European long-term ecosystem, critical zone and socio-ecological systems research infrastructure PLUS

Requirements for in-situ observations in the calibration/validation process of Earth Observation data

Deliverable D3.2

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Saku Anttila[1], Kristin Böttcher[1], Ulf Mallast[2], Carmela Marangi[3], Jian Peng[2], Steffen Zacharias[2], Ricardo Díaz-Delgado[4], Severio Vicario[3], Diego Garcia[7], Jaana Bäck[5,] Michael Mirtl[2], Marcus Schaub[6], Volodymyr Trotsiuk[6], and the eLTER PLUS Research Themes

[1] *Finnish Environment Institute, Finland*

[2] *UFZ Helmholtz Centre for Environmental Research, Germany*

[3] *Consiglio Nazionale delle Ricerche, Italy*

[4] *Estación Biológica de Doñana, Spain*

[5] *Department of Forest Sciences, University of Helsinki, Finland*

[6] *Swiss Federal Institute for Forest, Snow and Landscape Research WSL,*

[7] *Spanish National Research Council*

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Terms and abbreviations

Calibration: practice of assuring instrument performance to SI (International System of Units) or community accepted standards (Sterckx et al. 2020)

Validation: is the practice of quantifying the accuracy of satellite-derived geo and biophysical products (Justice et al.2000)

BRM	Biomass Reference Measurement
CEOS	Committee on Earth Observation
CCVS	Toward a Copernicus Calibration and Validation Solution project
Copernicus	EU programme aimed at developing European information services based on satellite Earth Observation and in situ
cal/val	calibration and validation
DHP	Digital Hemispherical Photographs
DLR	Federal Republic of Germany's research centre for aeronautics and space
eLTER	Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research
EEA	European Environment Agence
EO	Earth Observation
ESA	European Space Agency
ESU	Elementary Sampling Unit
Eumetsat	The European Organization for the Exploitation of Meteorological Satellites
FRM	Fiducial Reference Measurements
GBOV	Ground-Based Observation for Validation
ICOS	Integrated Carbon Observation System
In-situ	In its original place, located directly at the point of interest and in contact with the subject of interest. In the EO field, used to refer to the ground truth observations that may also include local air-based observations.
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index
LPV	Land Product Validation
LUCAS	Land Use and Coverage Area frame Survey
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NEON	National Ecological Observatory Network
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real-Time
OLIVE	Online Interactive Validation exercice
QA4SM	Quality Assurance for Soil Moisture
ROI	Region of interest
RI	Research Infrastructure
SMOS	Soil Moisture and Ocean Salinity

SO	Standard observation
USGS	United States Geological Survey
WGCV	Working Group on Calibration and Validation

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1 Background

The entire LTER-Europe network consists of several hundred formally accredited LTER Sites for ecosystem research distributed across Europe (https://deims.org/). The extensive spatial coverage of the eLTER site network and already existing infrastructure for observing different components in Earth systems, create a distinct potential for collecting spatially and temporally representative data sets.

The accuracy assessment of satellite data, and derived products, require biophysical in-situ information for the validation processes. European Union's Earth observation programme Copernicus include a dedicated In-situ component coordinated by the European Environment Agency (EEA) to ensure and advance the availability of in-situ data. These data are essential for Earth Observation (EO) products Copernicus provides in particular for the model initialization and assimilation as well as calibration and validation purposes (Fjæraa et al., 2021). The Copernicus programme has also identified scientific research networks as sources of valuable in-situ data (https://insitu.copernicus.eu/). In addition, Ground-Based Observations for Validation (GBOV), as part of the Copernicus Global Land Service, facilitates further the use of observations from operational ground-based monitoring networks and their comparison to Earth Observation based land products (https://gbov.acri.fr). Within GBOV, raw observations from existing networks are collected and processed to prepare suitable datasets for the validation of global products, such as soil moisture and vegetation products.

The demand to gather and advance in-situ observations for calibration and validation purposes is common for all agencies delivering or working with Earth Observation data. Globally, the Committee on Earth Observation Satellites (CEOS - a consortium of 61 space agencies operating 172 satellites worldwide) coordinates and provides guidance for these activities with working groups on calibration & validation aiming to ensure long-term confidence in the accuracy and quality of Earth Observation data and products. In-situ data provisioning for the EO validation / calibration and guidance for this are also developed in several recent and ongoing projects. The Toward a Copernicus Calibration and Validation Solution -project (CCVS; EU; https://ccvs.eu/), for instance, advises Copernicus programme in its future development and have identified European research infrastructures, including eLTER, as important providers for in-situ data.

Despite the increasing demand and recent advances in the in-situ data provisioning for the EO calibration/validation, there are still obvious deficit and further development needs identified in this context (c.f. CCVS, 2021a and CCVS, 2021b). The maturity level of in-situ data provider organisations and respective networks varies, thus harmonized development under European and long-lasting RI context is highly important.

The eLTER RI is currently formalizing a framework for its standard observations (Zacharias et al., 2022 a.k.a eLTER D3.1), that define a minimum set of variables and associated methods and protocols that are relevant to monitor Earth systems noting the feasibility, cost efficiency and relevance on measurements. The proposed eLTER standard observations framework follows the Whole Systems Approach (Mirtl et al., 2021 in preparation) and serves 5 main spheres - geosphere, hydrosphere, biosphere, atmosphere and sociosphere. The framework is also an essential tool for the process aiming to standardize and harmonize observations across eLTER sites.

In this document, we identify those proposed eLTER standard observations in all 5 spheres that are relevant for the validation processes of major Earth Observation data providers. We also identify key steps for the eLTER RI required to develop research infrastructure activities to be able serve these validation processes.

2 Basics on calibration and validation of Earth Observation data

The theoretical steps for the calibration and validation of satellite missions were described in Sterckx et al. 2020 (Figure 1). Calibration and validation activities for satellite missions include pre-launch calibration, in orbit calibration, satellite reference calibration. To get calibrated Level-1 data (e.g. radiance, reflectance and transmittance), post-launch calibration and verification is required. The calibrated Level-1 data are a prerequisite for the retrieval of geophysical Level-2 products (geophysical and geochemical parameters). For the generation of long-term series of satellite data (or climate data records), satellite intercomparisons need to be carried out to quantify potential bias between successive sensors(c.f. Global Space-based Inter-Calibration System; gsics.wmo.int). The calibration and validation of satellite missions include the algorithm verification as well as the validation of Level-2 and Higher-Level products. In the product validation, independent estimates of the same measurand are compared to the satellite product. In this step eLTER RI could support the validation of a range of geophysical products (and ancillary data for satellite retrievals). Ideally, Fiducial Reference Measurements (FRMs) that are in-situ observations tailored to satellite validation needs, are utilized in the product validation (Figure 2).

