
<tr><td>2</td><td colspan="3">
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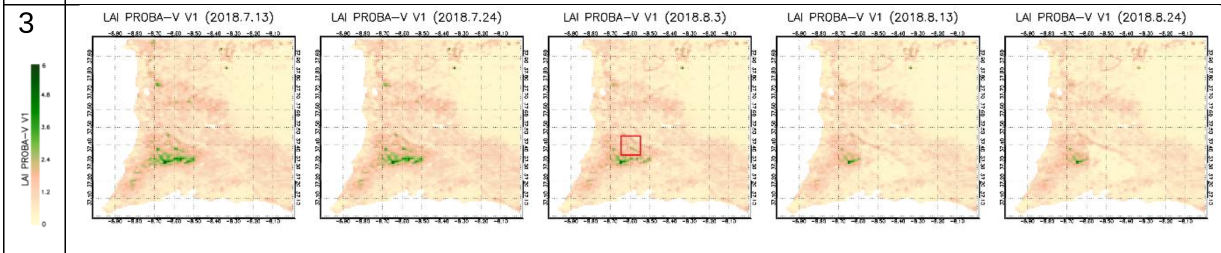
<tr><td>3</td><td colspan="3">
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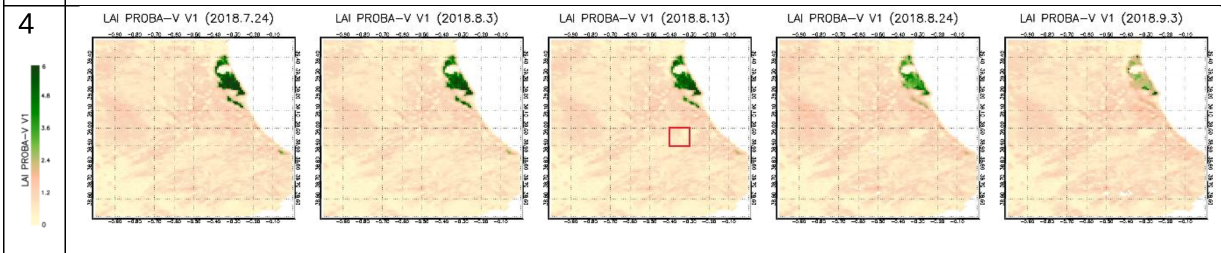
<tr><td>4</td><td colspan="3">
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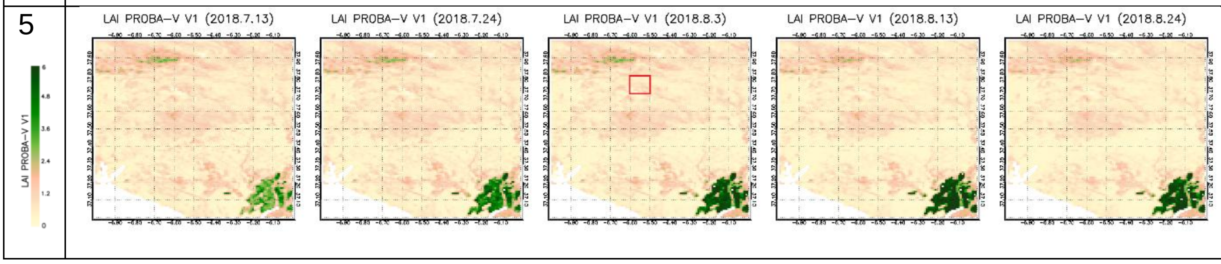
<tr><td>5</td><td colspan="3">
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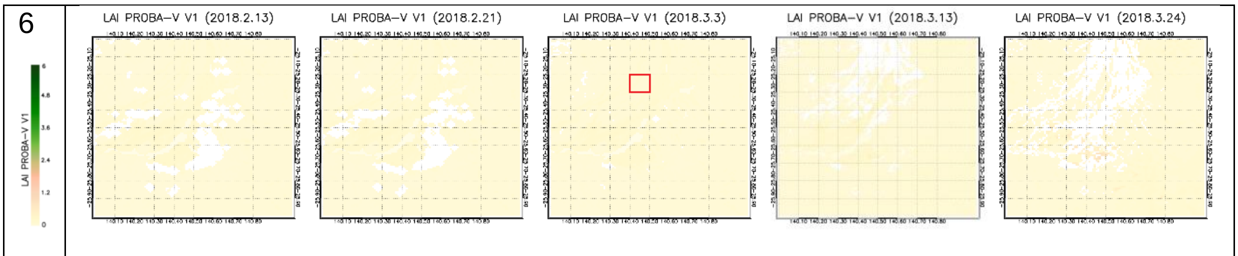
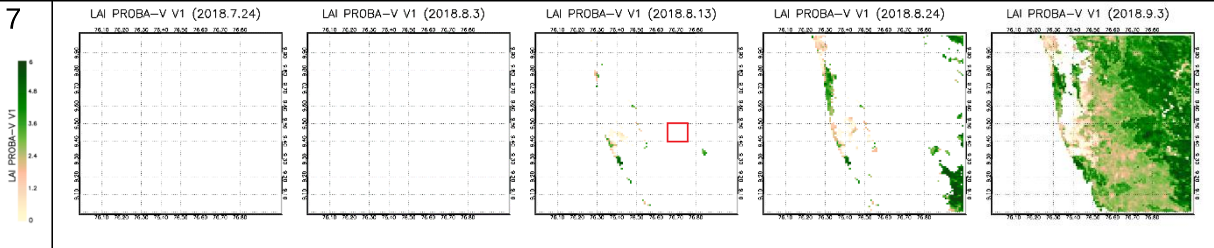
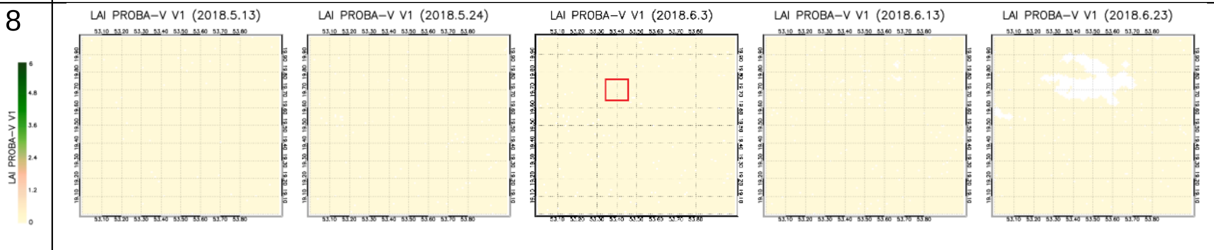
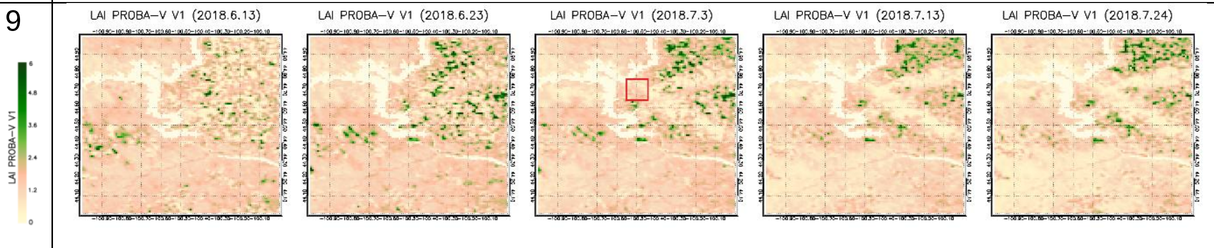
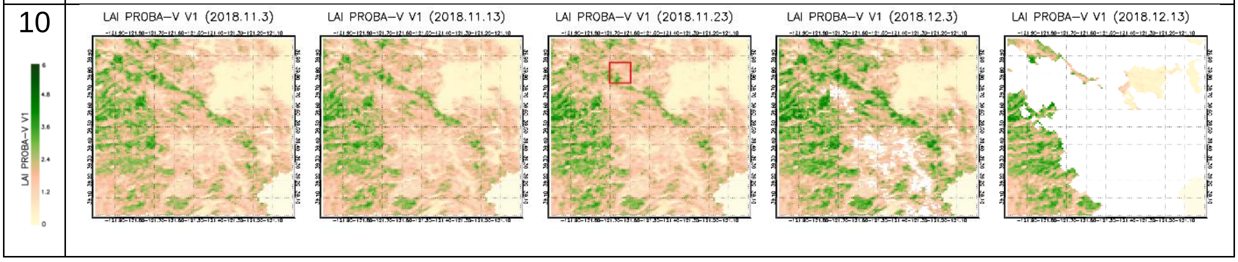
6	
7	
8	
9	
10	

