EO MAJI
EO AFRICA EXPLORERS

VALIDATION METHODOLOGY

V1

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1 Introduction

1.1 Project objective

This project aims to implement a prototype for irrigation mapping and crop yield estimation using inputs from the scientific ECOSTRESS and PRISMA missions. The final aim is to develop workflows, in collaboration with the African Early Adopters and EO partner(s), that support African irrigation and food security management, as well as transferring these R&D learning and results to African end-users and stakeholders. More specifically the project objectives in this project can overall be listed as:

- Exploration of the capabilities for future operational Copernicus missions (LSTM+CHIME) to estimate ET and crop water stress.
- Investigate the potential of PRISMA hyperspectral observations and thermal-based crop stress metrics to improve crop yield/biomass estimations to support agricultural monitoring
- Complement the ET retrievals with crop yield, in order to acquire a better understanding of water use efficiency (WUE) of cultivated landscapes.
- Direct involvement of African Early Adopters, in order to secure the usefulness and applicability of the prototype.
- Publish the findings in a freely available code repository and as scientifically peer-reviewed papers, as well as to promote the codes through other outreach activities such as development of digital notebooks.

All activities are to be carried out within the duration of the project lifetime from 1 December 2022 to 30 November 2024.

1.2 Scope of Document

This document presents the Validation Methodology (VM) that key reference used to evaluate the algorithms and prototypes developed for the project “EO MAJI – EO Africa Explorers” (ESA AO/1-11038/21/I-DT). This VM will be later followed up by the Integration of Validation Data Final Report at the end of Phase A and its Update at the of the project. These three documents forms the Deliverable 6 described in [REF-1].

1.3 Reference documents

REF-1	Statement of Work: ESA-EOP-SD-SOW-0250 – EO AFRICA EXPLORERS
REF-2	EO MAJI proposal dated 18/02/2022
REF-3	Clarification request from ESA dated 06/06/2022
REF-4	Response to clarification dated 22/06/2022
REF-5	Contract No. 4000139395/22/I-DT

1 Data availability

1.1 Land surface temperature

Land surface temperature (LST) is a starting product required for use in the evapotranspiration modelling. According to the community agreed LST validation categories[1] the validation activities for LST in this project fall under Category A (comparison with in-situ measurements), which will be discussed herein.

Comparisons with simultaneous observations of LST from in-situ radiometers is the traditional and arguably best approach in validating satellite LST datasets. To ensure the highest possible quality of validation, the location and measurements performed at these sites must meet a strict protocol, which is discussed in this Section.

1.1.1 Site characteristics

The validation sites need to meet the site requirements detailed[1]. Validation sites must be representative of the immediate surroundings as well as the land cover type that the site is meant to describe. Each validation site must either have:

- Homogeneous surface properties on a scale of several metres to many kilometres, consistent over an area of at least 3 x 3 SLSTR ground pixels. The spatial variability (standard deviation) of the LST of the validation site must be < 0.5 K.
- Heterogeneous surface properties, where the BT and emissivity of each endmember is measured independently by radiometers, and the spatial distribution of the endmembers is adequately described.

1.1.2 Ideal measurement protocol

Observations at these sites must be made during clear-sky conditions, and when the aerosol content of the atmosphere is low. Ideally, measurements made at these validation sites should also adhere to the following protocol:

- In-situ instruments must be calibrated to an accuracy of ±0.1 K, and be traceable to a National Institute of Standards and Technology (NIST) blackbody.
- Vertical profiles of moisture and temperature should be obtained available within ±10 minutes of a radiometer measurement, and < 10 km away from the validation site.
- In addition to surface BT measurements, directional sky radiance measurements (i.e. at ~53° from zenith) using a ground-based duplicate radiometer at the target should also be made at the time of the satellite overpass. As well as this, sufficient directional measurements should also be made to allow for an accurate determination of the flux density of spectral sky radiance.
- In order to measure aerosol optical depth (AOD), sun photometer measurements are required using the same time and location constraints as the vertical profile measurements mentioned above.
- Directional spectral (8 – 14 µm) emissivity measurements should be made at the site with appropriate spatial sampling. These measurements should be made as close as possible to the local satellite overpass time, but can be made within several days of the satellite overpass, provided that no significant change changes have occurred at the site since then (e.g. fire, rainfall, etc.).