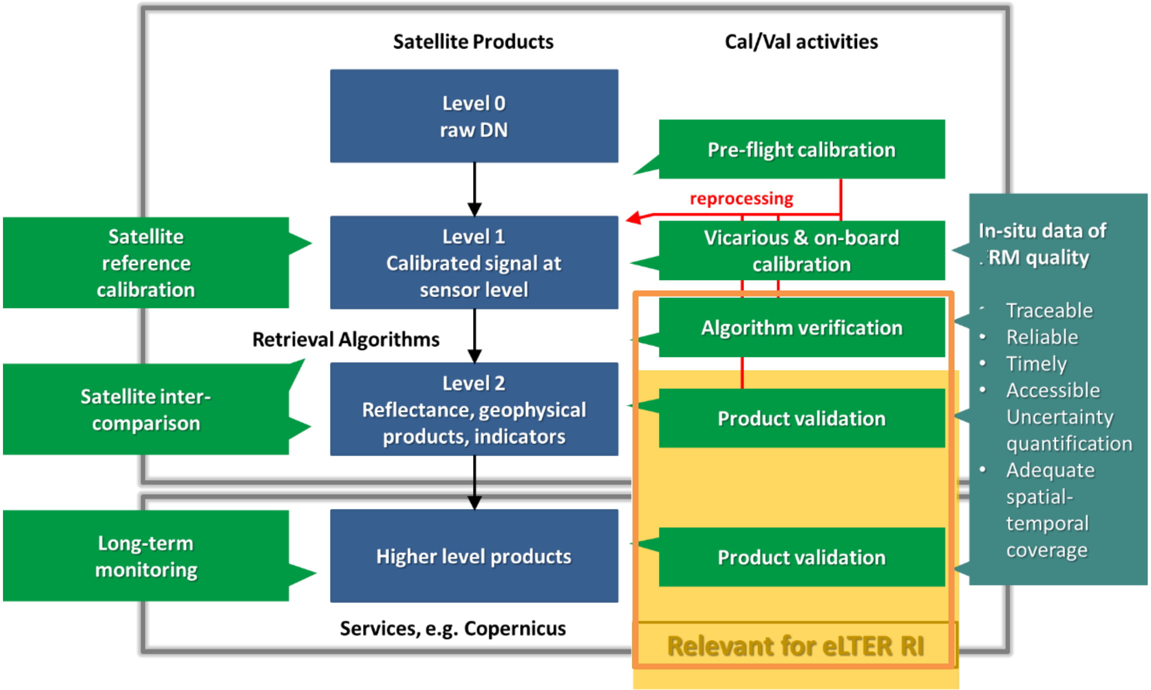

Figure 1. Steps for comprehensive calibration and validation activities for satellite missions from Sterckx et al. 2020. Blue boxes show the steps for the production of geophysical satellite data products and green boxes indicate specific calibration and validation activities. For the development of the eLTER RI data for product validation are most relevant (orange box).

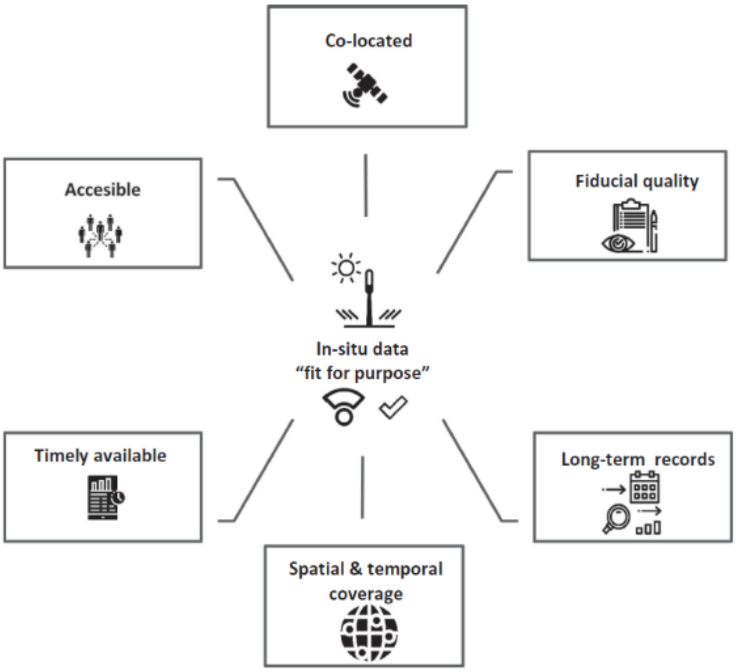

Figure 2. Requirements for in-situ observations in order to be fit for satellite calibration and validation from Sterckx et al. 2020.

Requirements for the in-situ observations include sufficient spatial and temporal coverage and information on their spatial and temporal representativeness (site characteristics and sampling design). Access to in-situ data need to be timely, open and sustainable. Ideally, in-situ observations uncertainty and uncertainty due to imperfect spatial and temporal co-location need to be well characterized. One rather mature example on the validation process of soil moisture Earth Observation product is described in Gruber et al. (2020; Figure 3). The arrangement of multiple reference data at a site (e. g. supersites with geophysical, geochemical and atmospheric data sets) would be highly beneficial for the validation of multiple products and sensors.