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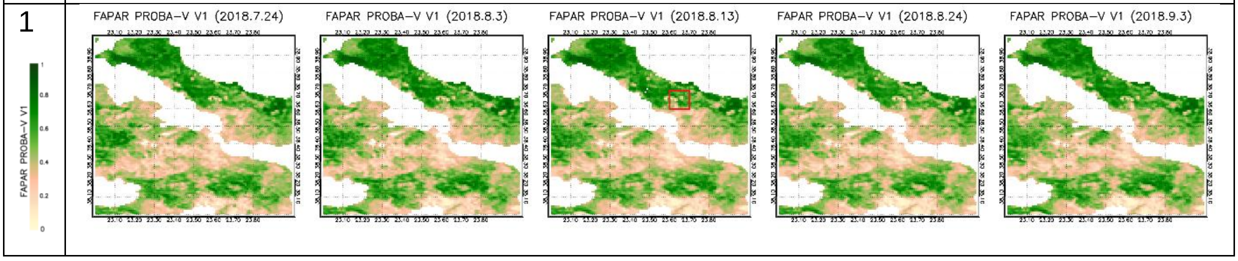
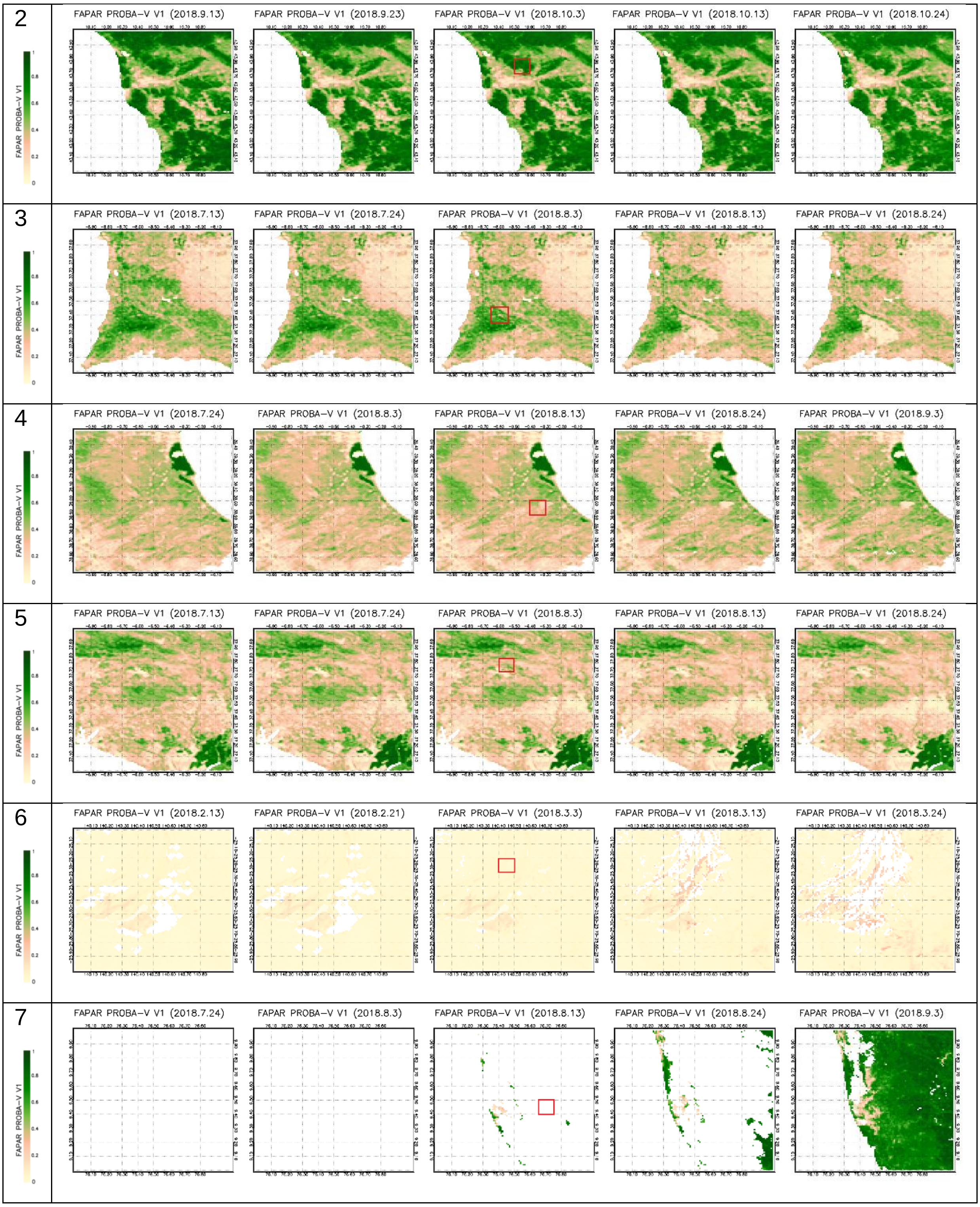
1			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FAPAR PROBA–V V1 (2018.9.23)
FAPAR PROBA–V V1 (2018.10.3)
FAPAR PROBA–V V1 (2018.10.13)
FAPAR PROBA–V V1 (2018.10.24)
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FAPAR PROBA–V V1
FAPAR PROBA–V V1 (2018.7.13)
FAPAR PROBA–V V1 (2018.7.24)
FAPAR PROBA–V V1 (2018.8.3)
FAPAR PROBA–V V1 (2018.8.13)
FAPAR PROBA–V V1 (2018.8.24)
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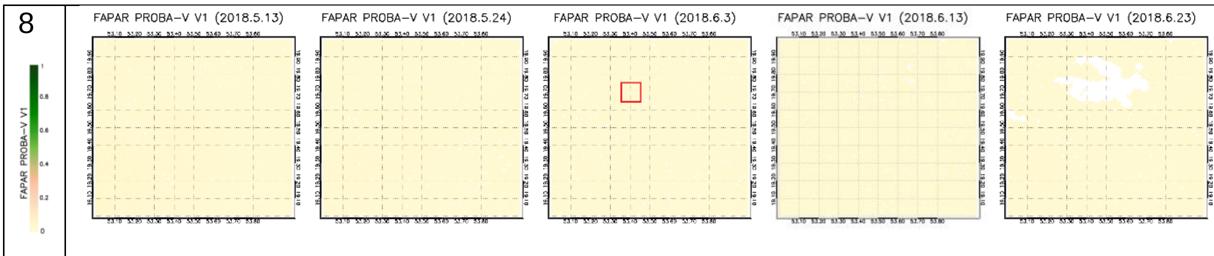
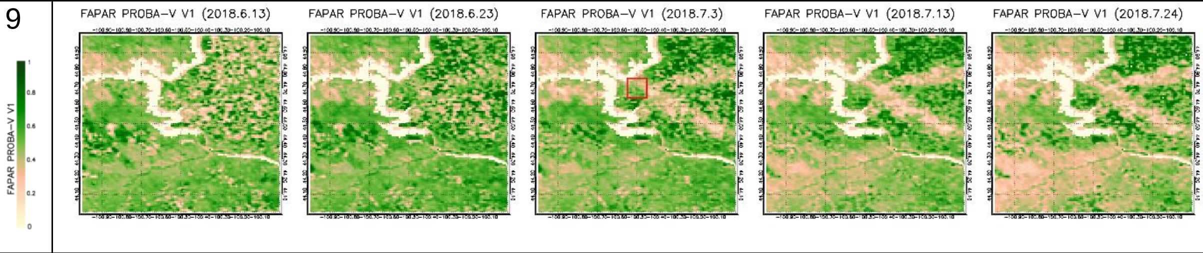
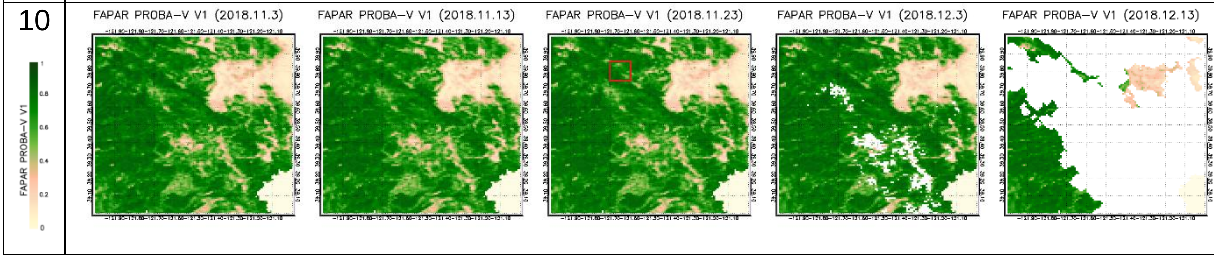
FAPAR PROBA–V V1
FAPAR PROBA–V V1 (2018.7.24)
FAPAR PROBA–V V1 (2018.8.3)
FAPAR PROBA–V V1 (2018.8.13)
FAPAR PROBA–V V1 (2018.8.24)
FAPAR PROBA–V V1 (2018.9.3)
5
FAPAR PROBA–V V1
FAPAR PROBA–V V1 (2018.7.13)
FAPAR PROBA–V V1 (2018.7.24)
FAPAR PROBA–V V1 (2018.8.3)
FAPAR PROBA–V V1 (2018.8.13)
FAPAR PROBA–V V1 (2018.8.24)
6
FAPAR PROBA–V V1
FAPAR PROBA–V V1 (2018.2.13)
FAPAR PROBA–V V1 (2018.2.21)
FAPAR PROBA–V V1 (2018.3.3)
FAPAR PROBA–V V1 (2018.3.13)
FAPAR PROBA–V V1 (2018.3.24)
7
FAPAR PROBA–V V1
FAPAR PROBA–V V1 (2018.7.24)
FAPAR PROBA–V V1 (2018.8.3)
FAPAR PROBA–V V1 (2018.8.13)
FAPAR PROBA–V V1 (2018.8.24)
FAPAR PROBA–V V1 (2018.9.3)