[1] Guillevic, P., Göttsche, F., Nickeson, J., Hulley, G., Ghent, D., Yu, Y., Trigo, I., Hook, S., Sobrino, J.A., Remedios, J., Román, M. & Camacho, F. (2018). Land Surface Temperature Product Validation Best Practice Protocol. Version 1.1. In P. Guillevic, F. Göttsche, J. Nickeson & M. Román (Eds.), Best Practice for Satellite Derived Land Product Validation (p. 58): Land Product Validation Subgroup (WGCV/CEOS), doi:10.5067/doc/ceoswgcv/lpv/lst.001

- For validation sites in vegetated regions, measurements of the canopy height and density of the vegetation may also be useful. The fractional vegetation cover and emissivity of the components should also be measured.
- Both daytime and night-time validation measurements are required.
- To provide an objective measurement of cloudiness and so identify clear-sky conditions, an all-sky camera must be used at the site during the daytime. At night-time, an upward-viewing pyrgeometer should be used to provide the same measurement.

1.1.3 Instrumentation

Homogeneous sites usually require only one calibrated radiometer, though several radiometers can be deployed throughout the area in order to measure the spatial variability of the LST. For heterogeneous sites, it is necessary to have at least one radiometer per each of the site's endmembers in order to quantify the effect of each composite surface type on the overall emissivity and LST.

Radiometers deployed in validation sites should have an accuracy of ±0.1 K, and calibrated to a traceable SI reference standard such as those provided by NIST. Additionally, each radiometer at a given validation site must be independently calibrated before and after field campaigns, or at regular intervals if part of a longer continuous collection period. This is to ensure that potential drift in the in-situ measurements are detected and quantified. Radiometers should also be inter-compared with other radiometers, and be well documented such that the documentation is available to the other LAW partners.

Standard meteorological observations of the following variables should also be made at validation sites, or at least < 50 km of the site:

- Air temperature,
- Humidity,
- Air pressure,
- Wind speed and direction,
- Shortwave solar radiation,
- Precipitation (to investigate potential impact on emissivity – only from measurements at the actual site itself)

Vertical profile data of temperature and humidity should ideally come from radiosondes launched at or near the validation site, during the satellite overpass. While profiles from reanalysis datasets such as ECMWF ERA5[2] can be used, it is preferable to use radiosondes at the validation site due to their greater accuracy, especially given that spatial and temporal matching between reanalysis data and overpass measurements adds uncertainty.

1.1.4 Obtaining surface emissivity

Accurate information of the surface emissivity is vital to converting the observed BT into the true site LST. While a single emissivity is sufficient for homogeneous sites, it is necessary to provide multiple emissivity values for each of a heterogeneous site's endmembers. Additionally, for some heterogeneous sites (e.g. Evora, Portugal) the emissivity of various endmembers also changes with season because of the phenology of the vegetation. Therefore, temporally varying values covering at least the major changes in site emissivity are required for such validation sites.

[2] Hersbach, H., Bell, B., Berrisford, P., et al. (2020). The ERA5 global reanalysis. Q J R Meteorol Soc., 146, 1999-2049

Surface emissivity values can be estimated from in-situ radiometer measurements using techniques like the 'two-lid emissivity box' method [RD – 26]. If in-situ emissivity measurements are not taken, then surface emissivity values for each endmember can instead be sourced from reference datasets like the ECOSTRESS spectral library[3].

1.1.5 Specific sites

There are no LST validation sites within the Areas Of Interest of the African Early Adopters and thus the LST data from ECOSTRESS will be validated elsewhere.

We will use data from the KIT-managed stations located in similar climate zones and which represent stable land covers that experience seasonal variation only. The specific sites are:

- ❖ Temperate Mediterranean climate, cork-oak trees and grass: Evora, Portugal, since 2005:

  At Evora, radiometers observe grass and the crown of an oak tree. A static tree crown cover of 32% (determined from high-resolution satellite imagery[4]) is used for the current validation scheme of satellite LST with in situ data from Evora.

- ❖ Arid Desert hot climate, gravel desert: Gobabeb, Namibia, since 2007, since 2012 part of BSRN:

  GBB_W station is located on the large and homogeneous gravel-plains of the Namib Desert at 405 m asl. in Namibia[5]. Performing measurements along a 40 km track[6] showed that the station LST is representative for an area of several 100 km^2.

- ❖ Arid desert hot climate at high elevation, Kalahari bush: Kalahari Farm Heimat, ~1450m asl, 2011 – 2019:

  The farm is located in the Kalahari semi-desert in Namibia. The climate there is hot and arid, with two rainy seasons. The small rainy season is from September to November with little rain and the big one from January to March. Except for the time of the big rainy season, the grass in the Kalahari desiccates quickly and the region is dry. The station LST is measured at Farm Heimat from 2011 to 2019.