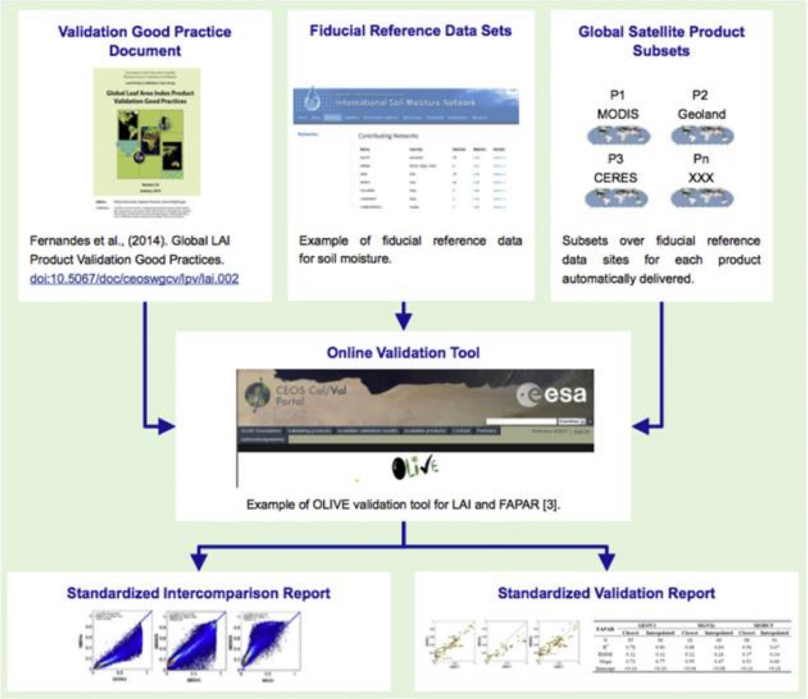

Figure 3. Soil moisture validation process as described in Gruber et al. (2020)

2.1 Requirements for in-situ observations

General quality requirements for in-situ measurements

Fiducial quality of in-situ measurements used for Earth Observation data validation consist of several aspects. Ideally, the in-situ measurements used should follow an un-broken processing chain that utilizes generally adopted standards, where measurement accuracy and uncertainty is routinely determined and documented. Further, the measurements should be long term and with known lifecycle, described with rich metadata and managed as well as shared following the FAIR-principles. These requirements are further described in Thorne et al (2017) as:

- Methodology used in the measurements and respective processing chain follow generally accepted standards and are well documented
- The measurement and its uncertainty are verified through complementary, redundant, observations of the same measurand on a routine basis.
- Uncertainties arising from each step in the processing chain used in deriving the final data product are fully quantified and included in the resulting data, regularly updated, documented
- Full metadata concerning the measurements is captured and retained and findable
- The observations/measurements are actively managed and shared following the FAIR principles and data provided is commitment to a long-term operation.
- Change management is robust including a sufficient programme of parallel and/or redundant measurements to fully understand any changes that do occur. Unnecessary changes are minimised.
- Measurements are accompanied with documentation noting the above-mentioned aspects, that is regularly updated and easily accessible for the users.

In practice, all these requirements are rarely achieved and organizations providing in-situ data have different maturity levels in the ability to provide measurements with fiducial quality. One of eLTER RI aims, however, is to develop the In-situ data provisioning for the main public Earth Observation data provider organizations and thus develop the quality of measurements provided.

Spatial and temporal representativeness

A basic assumption in the process of the validation of Earth Observation that the area measured on the ground at each sample plot can be spatially and temporally matched with the same area as observed by remote sensing (Rejou-Mechain et al. 2019). Several sources of deviations can lead to a spatial-temporal mismatch: (i) disagreement between field plot and pixels size and shape, (ii) spatial co-registration errors, (iii) a mismatch in the observed ecosystem components and (iv) a temporal difference in field and Earth Observation measurements.

To ensure the representation of the pixel size of the sensor, the site extent must be compatible with the spatial resolution of the sensor to be validated. However, because of geolocation inaccuracies and the point spread function effect, it is recommended to position the samples in homogenous areas and to define a larger site extent (3 x 3 or 5 x 5 pixels) than the minimum area compatible with the spatial resolution of the sensor and (Soto-Berelov et al.2018).

The sampling design for field measurements need to be defined by (i) the footprint of the measurement and (ii) the upscaling procedure that is used to integrate field measurements and high-resolution imagery. A multi-scale, two tier sampling scheme based on elementary and secondary sampling units is widely used in the acquisition of in-situ data for the validation of Earth Observation products (e.g. Baret et al. 2006, Hufkens et al. 2008, Figure 3). In this approach, elementary sampling units (ESUs) describe the variability of the product being validated across the study site. Secondary sampling units represent the locations where measurements are recorded and are distributed across the ESU. Within the ESU sampling design can vary (Morisette et al. 2006), such as fixed pattern, transects and randomised design.

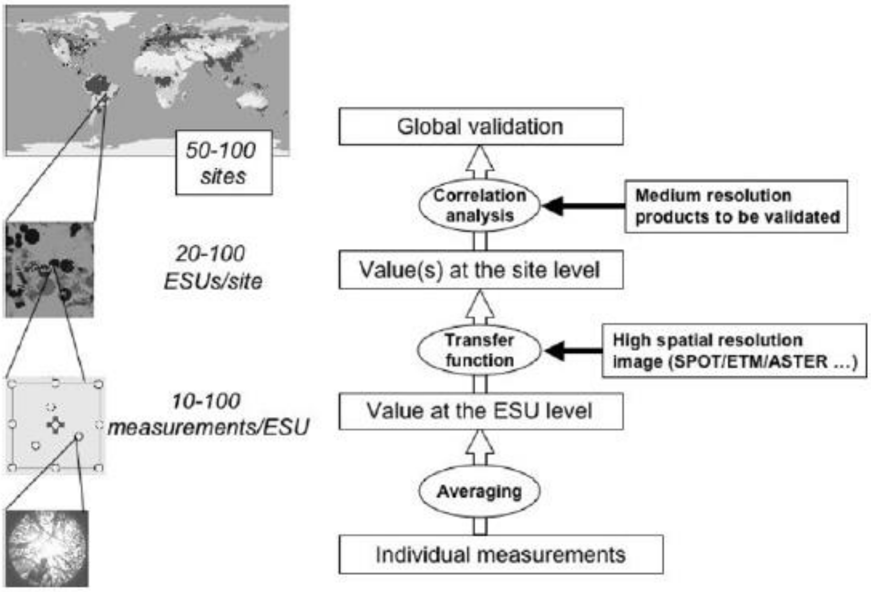

Figure 4. Validation and up-scaling procedure applied to LAI from Morisette et al. 2006.

For the validation of moderate resolution satellite products, field measurements are commonly upscaled through their integration with high resolution images (e. g. by a transfer function), thus providing a high resolution map of the variables measured in the field (see e.g. Morisette et al.2006, Baccini et al. 2007). In the upscaling procedure, the field measurements (at plot-scale) are extrapolated to a continuous spatial area that corresponds in scale to the spatial resolution of the Earth Observation product (Baccini et al. 2007). Upscaling approaches include:

1) Data driven/ structural approach
    a. Including spatial statistics through kriging techniques, which requires a spatial covariate, e.g. a vegetation index for upscaling of the Leaf Area Index (LAI).
2) Functional approaches
    a. Using a functional relation that relates the predicator variable to target variable (e.g. LAI to the Normalized Difference Vegetation Index (NDVI)),
    b. Based on causal relationships based on physical principles,
    c. Based on non-linear inversion of a radiative transfer model constraining parameters with the field measurements over the ESUs.