8	
9	
10	

- FCOVER

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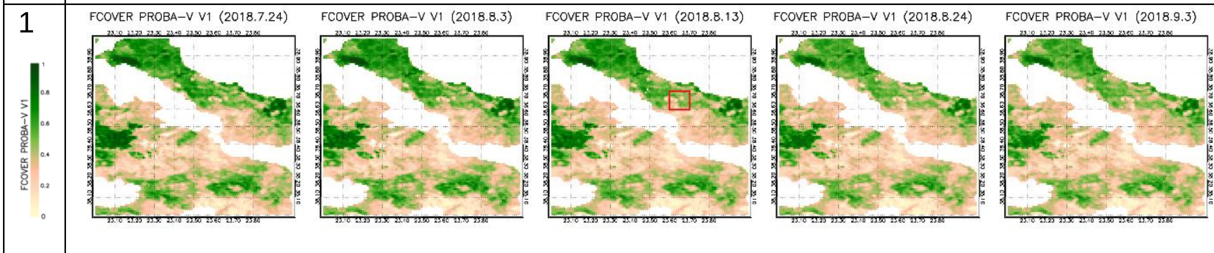
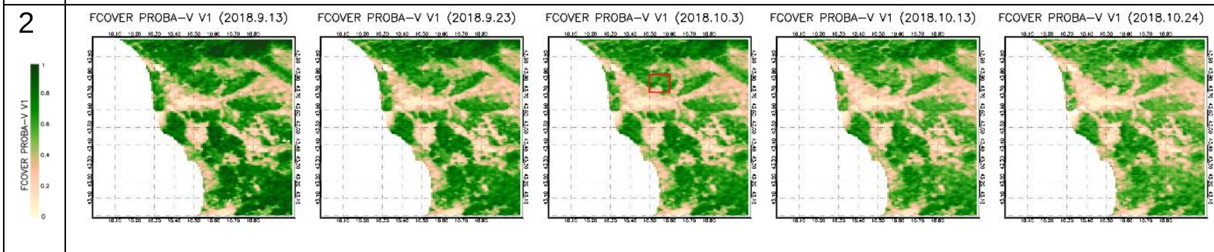
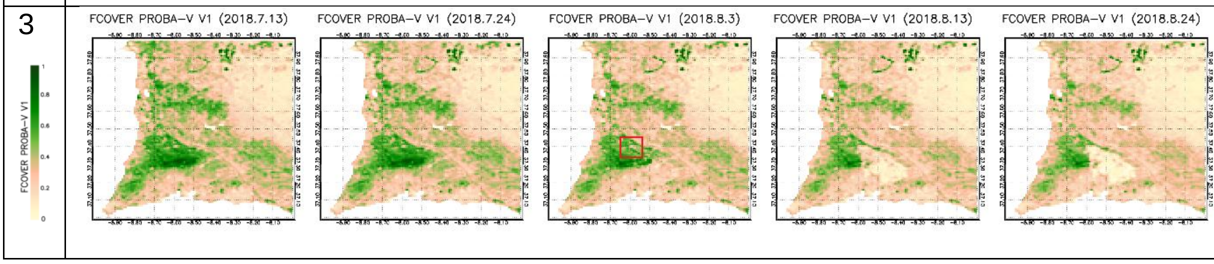
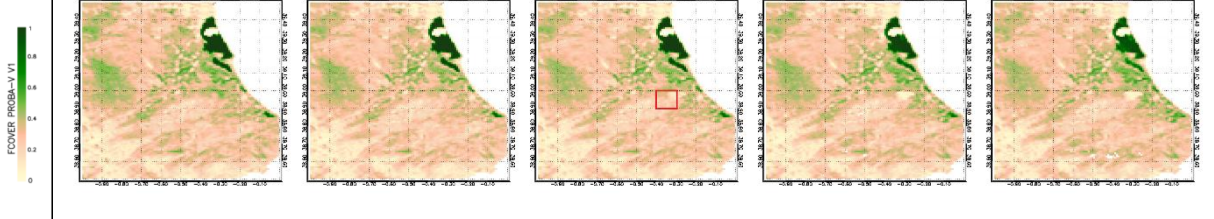
1			
2			
3			

4	FCOVER PROBA–V V1
FCOVER PROBA–V V1 (2018.7.24)
FCOVER PROBA–V V1 (2018.8.3)
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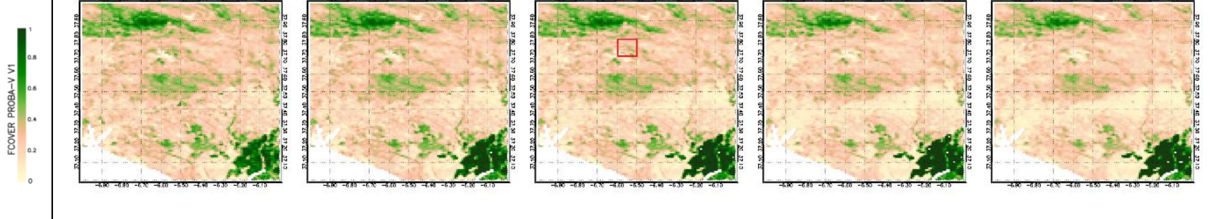
5	FCOVER PROBA–V V1
FCOVER PROBA–V V1 (2018.7.13)
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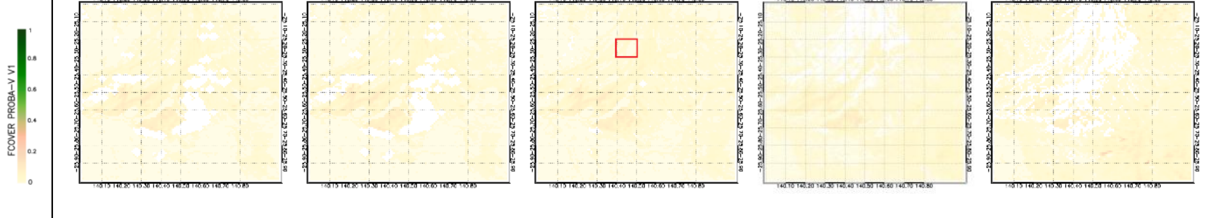
6	FCOVER PROBA–V V1
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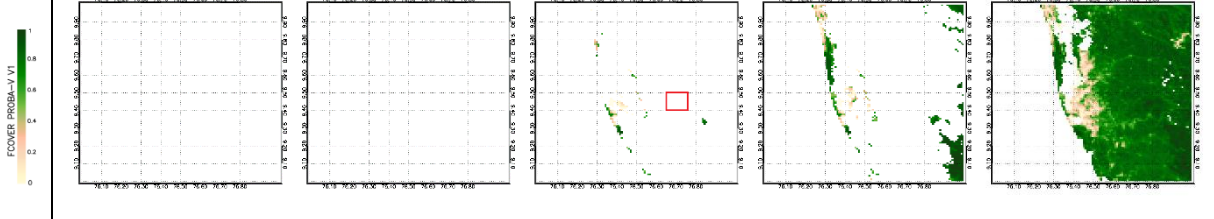
7	FCOVER PROBA–V V1
FCOVER PROBA–V V1 (2018.7.24)
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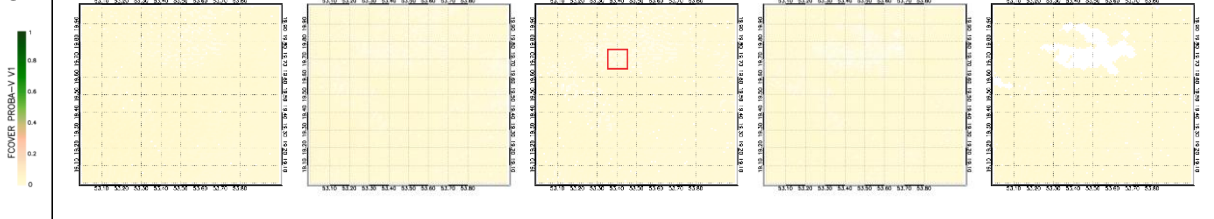
FCOVER PROBA–V V1 (2018.8.13)
FCOVER PROBA–V V1 (2018.8.24)
FCOVER PROBA–V V1 (2018.9.3)
8	FCOVER PROBA–V V1
FCOVER PROBA–V V1 (2018.5.13)
FCOVER PROBA–V V1 (2018.5.24)
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FCOVER PROBA–V V1 (2018.6.13)
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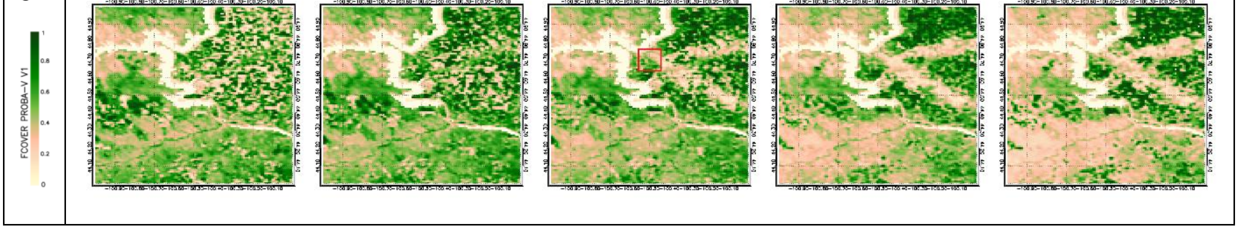
9	FCOVER PROBA–V V1
FCOVER PROBA–V V1 (2018.6.13)
FCOVER PROBA–V V1 (2018.6.23)
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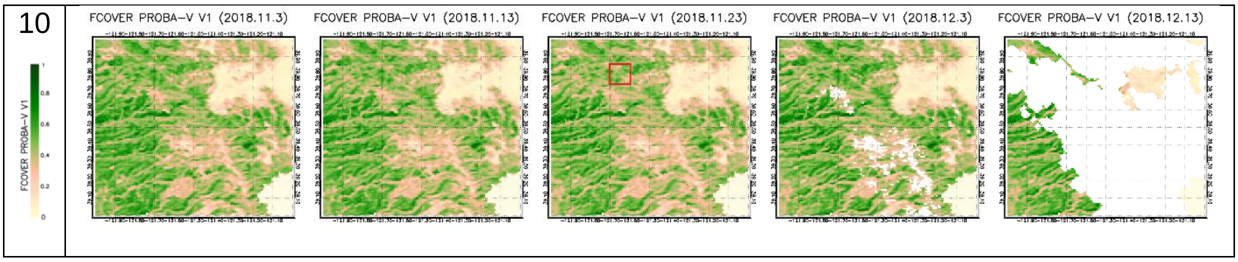
10