Finally, we will use a recent LST validation dataset from the Skukuza tower in South Africa (since 2022). This was deployed under the Ground-Based Observations for Validation (GBOV) of Copernicus Global Land Products project. This site is located is a semi-arid climate, subtropical bush.

All the validation stations have a sampling rate of 1 minute, and measure directional TIR radiance from the ground and the sky. They provide standard meteorology, and two stations additionally measure upwelling and downwelling hemispherical shortwave and longwave broadband radiances.

The main instrument for the in situ determination of land surface temperature at KIT's validation stations is the precision radiometer 'KT15.85 IIP' produced by Heitronics GmbH, Wiesbaden, Germany. These instruments measure thermal infrared radiances between 9.6 µm and 11.5 µm with a temperature resolution of 0.03 K and an accuracy of ± 0.3 K over the relevant temperature range. The KT15.85 IIP has a drift of less than 0.01 % per month: the high stability is achieved by linking the radiance measurements via beam-chopping (a differential method) to internal reference temperature measurements.

[3] S. K. Meerdink, S. J. Hook, D. A. Roberts, and E. A. Abbott, 'The ECOSTRESS spectral library version 1.0', Remote Sensing of Environment, vol. 230, p. 111196, Sep. 2019, doi: 10.1016/j.rse.2019.05.015

[4] Bork-Unkelbach, A. Extrapolation von in-situ Landoberflächentemperaturen auf Satellitenpixel. Phd thesis, Karlsruher Institut für Technologie, 2012. DOI: 10.5445/IR/1000032489

[5] Göttsche, F.M.; Olesen, F.S.; Trigo, I.; Bork-Unkelbach, A.; Martin, M. Long Term Validation of Land Surface Temperature Retrieved from MSG/SEVIRI with Continuous in-Situ Measurements in Africa. Remote Sensing 2016, 8, 410

[6] Göttsche, F., Olesen, F., Poutier, L., Langlois, S., Wimmer, W., Garcia Santos, V., Coll, C., Niclos, R., Arbelo, M., and Monchau, J-P., Report from the Field Inter-Comparison Experiment (FICE) for Land Surface Temperature. http://www.frm4sts.org/wp-content/uploads/sites/3/2018/10/FRM4STS_LST-FICE_report_v2017-11-20_signed.pdf

1.2 Evapotranspiration

Evapotranspiration is an intermediate product required for the primary irrigation and crop yield products. Different EO ET models have already been validated. In particular within the ESA's SEN-ET and ET4FAO projects, TSEB model has successfully proved in producing reliable accurate ET maps at 20m resolution, by merging Sentinel-2 Sentinel-3 and Landsat data. Nevertheless, ET maps from ECOSTRESS+PRISMA should be validated against existing flux towers yet. However there is no in situ flux data within the Areas Of Interest of the African Early Adopters and thus the ET maps should be validated elsewhere, where flux data is available, such as the ICOS (https://www.icos-cp.eu/observations/ecosystem/stations), FLUXNET (https://fluxnet.org/sites/site-summary) or ICARDA (https://www.icarda.org/about-us) EC sites or the lysimeters installed in Las Tiesas experimental farm in Barrax (Spain). For EOMAJI we will focus on semi-arid sites over croplands and efforts will be coordinated with the EEH team, as they are also working on using ECOSTRESS for modeling ET using TSEB, among other models.

1.3 Irrigation delimitation

Both the early adopters from Burkina Faso and Botswana have interest in delimitation of existing irrigation perimeters. In both countries the climate is semi-arid and agriculture mainly rainfed. Therefore, development of irrigation infrastructure is of high priority to the relevant governments.

In Burkina Faso the irrigation is mainly conducted in wetland areas or close to rivers and reservoirs which are the source of irrigation water. The irrigation is either flood irrigation (mainly on rice fields) or sprinkler irrigation (mainly on potato fields). The irrigation schemes are usually managed by farmer associations and supported by local offices of the Ministry of Agriculture. Central government might not have a database holding the locations and extents of all the irrigation schemes but some data might be made available to the project from the local offices.

In Botswana, irrigation is mainly used in commercial vegetable (cabbage, tomato, cucumber) and fruit (citrus and mango) farms. It is usually deployed as drip systems although some sprinkler systems are also present. Irrigation perimeters are concentrated along major rivers, such as Limpopo and Zambezi, and in the Eastern part of the country where soil quality is better. An early version of water licensing scheme is operational in Botswana and therefore there should be a database of irrigation scheme locations although water use and extraction data might be harder to come by.