Examples for the structural and functional upscaling approach are described in Fernandez et al. (2014) for the validation of LAI.

To achieve temporal representativeness, the collection of in-situ data should be carried out close to the satellite overpass. The maximum delay between the satellite overpass and in-situ observations for validation is dependent on the dynamics of the observed variable.

2.2 Supersites for land product validation

The CEOS Working Group on Calibration and Validation (WGCV) on Land Product Validation (LPV) defined core sites for the satellite land product validation using the following criteria:

- Characterization of the canopy structure and bio-geophysical variables based on well-established protocols useful for the validation of satellite land products (at least 3) and for radiative transfer modelling approaches
- Active and long-term operations that are supported by appropriate funding and infrastructural capacity
- Supported by airborne LiDAR and hyperspectral acquisitions (desirable).

Supersites were selected from established networks, such as Integrated Carbon Observation System (ICOS) or National Ecological Observatory Network (NEON), or they were nominated by LPV focus areas. Sites were ranked for their suitability based on data availability and spatial representativeness. Furthermore, ranking was carried out on how many variables could be validated by site and if structural information and atmospheric and other properties were measured. Currently 55 globally distributed supersites were endorsed at the CEOS_LPV level https://lpvs.gsfc.nasa.gov/LPV_Supersites/LPVsites.html (CEOS Land Product Validation Subgroup (nasa.gov)).

3 eLTER SO’s and how they could serve EO calibration and validation

3.1 The relevance assessment of SO’s for the main Earth observation data providers

The eLTER RI has great potential in developing collaboration with the main public EO data providers (Table 1), especially Copernicus programme, and the future RI could contribute certain in-situ data with above-mentioned properties (Table 2).

Table 1: The main public EO data and service providers

EO data provider	Provider website
ESA	https://earth.esa.int/web/guest/home
Copernicus	https://www.copernicus.eu/en/copernicus-services
Eumetsat	http://www.eumetsat.int/website/home/index.html
USGS	http://earthexplorer.usgs.gov/
NOAA	http://www.ospo.noaa.gov/
NASA	https://earthdata.nasa.gov/earth-observation-data
Japan	http://www.eorc.jaxa.jp/en/about/distribution/index.html
China	http://www.cma.gov.cn/en
India	http://bhuvan.nrsc.gov.in/bhuvan_links.php

The requirements for in-situ observations (Table 2) were collected from the Copernicus in-situ component (Copernicus In-situ Information System (2020 a, b, c), GBOV (2020) and the CEOS WGCV LPV (http://calvalportal.ceos.org/). Furthermore, information was exchanged with the European Environmental Agency (EEA), coordinating the Copernicus In-situ component. Additional requirements from other relevant sources (including the Group on Earth Observation) were also considered. Requirements for in-situ data of the Copernicus services that were collected in the Copernicus In-situ Component Information System (CIS2) (Copernicus In-situ Information System,2020 a,b,c) were utilized in this report. In the discussion with the EEA, the cal/val needs for the Copernicus High Resolution Vegetation Phenology and Productivity (HRVPP) pan-European product were highlighted.

Here we list the identified SO’s and respective variables with Earth Observation product validation relevance in the 5 spheres of eLTER Whole System Approach (Mirtl et al., 2021 in preparation). It is important to note, that for many Earth Observation applications, there is not yet a well-defined protocol or method for the collection of insitu-observations provided. The validation activities are in many cases adjusted to the information available. Therefore, also the information on EO requirements collected in following tables are based on currently available information that can be updated as the protocols develop. A list of variables that are not included in the current list of eLTER standard observations, but which are relevant for the calibration and validation of Earth Observation products are included in the Annex I.

3.2 Geosphere

Table 2: eLTER SO's and variables related to eLTER WAILS Geosphere component and summary on related in-situ data requirements by global EO product providers for validation purposes.

SO	SO variable	Delineated requirements for in-situ observations to serve EO products
SOGEO_001 – Soil inventory – geological characterization	Soil texture, soil hydraulic conductivity, bulk density, organic matter, soil type classification. Characterized geological site conditions.	**Definition:** Topsoil physical and chemical characteristics (including texture, organic carbon content, CaCO) **Unit**: depend on the variable (e.g. Organic carbon content in g/kg for soil organic C) **Method and protocol:** Land Use and Coverage Area frame Survey (LUCAS, https://ec.europa.eu/eurostat/web/lucas/overview); soil sampling; 500 gr top-soil sample is taken in one out of 10 points. Physical and chemical analysis in a laboratory (Toth et al. 2013) **Spatial coverage of measurement/sampling scheme:** Multi-stage stratified random sampling (Toth et al. 2013) **Return interval:** ~5 years (depends on the application) **Time from field acquisition**: <=1 year **Related EO product:** Soil organic carbon content **Requirements from literature/CIS2 database/EO product**: No operational Copernicus product exists, related https://land.copernicus.eu/global/products/ssm and https://cis2.eea.europa.eu/requirement/199/ (surface soil moisture
SOGEO_002 – Soil temperature	Soil temperature	**Definition:** Soil temperature profile, 5 to 10 cm depth **Unit**: °C **Method and protocol:** Digital soil moisture sensors measuring dielectric constant, electric conductivity, and soil temperature **Spatial coverage of measurement/sampling scheme:** Distributed sampling scheme covering typical soil type and land cover classes of the satellite pixel (e.g. Soil Moisture and Ocean Salinity (SMOS) 25 x 25 km) (see e.g. Ikkonen et al. 2016; Copernicus Global Land Operations, 2021). **Return interval:** at approximate time of satellite overpass **Time from field acquisition**: Near Real-Time (NRT) to <= 1year (depends on the application) **Related EO product:** Soil freeze and thaw (https://earth.esa.int/eogateway/catalog/smos-soil-freeze-and-thaw-state); soil moisture content (https://land.copernicus.eu/global/products/ssm)