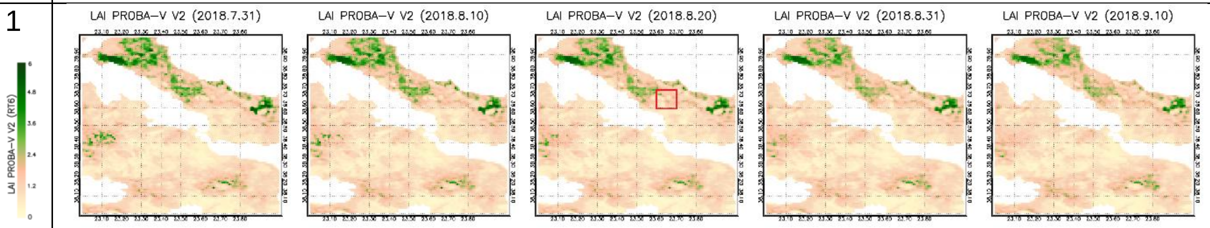


PROBA-V Collection 1km V2

- LAI

#	Before	Event date	After

1



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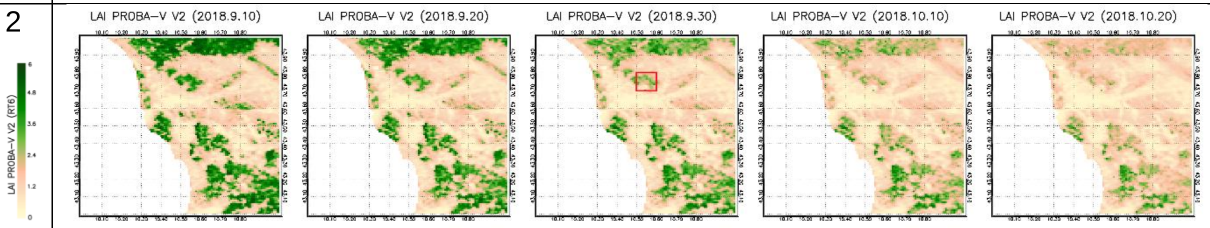

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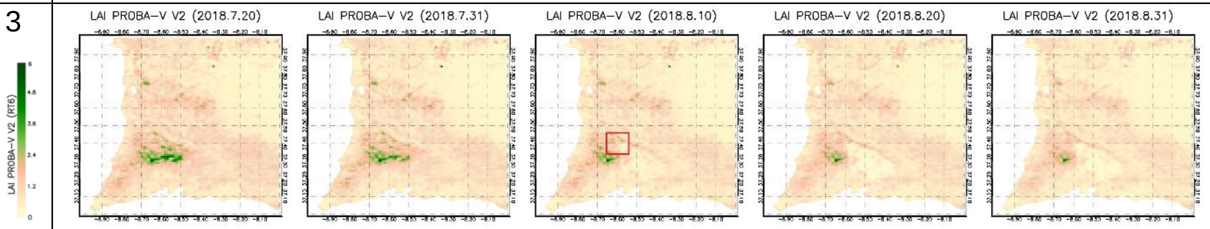

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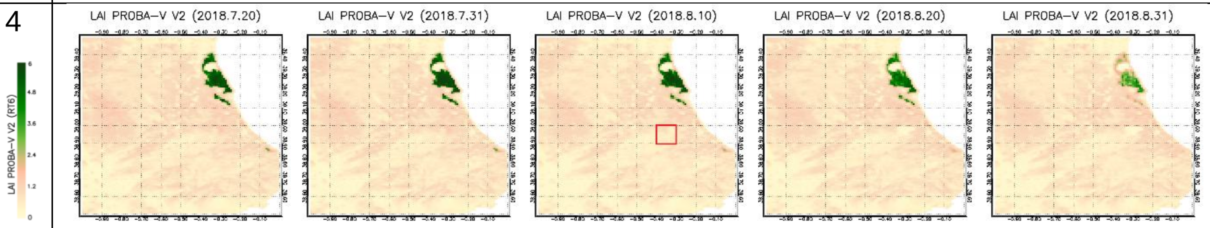