In both countries we will work with the Early Adopters to obtain as much irrigation perimeter data from central and local government offices as possible. In parallel, we will undertake manual digitization of representative number of irrigation parameters, guided and assisted by the Early Adopters. This will be performed using 10 m Sentinel imagery and, if available, higher resolution observations. Despite both countries sharing a similar climate, we should be able to get a representative sample of different irrigation techniques (flood, sprinkler and drip) covering different types of crops (rice, potato, vegetable, fruits) which will result in a robust validation dataset.

1.4 Irrigation accounting

Due to water scarcity, both Early Adopters are interested in accounting the irrigation applied by farmers in order to better manage the water resources.

In Burkina Faso irrigation is managed by farmer associations but due to their poor education and training the management of irrigation is not efficient. The Ministry of Agriculture supports these farmer associations with local offices in the area and thus they are interested in providing tools and training to the for a better water management. In addition, these local offices collect eventually water supply data, but not systematically. Currently the Ministry of Agriculture of Burkina Faso has provided to EO-MAJI water supply data in the Kou Valley, but this data spans from 2011 to 2024. This data consists on daily records of water flow rate (l/s) at the main canal inlet of the irrigation scheme as well as in 7 secondary canal units. In collaboration with the Ministry of Agriculture and its local offices we will try to get more recent data that could be used to validate the irrigation accounting with actual ECOSTRESS+PRISMA+Sentinel data. In s, we will also work with them to convert the supplied flow rate to water usage.

In Botswana irrigation is mostly applied by commercial farms where drip irrigation is dominant. Although there is a large competition for water in Botswana, the Ministry of Lands and Water Affairs do not have any figures on how much water is extracted so far. Indeed, this lack of information and data availability is the main reason of their interest of an irrigation accounting product, which they could use for assisting on irrigation licensing schemes, to find areas irrigated outside the scheme and to develop estimates of amount of water that can be extracted from river.

1.5 Crop Yield

In Burkina Faso the most irrigated crop is rice, followed by maize. The technicians from the local offices of the Ministry of Agriculture are in charge of surveying the yield of rice at regional level during the wet and dry seasons. To do so, they gather the number of bags collected by local producers and calculate the total yield, considering that each bag weights 80kg. The rice yield per area (kg/ha) is then calculated based on the field area owned by each farmer (ranging between 0.125 to 0.5 ha per farmer). So far the Ministry of Agriculture of Burkina Faso has provided to EO-MAJI these reports for several irrigation schemes of the country: Kou Valley in the Hauts-Bassins region, Bagrepole in the Central-East region, Douna Perimeter in the Cascades region, the Valorisation of the Sourou Valley Authority (AMVS) in the Boucle du Mouhoun, and the Three Wetlands also the Boucle du Mouhoun. These data is collected separately for the two seasons of the year (wet and dry) and it spans so far the years 2014 to 2019, but is might be possible to obtain data for the more recent years.

In Burkina Faso the main crops that are irrigated are vegetables (cabbage, tomatoes cucumber), and fruit trees (citrus and mango). Other crop such as maize, beans or peanuts are however under rainfed conditions. As it was mentioned before, most relevant farms are commercial, and thus it is difficult to get from them yield estimates, but might be possible. However, estimating yield from remote sensing for vegetables and fruits is extremely complicated and thus it is better to focus in other crops such as maize or potato. Indeed according to the Ministry of Lands and Water Affairs and the University of Gaborone potato could be a good test-case since fields are large (35ha) and it might be easier to get in situ yield estimates.

2 Evaluation metrics

2.1 Land surface temperature

The true LST can be derived from the BTs measured by the downward and upward-facing radiometer measurements, along with the surface emissivity. First, the upward and downward-facing BTs measured at the validation site are converted to spectral radiances in W·sr^{-1}·m^{-2}at the central wavelength of the radiometer using the Planck function:

$$L(\lambda,T)=\frac{c_1}{\lambda^5\left(e^{\frac{c_2}{\lambda T}}-1\right)}$$

Equation 1: Planck Function.

Where:

$L(\lambda,T)$ = spectral radiance (W·sr^{-1}·m^{-2})
$c_1 = 2hc^2$

$$c_2 = \frac{hc}{k}$$

h = Planck Constant: 6.62606957 × 10^{-34} Js
c = speed of light: 299792458 ms^{-1}
k = Boltzmann Constant: 1.3806488 × 10^{-23} JK^{-1}
λ = Radiometer Central Wavelength
T = BT measured by the radiometer

Next, the land surface radiance is calculated from the downwelling and upwelling spectral radiances calculated using Equation :

$$B(T_s) = \frac{L_\uparrow - (1-\varepsilon) L_\downarrow}{\varepsilon}$$

Equation 2: Calculation of Land Surface Irradiance or Land Surface Radiance.