		Requirements from literature/CIS2 database/EO product: e.g. Dorigo et al. 2021, Ikkonen et al. 2016, related requirements https://cis2.eea.europa.eu/requirement/265/ (land surface temeperature)
SOGEO_003 – Soil chemical and physical characteristics	Organic carbon concentration, CEC Total nitrogen, total phosphorus, plant available N and P, pH, soil base saturation, bulk density (per horizon)	**Definition:** Topsoil physical and chemical characteristics (including texture, organic carbon content, CaCO) **Unit**: depend on the variable (e.g. Organic carbon content in g/kg for soil organic C) **Method and protocol:** Land Use and Coverage Area frame Survey (LUCAS, https://ec.europa.eu/eurostat/web/lucas/overview); soil sampling; 500 gr top-soil sample is taken in one out of 10 points. Physical and chemical analysis in a laboratory (Toth et al. 2013) **Spatial coverage of measurement/sampling scheme:** Multi-stage stratified random sampling (Toth et al. 2013) **Return interval:** ~5 years (depends on the application) **Time from field acquisition**: <=1 year **Related product:** Soil organic carbon content **Requirements from literature/CIS2 database/EO product**: No operational Copernicus product exists, but products are developed mostly at national scale for agriculture areas. c.f. Castaldi et al., 2019 a, b)

3.3 Hydrosphere

Table 3: eLTER SO's and variables related to eLTER WAILS Hydrosphere component and summary on related in-situ data requirements by global EO product providers for validation purposes

SO	SO variable	Delineated requirements for in-situ observations
SOHYD_001 – Profiles of physical and chemical water characteristics – surface waters (stagnant waters)	SAC 254 (Spectral Absorption Coefficient at 254 nm) turbidity water temperature,	**Definitions:** coloured Dissolved Organic Matter (cDOM) is optically active water quality parameter observable from space and related to the SAC254 measures. The turbidity describes water clarity that is affected by in-organic and organic matters in the water column. EO methods allow the estimation of the water temperature close to the surface layer. **Method and protocol:** see Carvalho et al. 2021; Mercator Ocean International, EUROGOOS, and CMEMS partners (2021) **Spatial coverage of measurement/sampling scheme:** transect or point source water quality measurements **Return interval:** at approximate time of satellite overpass **Time from field acquisition**: NRT time to once a year, depending on the product **Related EO product:** chlorophyll a concentration, secchi depth, algae blooms, total suspended matter, water colour/reflectances.

		Requirements from literature/CIS2 database/EO product: https://data.marine.copernicus.eu/products
SOHYD_009 – Ice cover	Ice cover stagnant water	**Definition:** Lake ice extent **Unit**: Categories **Method and protocol:** Exact definitions for in-situ measurement protocols for EO do not exists. Currently, e.g. Lake ice measurement standard, lake ice break-up and ice thickness and snow on ice thickness (VHJ, 1984); higher resolution satellite images are used in the validation of Lake ice extent. **Spatial coverage of measurement/sampling scheme:** Distributed observations preferred, but point measurements still useful **Return interval:** 1 day during the ice season **Time from field acquisition**: NRT to once a year **Related EO product:** Lake ice extent **Requirements from literature/CIS2 database/EO product**: https://land.copernicus.eu/global/products/lie/ https://cis2.eea.europa.eu/requirement/267/
SOHYD_010 – Snow cover and depths	Snow cover and depth	**Definition**: Snow extent is defined as the unique area of snow covered surfaces projected on the local horizontal datum within a spatial mapping unit at a specified time. Fraction of snow on land, extent of snow (Copernicus pan European in-situ requirements); Snow water equivalent: The water content obtained from melting accumulated snow. **Unit:** Binary snow cover: snow/non-snow. Snow cover fraction: expressed as a percentage or m^2 Snow Water Equivalent (SWE) : mm w.e. or kg m^{-2} **Method:** Mainly pointwise snow depth measurements (manual or sonic sounders) from weather stations; snow transect and webcam observations. Snow extent and SWE validation good practices are compiled in the ESA Satellite Snow product Intercomparison and Evaluation Experiment (SnowPEx, http://snowpex.enveo.at/). Exact definitions for in-situ measurement protocols for EO do not exists. **Spatial coverage of measurement/sampling scheme:** Distributed measurements covering different land cover classes of the satellite pixel preferred; point observation e.g. at meteorological stations still useful **Return interval:** 1 day during snow season **Time from field acquisition**: NRT to once a year (depends on the application) **Related EO product:** Snow cover extent, snow water equivalent **Requirements from literature/CIS2 database/EO product**::

		https://cis2.eea.europa.eu/requirement/268/; https://land.copernicus.eu/global/products/swe; https://land.copernicus.eu/global/products/sce
SOHYD_011 – Soil Water Content	Soil water content	**Definition:** Soil Moisture at 5 cm; Volume fraction of condensed water in soil **Unit**: $m^3.m^3$ **Method and protocol:** Probes deployment at permanent sites; Good practice guide for satellite validation by Montzka et al. (2020) **Spatial coverage of measurement/sampling scheme:** Samples need to capture full range of vegetation and moisture conditions; at least 15 sites/fields by pixel and at least 15 sampling points with 4 replicates for each site; minimize number of heterogenous variables in the field site (e.g. land cover, soil texture) **Return interval:** at approximate time of satellite overpass (soil moisture changes during the day) **Time from field acquisition**: NRT or at satellite overpass **Related product:** Soil moisture content **Requirements from literature/CIS2 database/EO product**: https://land.copernicus.eu/global/products/ssm/; https://land.copernicus.eu/global/products/swi https://cis2.eea.europa.eu/requirement/207/

3.4 Biosphere

Table 4: eLTER SO's and variables related to eLTER WAILS Biosphere component and summary on related in-situ data requirements by global EO product providers for validation purposes

SO	SO variable	Delineated requirements for in-situ observations
SOBIO_003 – Vegetation phenology – site scale		**Definition:** land surface phenology (LSP) describes the seasonal changes in vegetation greenness and photosynthetic leaf area at the landscape scale, including canopy greenup date (start of season), peak date, senescence date (end of season) and season length. **Unit:** start and end of season (day of year), length of season (days) **Method and protocol**: Plant phenological events can be obtained from eddy covariance measurements, ground-based imaging or continuous spectral measurements; species-specific phenological observations. Currently no validation protocol existing. CEOS LPVS is working on a validation good practice protocol and golden standard phenology validation database (CEOS Land Product Validation Subgroup (nasa.gov) **Return interval:** <= 1 week **Time from field acquisition:** 1 year **Related product:** Vegetation phenology (start and end of season)