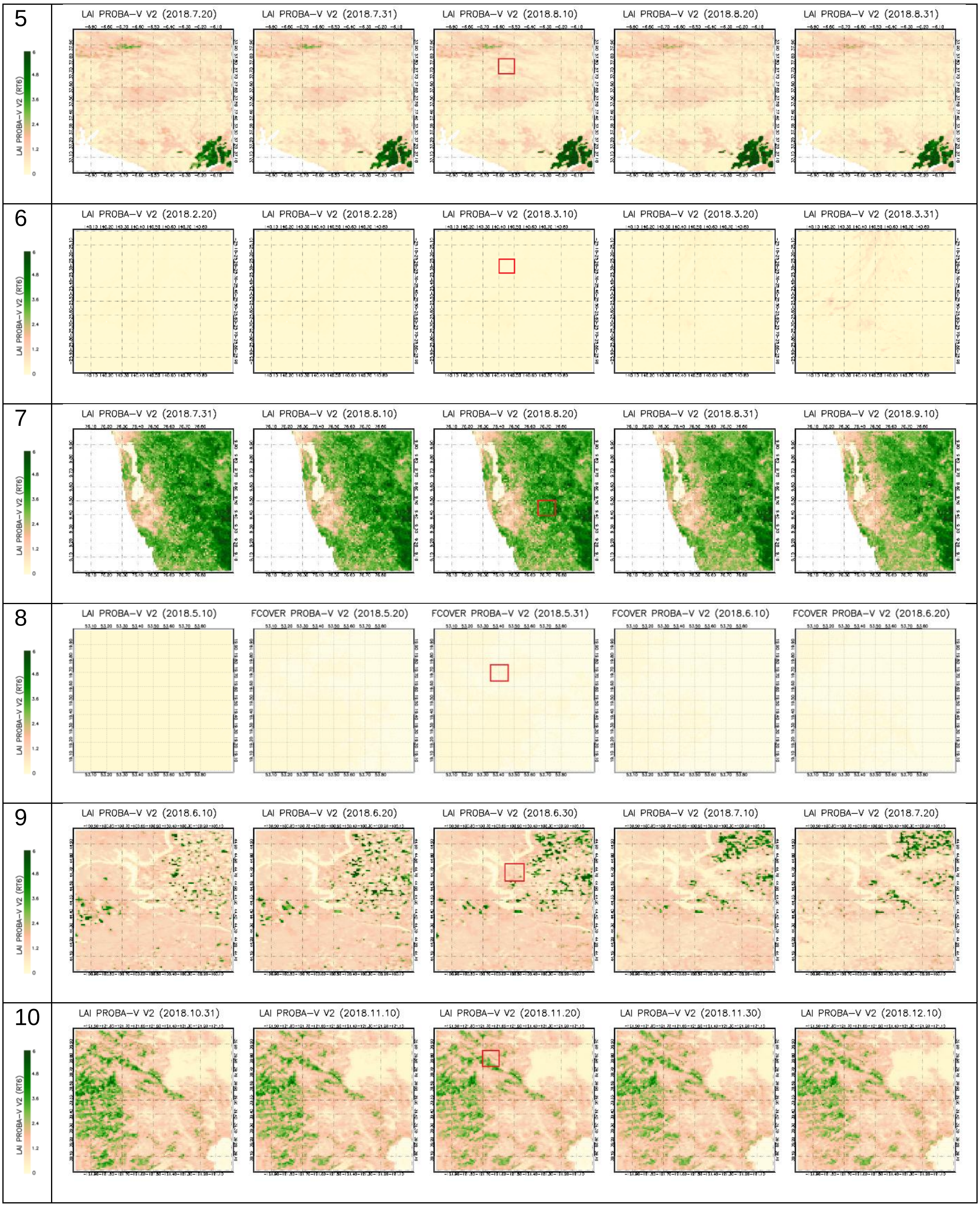
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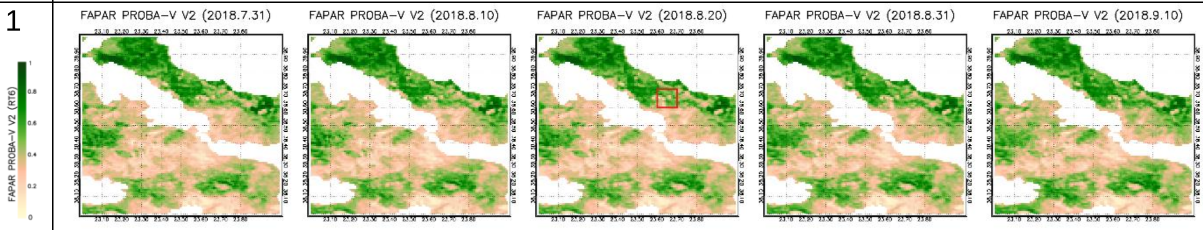
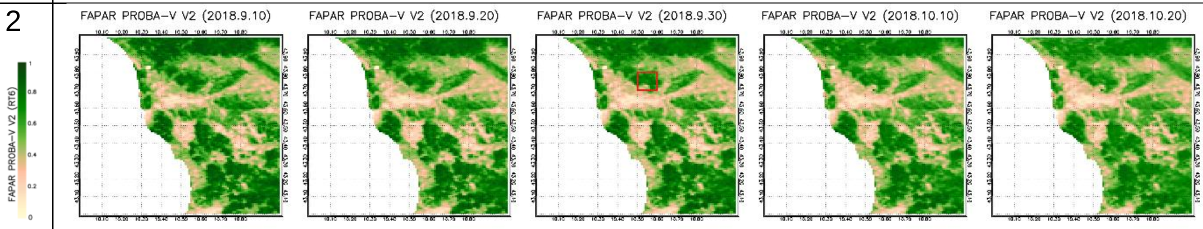
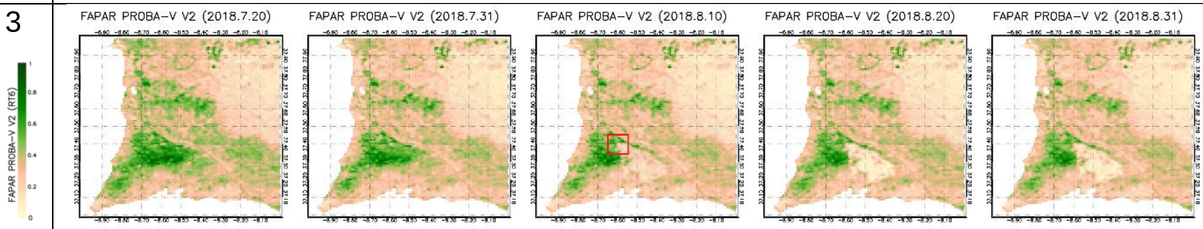
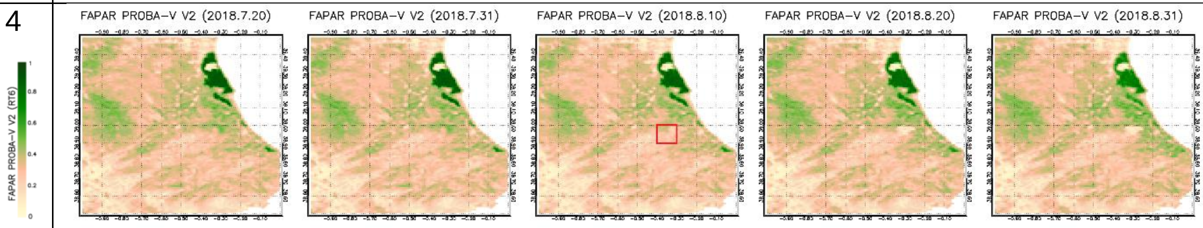
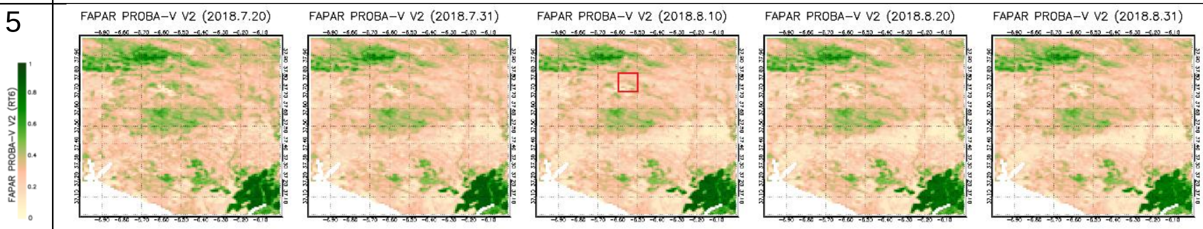
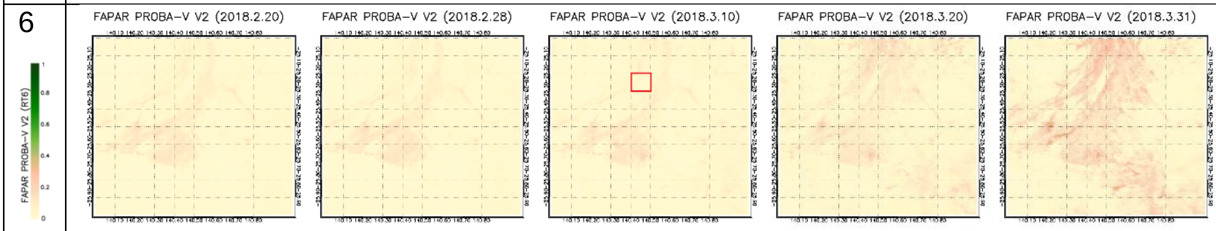
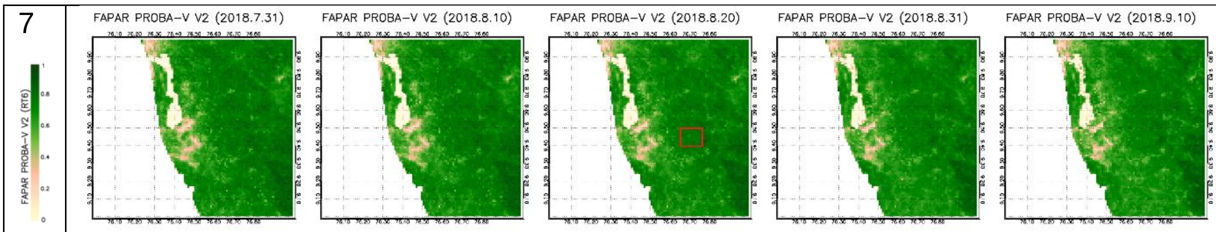
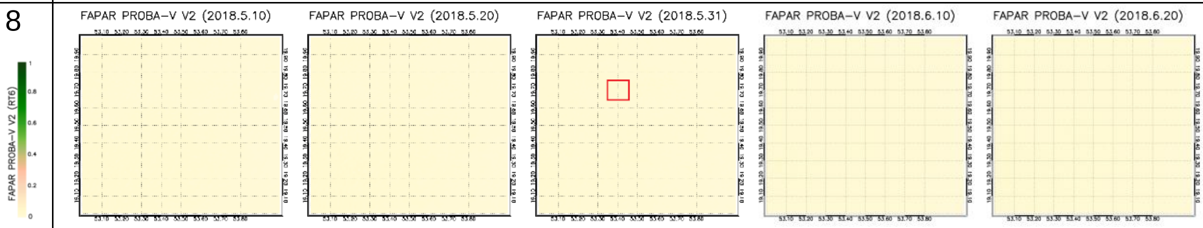
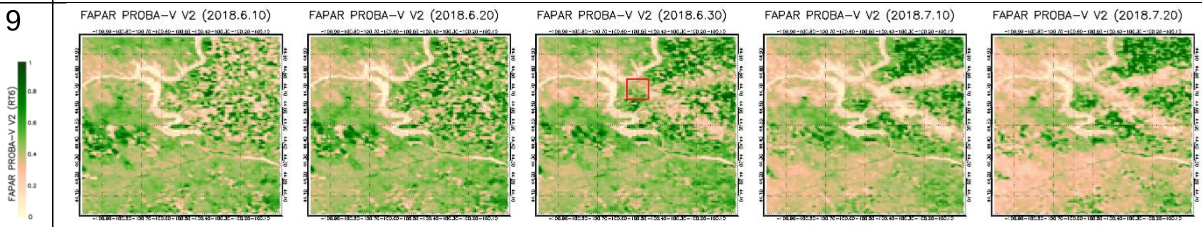
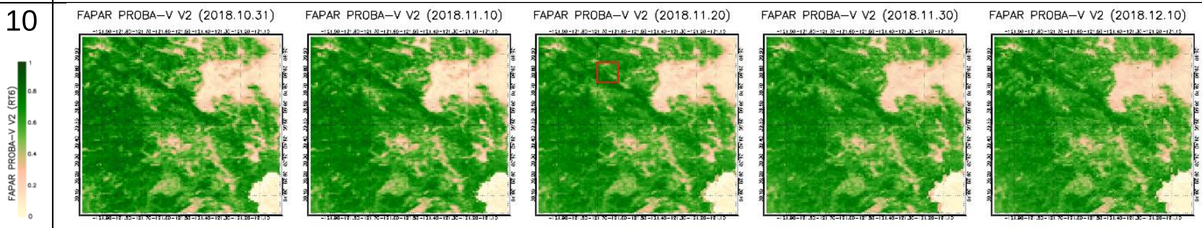
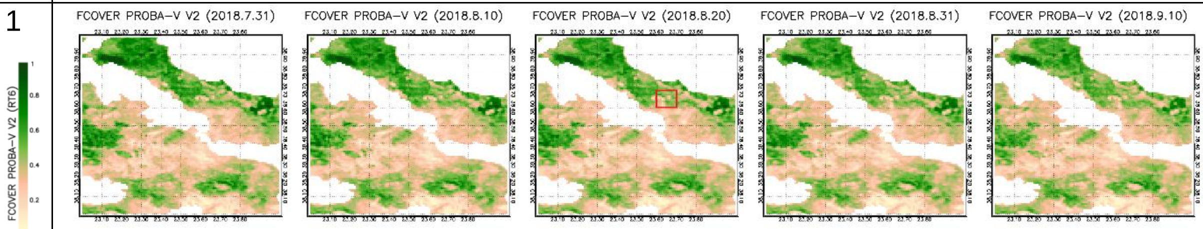
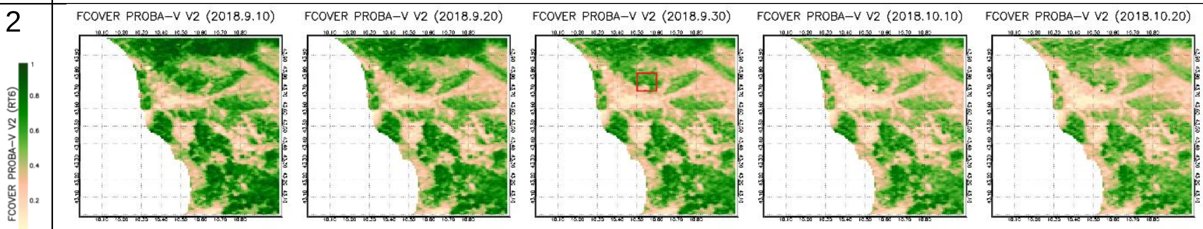
LAI PROBA-V V2 (2018.7.20)
LAI PROBA-V V2 (2018.7.31)
LAI PROBA-V V2 (2018.8.10)
LAI PROBA-V V2 (2018.8.20)
LAI PROBA-V V2 (2018.8.31)
6
LAI PROBA-V V2 (2018.2.20)
LAI PROBA-V V2 (2018.2.28)
LAI PROBA-V V2 (2018.3.10)
LAI PROBA-V V2 (2018.3.20)
LAI PROBA-V V2 (2018.3.31)
7
LAI PROBA-V V2 (2018.7.31)
LAI PROBA-V V2 (2018.8.10)
LAI PROBA-V V2 (2018.8.20)
LAI PROBA-V V2 (2018.8.31)
LAI PROBA-V V2 (2018.9.10)
8
LAI PROBA-V V2 (2018.5.10)
FCOVER PROBA-V V2 (2018.5.20)
FCOVER PROBA-V V2 (2018.5.31)
FCOVER PROBA-V V2 (2018.6.10)
FCOVER PROBA-V V2 (2018.6.20)
9
LAI PROBA-V V2 (2018.6.10)
LAI PROBA-V V2 (2018.6.20)
LAI PROBA-V V2 (2018.6.30)
LAI PROBA-V V2 (2018.7.10)
LAI PROBA-V V2 (2018.7.20)
10
LAI PROBA-V V2 (2018.10.31)
LAI PROBA-V V2 (2018.11.10)
LAI PROBA-V V2 (2018.11.20)
LAI PROBA-V V2 (2018.11.30)
LAI PROBA-V V2 (2018.12.10)
LAI PROBA-V V2 (RT6)