Where:

B = Planck Function
T_s = Surface Temperature
$L_\uparrow$ = Upwelling irradiance or radiance
$L_\downarrow$ = Downwelling irradiance or radiance
ε = Surface emissivity

Finally, the LST is calculated from the land surface radiance using the inverted Planck function, as shown in Equation (assuming a Lambertian surface):

$$LST = \frac{c_2}{\lambda \ln\left(\frac{c_1}{B(T_s)\lambda^5} + 1\right)}$$

Equation 3: Inverse of the Planck Function for wavelengths in microns.

The following metrics will be calculated from the satellite – in-situ matchups for each validation site to quantify the Sentinel-3 LST validation:

- **Accuracy**: Median error, median and percentiles of residuals, box-plots of residuals vs LST
- **Precision**: Median absolute deviation
- **Uncertainty**: Scatter plot of match-ups, median and percentiles of absolute residuals, RMSE box plot of absolute residuals vs LST
- **Completeness**: Gap size distribution

2.2 Evapotranspiration

Evapotranspiration will be validated against in situ eddy covariance measurements. Since we are mainly interested in cumulative ET and seasonal crop stress, not only instantaneous fluxes (sensible and latent heat) but also daily and seasonal ET will be evaluated. For that we will use the best quality flux data and use standard

EC gap filling techniques, as suggested by the FLUXNET community to produce daily, weekly and monthly in situ ET values.

Standard error metrics will be used to compare the EO predicted (P) and the EC observed values (O), such as Mean Bias Error, Root Mean Squared Error and Mean Absolute Error (Eq. 1) as well as agreement metrics such as correlation coefficient, index of agreement or the comparison of standard deviations of observed and predicted.

$$MBE = \frac{\sum_{i}^{N} O_i}{N} - \frac{\sum_{i}^{N} P_i}{N}$$
$$RMSE = \frac{\sqrt{\sum_{i}^{N} (O_i - P_i)^2}}{N} \quad (1)$$
$$MAE = \frac{\left| \sum_{i}^{N} (O_i - P_i) \right|}{N}$$

2.3 Irrigation delimitation

Irrigation delimitation is a classification problem: separating pixels located in irrigated agriculture from pixels located in rainfed agriculture and natural areas (e.g. wetlands). Therefore the main evaluation metrics are chosen from the classification domain: user accuracy (the probability that a value predicted to be in a certain class really is that class), producer accuracy (the probability that a certain land cover of an area on the ground is classified as such), overall accuracy (the number of correctly classified sites and divided by the total number of reference sites) and kappa statistic (the closer to 1 the better the classification accuracy).

2.4 Irrigation accounting

As opposed to the Irrigation Delimitation product, accounting irrigation is a scale variable and thus the main evaluation metrics would be based on the comparison between the predicted and observed/measured values. Therefore standard error metric such as mean bias, root mean squared error, mean absolute error will be computed (Eqs. 1) together with agreement metrics such as correlation coefficient between the observed and the predicted, the index of agreement or the comparison of standard deviations of observed and predicted.

However, in case in situ measurements of irrigation accounting were not available for validation other qualitative methods will be assessed in order to evaluate the performance of the prototypes. These include evaluation/survey by the end-users, but also evaluation of spatio-temporal consistency of estimates. For example checking that the estimates of irrigation accounting over rainfed areas or outside the irrigation period approach are zero or near zero.

2.5 Crop yield

As with the Irrigation Accounting product, Crop Yield will be evaluated as a scale variable and thus the accuracy, uncertainty and precision will be computed based on the error and agreement metrics. Since crop yield is usually provided annually (or sub-annually for the two rice seasons in Burkina Faso) several years would be needed to increase the amount of data per validation. Nevertheless, in case of no further data were available a qualitative assessment of the products will be evaluated based on the Early Adopter’s expertise: e.g. spatio-temporal consistency based on regional and climatic variability.

On the other hand, it is worth noting that during the algorithm development of Phase A we also have access to a very detailed and complete yield database in Spain, provided by the Spanish Ministry of Agriculture (ESYRCE database, https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/). This source of information is available annually since 1990 and covers the whole Spanish territory in which yield data is gathered in situ from a geo-referenced 1km² sampling grid during the months of May to August. Approximately the annual coverage of the yield sub-sampling is about 1% of the Spanish total area (i.e. ~5000 points every year)