		Requirements from literature/CIS2 database/EO product:: https://land.copernicus.eu/pan-european/biophysical-parameters/high-resolution-vegetation-phenology-and-productivity
SOBIO_004 - Vegetation composition – plot scale		**Definition:** Habitat type level required **Unit:** Categories **Method and protocols:** Transect and distributed sampling covering different habitat types within the satellite pixel. Exact definitions for in-situ measurement protocols for EO do not exists. **Return interval:** 5-10 years **Time from field acquisition:** 1-3 years depending on **Related EO product: Habitat maps** **Requirements from literature/CIS2 database/EO product**: e.g. https://land.copernicus.eu/local/natura
SOBIO_010 – Vegetation aboveground biomass – forest (site scale) and SOBIO_011 – Vegetation aboveground biomass – non-forested sites (site scale)	Above ground biomass	**Definition**: Defined as the above ground standing dry mass of live or dead matter from tree or shrub (woody plant) life forms, expressed as a mass or mass per unit area **Unit:** mass per unit area, typically Mg ha^{-1} **Method and protocol:** Derived from forest inventories, terrestrial laser scanning and airborne lidar (Duncanson et al. 2021) **Spatial coverage of measurement/sampling scheme:** Plot size 1 ha (0.25 minimum for dense forest), Squared plots,> 10-30 plots **Return interval:** ~5 years (depends on the application) **Time from field acquisition:** < 2 years **Related EO product:** Above ground biomass **Requirements from literature/CIS2 database/EO product**: https://catalogue.ceda.ac.uk/uuid/84403d09cef3485883158f4df2989b0c
SOBIO_012 – Leaf area index – forests (site scale)	Leaf Area Index (LAI)	**Definition:** LAI is defined as one half the total green leaf area per unit horizontal ground surface area (Chen et al. 1992). Green leaves correspond to vegetation matter capable of photosynthesis in ambient conditions. **Unit**: m^2 m^{-2} **Method and protocol:** Variety of valid methods for measuring LAI, Fernandez et al. 2014 **Spatial coverage of measurement/sampling scheme:** LAI of an Elementary Sampling Unit (of around 20x20m) and replicated for several locations depending on heterogeneity of the location. **Return interval:** < 10 years (depends on the application) **Time from field acquisition**: **Related EO product:** LAI **Requirements from literature/CIS2 database/EO product**: https://land.copernicus.eu/global/products/lai

3.5 Atmosphere

Table 5: eLTER SO's and variables related to eLTER WAILS Atmosphere component and summary on related in-situ data requirements by global EO product providers for validation purposes.

SO	SO variable	Delineated requirements for in-situ observations
SOATM_001 – Meteorological data	Relative air humidity Precipitation Air temperature Wind speed Surface atmospheric pressure	**Definition:** Wide range of data used for quality control, including atmospheric pressure, precipitation, air temperature and wind speed. **Unit**: according to variable **Method and protocol:** standard multi-parameter weather stations **Spatial coverage of measurement/sampling scheme:** Mainly distributed by the soil moisture monitoring sites in the frame of GBOV (2020). **Return interval:** at approximate time of satellite overpass **Time from field acquisition**: NRT **Related EO product:** soil moisture, ancillary information for quality control/ atmospheric correction of satellite products and soil moisture products **Requirements from literature/CIS2 database/EO product**: Various land products (see GBOV 2020)
SOATM002 – Radiation	PAR	**Definition:** FAPAR is generally defined as the fraction of photosynthetically active radiation (PAR) absorbed by vegetation, where PAR is the solar radiation reaching the vegetation in the wavelength region 400 nm to 700 nm. It is a dimensionless quantity varying from zero (over bare soil) to almost one for the largest amounts of green vegetation Unit: [ ] **Method and protocol:** Can be either derived from direct measurements or Digital Hemispherical Photographs (DHP) (GBOV, 2020, Brown et al. 2020). **Spatial coverage of measurement/sampling scheme:** The sampling strategy for FAPAR is based on the 'two-stage' or 'bottom-up' approach proposed by the CEOS WGCV LPV sub-group, which was originally developed for the validation of moderate spatial resolution LAI products (Brown et al.2020). **Return interval:** Depending on the dynamics of the vegetation dynamics; stronger change during beginning and end of the growing season **Time from field acquisition**: **Related EO product**: Fraction of absorbed Photosynthetically Active Radiation (FAPAR) **Requirements from literature/CIS2 database/EO product**: https://land.copernicus.eu/global/products/fapar
SOATM002 – Radiation	Global and solar radiation (diffuse and direct	**Definition:** Upward shortwave radiation (Shortwave radiation emerging from the ground)

	shortwave incoming radiation)	Downward total shortwave irradiance (Shortwave radiation incoming to the ground. This is the direct contribution i.e. incoming for the sun under a clear sky) Downward diffuse shortwave radiation flux (Shortwave radiation incoming to the ground. This “diffuse” radiation has been scattered by particles in the atmosphere such as cloud droplets and aerosols.), measured with cosine-collector light meter; Measured in the range 0.4 – 4 µm. **Unit**: W m^{-2} **Method and protocol:** measured with cosine-collector light meter; **Spatial coverage of measurement/sampling scheme:** **Return interval:** At time of satellite overpass **Time from field acquisition**: **Related EO product:** Top-of canopy reflectance/ Surface reflectance, Surface albedo **Requirements from literature/CIS2 database/EO product**: Various land products (see GBOV 2020)

3.6 Sociosphere

Table 6: eLTER SO’s and variables related to eLTER WAILS Sociosphere component and summary on related in-situ data requirements by global EO product providers for validation purposes

SO	SO variable	Delineated requirements for in-situ observations
SOSOC_019 – Land cover and structure (Orthophotos)	Land cover (*Orthophotos)*	**Definition:** Defined as the observed (bio)-physical cover on the Earth's terrestrial surface. Information and images on land cover and land cover change according to the EO classification systems (Copernicus global and pan European in-situ requirements) **Unit**: Categories or continuous variables (fraction of Tree Canopy Cover) **Method and protocol:** Very high-resolution imagery provided by commercial satellite constellations (RapidEye, PlanetScope); LUCAS survey with observations of land cover and land use, management and structural elements (https://ec.europa.eu/eurostat/web/lucas/methodology): Land cover validation guide by Strahler at al. (2006) **Spatial coverage of measurement/sampling scheme:** **Return interval:** 1-3 years; depending on land cover dynamics and land cover products **Time from field acquisition**: 1-5 year (depends on the application) **Related EO product:** Land cover/ use data products **Requirements from literature/CIS2 database/EO product**: https://cis2.eea.europa.eu/requirement/list/