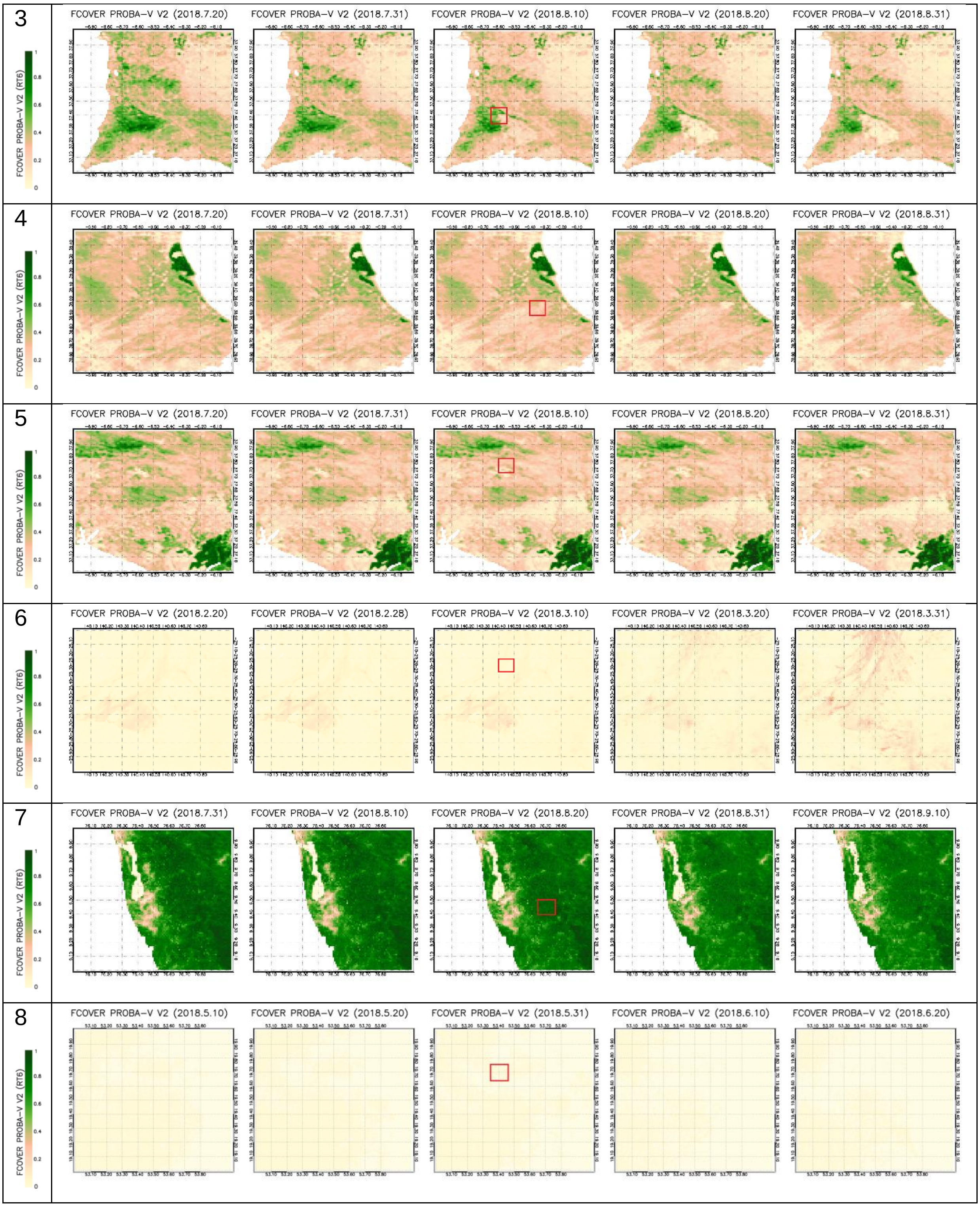
➢ FAPAR

#	Before	Event date	After
1			
2			
3			
4			
5			
6			

7	
8	
9	
10	

- FCOVER

#	Before Event date After
1	
2	


3
FCOVER PROBA-V V2 (RT6)
FCOVER PROBA–V V2 (2018.7.20)
FCOVER PROBA–V V2 (2018.7.31)
FCOVER PROBA–V V2 (2018.8.10)
FCOVER PROBA–V V2 (2018.8.20)
FCOVER PROBA–V V2 (2018.8.31)
4
FCOVER PROBA-V V2 (RT6)
FCOVER PROBA–V V2 (2018.7.20)
FCOVER PROBA–V V2 (2018.7.31)
FCOVER PROBA–V V2 (2018.8.10)
FCOVER PROBA–V V2 (2018.8.20)
FCOVER PROBA–V V2 (2018.8.31)
5
FCOVER PROBA-V V2 (RT6)
FCOVER PROBA–V V2 (2018.7.20)
FCOVER PROBA–V V2 (2018.7.31)
FCOVER PROBA–V V2 (2018.8.10)
FCOVER PROBA–V V2 (2018.8.20)
FCOVER PROBA–V V2 (2018.8.31)
6
FCOVER PROBA-V V2 (RT6)
FCOVER PROBA–V V2 (2018.2.20)
FCOVER PROBA–V V2 (2018.2.28)
FCOVER PROBA–V V2 (2018.3.10)
FCOVER PROBA–V V2 (2018.3.20)
FCOVER PROBA–V V2 (2018.3.31)
7
FCOVER PROBA-V V2 (RT6)
FCOVER PROBA–V V2 (2018.7.31)
FCOVER PROBA–V V2 (2018.8.10)
FCOVER PROBA–V V2 (2018.8.20)
FCOVER PROBA–V V2 (2018.8.31)
FCOVER PROBA–V V2 (2018.9.10)
8
FCOVER PROBA-V V2 (RT6)
FCOVER PROBA–V V2 (2018.5.10)
FCOVER PROBA–V V2 (2018.5.20)
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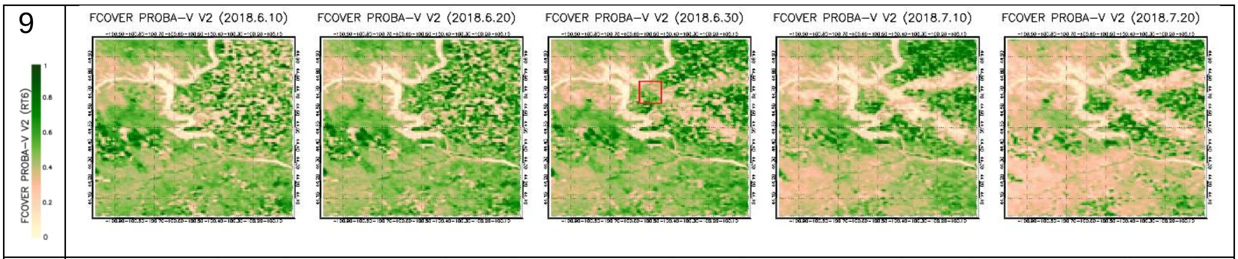
FCOVER PROBA–V V2 (2018.6.20)

9


FCOVER PROBA–V V2 (RT6)
FCOVER PROBA–V V2 (2018.6.10)
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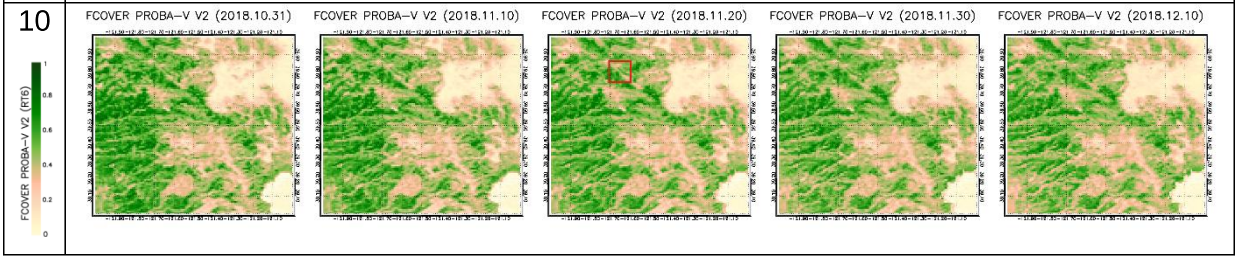
FCOVER PROBA–V V2 (2018.7.20)

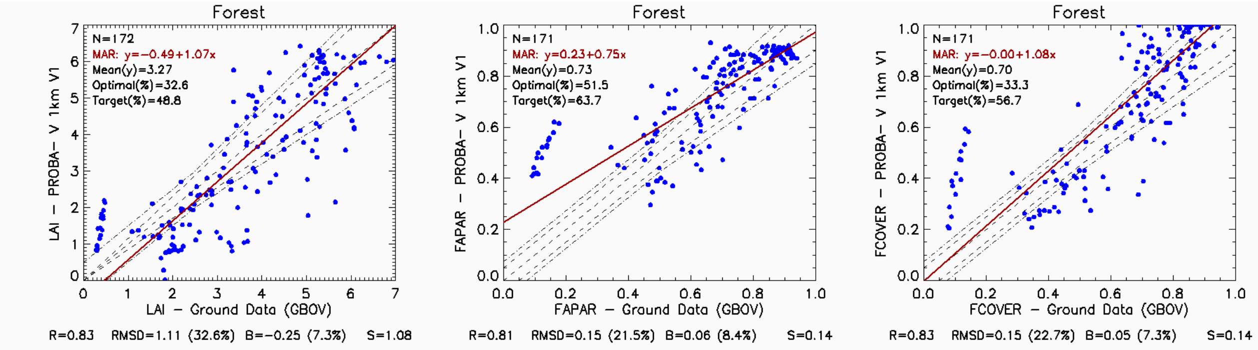
10


FCOVER PROBA–V V2 (RT6)
FCOVER PROBA–V V2 (2018.10.31)
FCOVER PROBA–V V2 (2018.11.10)
FCOVER PROBA–V V2 (2018.11.20)
FCOVER PROBA–V V2 (2018.11.30)
FCOVER PROBA–V V2 (2018.12.10)

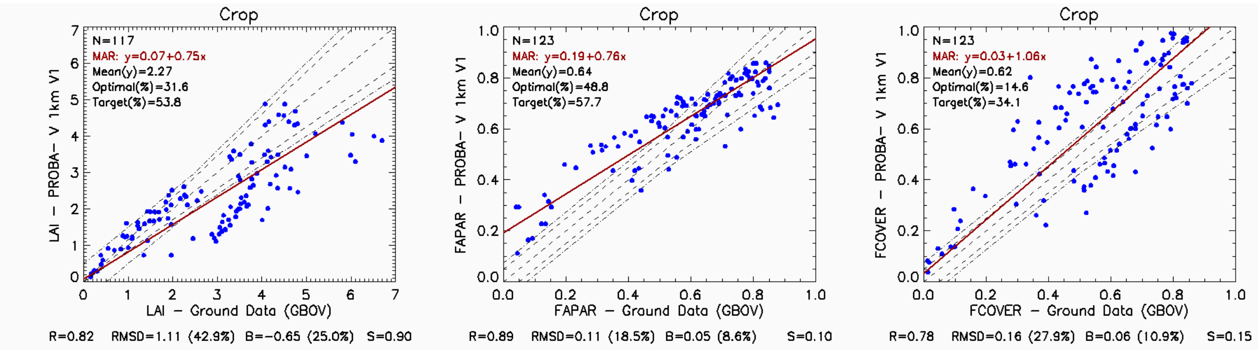
ANNEX III. ACCURACY ASSESSMENT PER MAIN BIOME TYPE