4 Validation protocols and tools

The CEOS WGCV LPV subgroup aims to improve the quantitative validation of higher-level global land products from Earth Observation. Objectives of the group include the identification and support of global test sites for reference measurements, the development of best practice guides for data collection, description and procedures for validation, data exchange and management. Among others, the LPV has developed protocols for the validation of several Earth Observation products (https://lpvs.gsfc.nasa.gov/documents.html). Summaries for the collection of reference data for aboveground biomass and LAI are given in sections 4.2 and 4.3. Furthermore, the status of the validation guidelines for land surface phenology products under development is described. In addition to good practice guidelines for validation, LPV provides access to validation tools and data bases (section 4.5). To ensure that eLTER protocols for SO fit the Earth Observation product validation needs, it is encouraged to provide the finalized eLTER SO measurement protocols to CEOS LPV for feedback. In addition, eLTER is encouraged to contribute to the development and co-design of validation protocols (e.g. land surface phenology, section 4.3) and can contribute with measurements to established calibration and databases, such as DIRECT 2.0 (see section 4.4).

4.1 Aboveground biomass

To assist biomass map producers and to facilitate consistent and transparent biomass product uncertainty estimation, the CEOS WGCV LPV established a good practice protocol for the validation of aboveground woody biomass (Duncanson et al. 2021). The guidelines give recommendations for the collection of new biomass reference data and the selections of existing field stations.

The following criteria were established for the utilization of existing field sites for the validation of biomass products:

(1) Availability of at least 10 already established 1 ha permanent sampling plots, according to the best forestry standards. Within the plot, each stem is mapped, its diameter measured, and its species is identified. The plots must have been inventoried in the past (multiple censuses) and be accurately geolocated;
(2) Potential for airborne LIDAR scanning (ALS) coverage over at least 1000 ha, flown over the permanent plots; capacity to conduct new airborne LIDAR scanning coverage on a regular basis;
(3) Potential for terrestrial LIDAR scanning (TLS) of a subset of the sampling plots;
(4) Availability of a weather station and automated soil moisture monitoring (ideally encompassing the at new reference sites (Biomass Reference Measurement (BRM) sites) are given in Table 3 . More details on each measurement type as well as on the upscaling and error estimation (Table 2) can be found in Duncanson et al. (2021).

Table 4. Recommendation for new biomass reference data acquisitions from Duncanson et al. 2021, Table 0.1.

Recommendations for all data collections ● Data should be free and open access within at most 1 year after data collection ● Data should be acquired in collaboration with long term field plot networks and local partners wherever possible	
Field Plot Recommendations	**Airborne LIDAR Recommendations**
● Square plots	

○ Easier to link to gridded products ● Large plots (minimum 0.25 ha in tropics, ideally 1 ha plots with 0.25 ha or 0.04 ha subplots) ○ Minimizes edge effects and geolocation uncertainties ● Smaller plots (<0.25 ha) are acceptable outside of tropics provided airborne LIDAR available ● Stem-mapped where possible ● Geolocated with high accuracy, and reported uncertainties ● Trained botanist should be employed for species identification	● Minimum ~4 pulses/m^2 with 4 returns /pulse, but minimum is ecosystem-dependent. Ideally $\geq$ 8 pulses/m^2 ● Preferably acquired same season as field plots ● Acquired within 2 years, ideally 1, of field data acquisition ● Repeated every ~5 years or when disturbance is detected ● Wall-to-wall coverage of at least 10 km^2 ○ Cover both the plots and local environmental and forest structure gradient ○ Smaller area of coverage acceptable if only UAV-LS LIDAR available
Spatial Distribution of Field Plots ● Plots cover environmental gradients under airborne LIDAR collection that are locally or regionally correlated to biomass (e. g. topographic gradients) ● Sufficient number of plots collected to train a LIDAR model (min approximately 30, depending on complexity of system)	**Terrestrial LIDAR Recommendations** ● Data collection in new or existing long-term plots ○ Data augments field measurements, does not replace them ● 1 ha plots preferable ● Data acquired in a grid pattern ● Spacing 10 m in dense forests, 20 m in open areas ○ Can be changed to ensure consistent sampling and minimize occlusion ● Instrument must have ability to range tallest trees in 1 ha plots (150 m range) ● Repeated ~ every 5 years or when disturbance is detected ● Multiple scans need to be coregistered (either through use of targets or with sensor that has automatic coregistration)

Table 5. Recommendations for linking field, airborne and satellite data and error estimation from Duncanson et al. 2021, Table 0.2.

Linking field, airborne and satellite data	● Collect large, well geolocated, preferably square plots (see above) ● Develop local AGBD maps using high-quality wall-to-wall airborne LIDAR data and locally trained AGBD models ● Maps should be at the spatial resolution of plots or subplots and can be subsequently aggregated

	● Estimate and report per-pixel uncertainties in LIDAR AGBD maps to aid validation
Error estimation and propagation	● Error reporting should comply with Intergovernmental Panel on Climate Change (IPCC) good practices guidelines ● Measurement and modeling errors should be estimated following appropriate inference methods and propagated to mapped products

Table 6. CEOS Biomass acquisition recommendations (Duncanson et al. 2021)

Protocol/ Measurement	**CEOS recommendation**
Field plots	
Plot shape	Square
Plot size	1 ha (0.25 minimum in dense forest)
Subplot size	25x25 m
Stem map	Yes, where possible
Number of plots	>10 -30
Cover local gradients (topography, biomass, range, ect.)	Yes
Airborne LIDAR sampling	
Shot density	4 shots/m^2 minimum
Area	~3x3 km minimum
Return interval	~5 years
Time from field acquisition	<2 years
Terrestrial LIDAR sampling	
Plot size	1 ha
Sampling pattern	Grid
Spacing	10 m (dense veg.) 20 m (open veg.)
Return interval	~5 years
Instrument	Range >150 m

4.2 Leaf Area Index

A validation good practice guide for LAI was developed by Fernandez et al. (2014). Furthermore, the FRM4VEG (Fiducial Reference Measurements for Vegetation) project details FRM protocols and procedures for LAI (Brown et al. 2020). Sampling strategies for LAI are described in Baret et al. (2006).