➢ PROBA-V Collection 1km V1

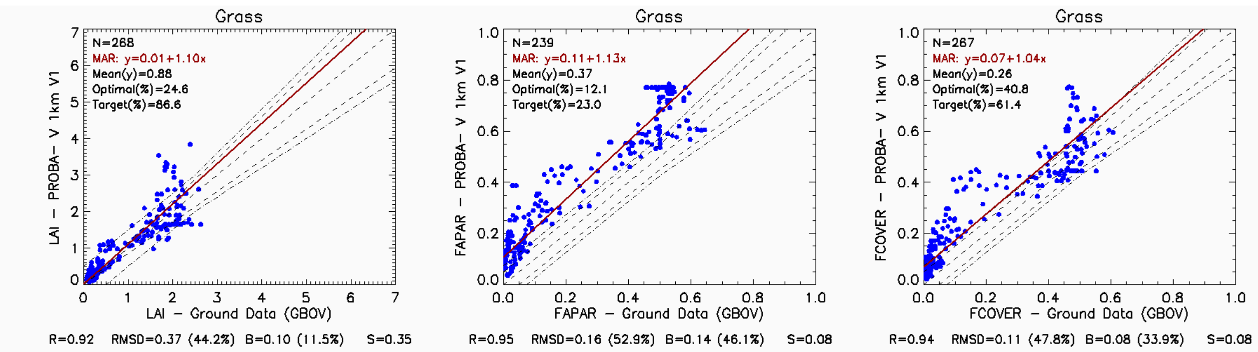
Forest



Crops



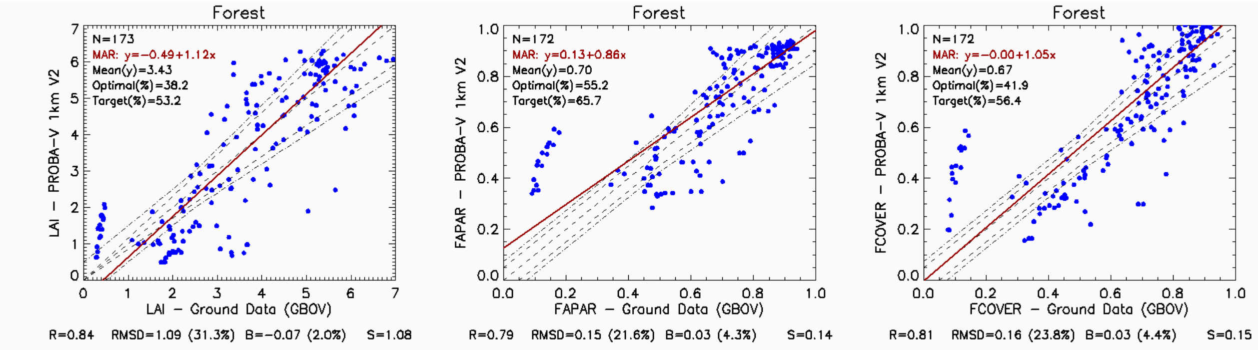
Grass



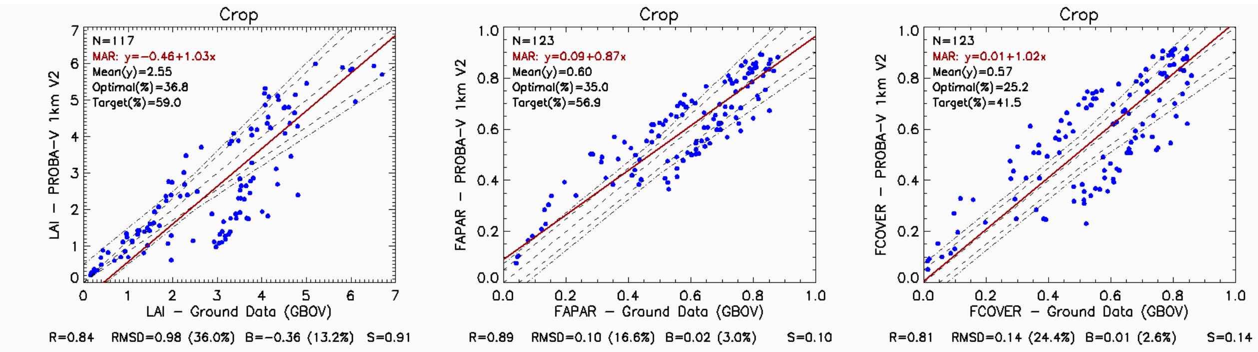
		PROBA-V 1km V1 vs Ground data (GBOV)					
		LAI		FAPAR		FCOVER	
Forest	N	172		171		171	
	Correlation	0.83		0.81		0.83	
	Bias	-0.25		0.06		0.05	
	RMSD	1.11		0.15		0.15	
	Offset	-0.49		0.23		0.00	
	Slope	1.07		0.75		1.08	
	p-value	0.148		0.001		0.150	
	%optimal	32.6	-	51.5	35.7	33.3	19.3
	%target	48.8	-	63.7	51.5	56.7	33.3
	%threshold	61.6	-	73.1	72.5	70.2	64.9
Crop	N	117		123		123	
	Correlation	0.82		0.89		0.78	
	Bias	-0.65		0.05		0.06	
	RMSD	1.11		0.11		0.16	
	Offset	0.07		0.19		0.03	
	Slope	0.75		0.76		1.06	
	p-value	0.001		0.001		0.282	
	%optimal	31.6	-	48.8	29.3	14.6	4.9
	%target	53.8	-	57.7	48.8	34.1	10.6
	%threshold	58.1	-	68.3	63.4	51.2	43.1
Grass	N	268		239		267	
	Correlation	0.92		0.95		0.94	
	Bias	0.10		0.14		0.08	
	RMSD	0.37		0.16		0.11	
	Offset	0.01		0.11		0.07	
	Slope	1.10		1.13		1.04	
	p-value	0.029		0.001		0.110	
	%optimal	24.6	-	12.1	1.3	40.8	7.5
	%target	86.6	-	23.0	5.4	61.4	13.9
	%threshold	95.1	-	37.7	12.9	71.16	25.1

- **PROBA-V Collection 1km V2**

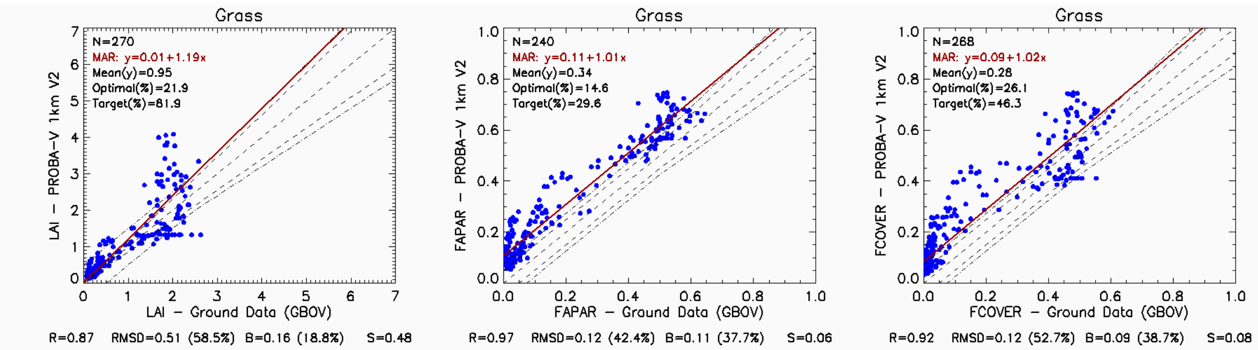
Forest



Crops



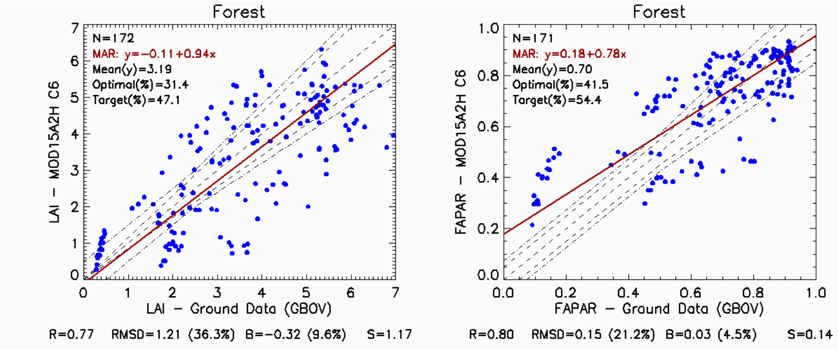
Grass



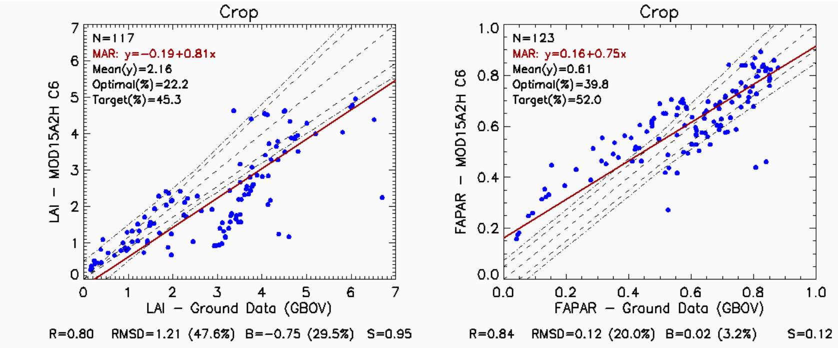
		PROBA-V 1km V2 vs Ground data (GBOV)					
		LAI		FAPAR		FCOVER	
Forest	N	173		172		172	
	Correlation	0.84		0.79		0.81	
	Bias	-0.07		0.03		0.03	
	RMSD	1.09		0.15		0.16	
	Offset	-0.49		0.13		0.00	
	Slope	1.12		0.86		1.05	
	p-value	0.015		0.011		0.400	
	%optimal	38.2	-	55.2	34.9	41.9	17.4
	%target	53.2	-	65.7	55.2	56.4	40.7
	%threshold	61.3	-	72.7	71.5	65.7	62.8
Crop	N	117		123		123	
	Correlation	0.84		0.89		0.81	
	Bias	-0.36		0.02		0.01	
	RMSD	0.98		0.10		0.14	
	Offset	-0.46		0.09		0.01	
	Slope	1.03		0.87		1.02	
	p-value	0.462		0.001		0.748	
	%optimal	36.8	-	35.0	18.7	25.2	10.6
	%target	59.0	-	56.9	34.1	41.5	19.5
	%threshold	65.8	-	74.8	68.3	48.8	42.3
Grass	N	270		240		268	
	Correlation	0.87		0.97		0.92	
	Bias	0.16		0.11		0.09	
	RMSD	0.51		0.12		0.12	
	Offset	0.01		0.11		0.09	
	Slope	1.19		1.01		1.02	
	p-value	0.002		0.446		0.366	
	%optimal	21.9	-	14.6	2.5	26.1	6.3
	%target	81.9	-	29.6	10.0	46.3	12.3
	%threshold	90.7	-	56.2	26.7	64.2	22.0

➢ MODIS C6

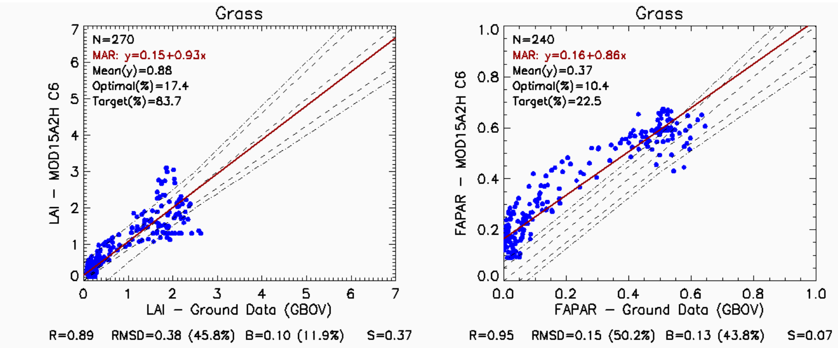
Forest



Crops



Grass



		MOD15A2H C6 vs Ground data (GBOV)			
		LAI		FAPAR	
Forest	N	172		171	
	Correlation	0.77		0.80	
	Bias	-0.32		0.03	
	RMSD	1.21		0.15	
	Offset	-0.11		0.18	
	Slope	0.94		0.78	
	p-value	0.213		0.001	
	%optimal	31.4	-	41.5	25.1
	%target	47.1	-	54.4	41.5
	%threshold	56.4	-	62.6	60.8
Crop	N	117		123	
	Correlation	0.80		0.84	
	Bias	-0.75		0.02	
	RMSD	1.21		0.12	
	Offset	-0.19		0.16	
	Slope	0.81		0.75	
	p-value	0.001		0.001	
	%optimal	22.2	-	39.8	23.6
	%target	45.3	-	52.0	39.8
	%threshold	54.7	-	64.2	63.4
Grass	N	270		240	
	Correlation	0.89		0.95	
	Bias	0.10		0.13	
	RMSD	0.38		0.15	
	Offset	0.15		0.16	
	Slope	0.93		0.86	
	p-value	0.083		0.001	
	%optimal	17.4	-	10.4	3.3
	%target	83.7	-	22.5	10.0
	%threshold	93.7	-	35.4	27.5