According to the recommendation by the good practice guide a variety of methods and sampling schemes are valid for the characterisation of LAI. In the first version of the GBOV service (http://gbov.copernicus.acri.fr), LAI is computed through Digital Hemispherical Photographs (DHP) that are distributed via the NEON portal (GBOV 2020). Sites in the GBOV service are currently located in the United States only.

The following recommendation for data collection for LAI are given by the CEOS WGCV LPV (Fernandez et al. 2014, personal communication F.Camacho 24.10.2022) :

- The measurement site should be representative of the vegetation type, homogenous in land cover and preferably flat to avoid topographic effects. Heterogeneous sites and sites near urban and water areas are discarded.
- There are a number of instruments that are useful for the measurements of LAI, such as DHP, LAI-2200 or Ceptometer. For dense canopies Ceptometers are preferred to DHP. Both, overstory and understory need to be characterized.
- The ICOS protocol for LAI measurements is suitable for forests.
- For the field plots, the LAI of an ESU (of around 20x20m) needs to be characterized and associated with a GPS coordinate and replicated in several locations of the study site. The more homogeneous the site the lower the number of ESUs that is required. However, for upscaling a number of around 20 ESUs is convenient. For agriculture areas, which are heterogeneous, a stratified sampling per crop type is required and the ESUs of the main crops needs to be characterized.
- A frequency of measurements is encouraged to be < 10 years for calibration and validation purposes, but is dependent on vegetation dynamics.

To link field measurements to satellite data, the estimates should be upscaled using high resolution land cover maps or satellite/airborne measurements. For the upscaling, the protocols in Fernandez et al. 2014 can be followed or equivalent or superior protocols in terms of accuracy can be utilized. Reference maps should be aggregated.

4.3 Vegetation phenology

CEOS WGCV LPV is currently developing protocols for validation of Land Surface Phenology with all available independent observations (https://lpvs.gsfc.nasa.gov/Pheno/Pheno_home.html, Joshua Gray, personal communication, 05.10.2021). The eLTER community is encouraged to contribute to the development of the validation protocol. Next steps towards a good practices protocol include the preparation of a golden standard phenology validation database using standard algorithms on the reference data across all sites. The best available reference data for satellite-derived land surface phenology products are provided from networks of : ii) species specific phenological observations (e.g. the Pan European phenological project, http://www.pep725.eu/) and ii) ground-based imaging/continuous spectral measurements (e.g. European Phenological Camera Network, http://european-webcam-network.net/), SPECNET, https://specnet.info/ and the Phenological Eyes network, www.pheno-eye.org). Near-surface remote sensing with digital web cameras is an important source of validation data for satellite-derived land surface phenology. Guidelines for the observation of canopy phenology using digital cameras for the ICOS ecosystem sites were established by Wingate et al. (2015), including recommendations for camera installation, orientation, and processing as well as metadata. Instructions for the installation and set-up of cameras are also provided by the Phenocam Network in the US (https://phenocam.nau.edu/webcam/tools/). There are many algorithms available for the analysis of digital images to create time series of vegetation color indices and determine phenological dates. An example of an open-source software is the Phenopix R package (Filippa et al. 2014). It provides standardized processing algorithms for extraction of vegetation colour indices and the dates of phenological events. Additionally, software routines were developed by the Phenocam network in the US, e. g. for the delineation of the region of interest (xROI, https://github.com/bnasr/xROI).

The process of the determination of region of interests (ROIs) in the webcam scene from which to extract signals (e. g. Green Chromatic Coordinates) remains subjective. Some ROIs may represent a few square meters to hundreds of square kilometers and the variability in the scene constituents from one camera to the other may be high. Thus, although from the satellite phenology producer's perspective, web camera data are extremely valuable, the major challenge is the upscaling of the information of the ROI to a pixel. Drones have been used to map and monitor phenology with the advantage to link the web camera scale (temporal continuous but spatially limited to a certain field of view) with the satellite scale (spatially continuous but limited in spatial and temporal resolution). Despite the advantage of combining different approaches (camera, drone, satellite), standardized protocols are missing that define ground truthing needs, image acquisition, and processing in a way that all imagery is interoperable and can be used in the process of upscaling from camera and/or drone imagery to satellite pixels.

4.4 Validation tools and data bases

DIRECT 2.1

CEOS WGCV LPV has established a large collection of in situ measurements for the validation of satellite vegetation products (LAI, FAPAR, FCover). The DIRECT 2.1 database (https://calvalportal.ceos.org/lpv-direct-v2.1) contains data from several international activities covering over 176 sites around the world for the period 2000 to 2021. The ground data was upscaled over 3 km x 3 km using the methods described in the CEOS WGCV LPV LAI good practice guide. New ground validation sites can be included in the DIRECT database when criteria by CEOS/LPV are fulfilled. In the DIRECT database 3 km x 3 km areas were selected, however the resolution of satellite LAI maps is improving (Sentinel-2 at 10 m), thus homogeneous areas of lesser extent would be also useful.

Online Interactive Validation exercise (OLIVE)

The Online Interactive Validation Exercise (OLIVE) tool (https://calvalportal.ceos.org/web/olive/descriptions, Weiss et al. 2014) , established by CEOS WGCV LPV, is an example on how to make validation data sets open and accessible to the user community. The tool is designed for the validation of global LAI, FAPAR and FCOVER. It allows users to run validation exercises of new products against ground measurements (e. g. DIRECT), intercompare products and generate validation reports. Validation results can be made public or kept private.

The Quality Assurance for Soil Moisture (QA4SM) service

The Quality Assurance for Soil Moisture (QA4SM) services (https://qa4sm.eu/ui/home) provides an easy interface for the comparison of satellite soil moisture data against in-situ measurements from the international soil moisture network and against land surface models. It provides the user traceable validation results as well visualizations and reports.

4.5 A framework to evaluate the maturity of in-situ observations for EO validation

The eLTER RI’s capability to provide in-situ observations is based on the network of more than 500 sites and over 50 larger LTSER Platforms across Europe and biogeographical regions. The RI aims for harmonised and standardised data provisioning as a service from these sites. However, eLTER RI is currently on its construction phase and consists of various entities and organizations with history of different practices, norms and data policies. Thus, involved sites and platforms currently possess different capabilities to provide in-situ observations as a service.

In-situ data provisioning for the main public Earth Observation data provider organizations is one of the provisional and currently developed services of the eLTER RI. Here we propose a general framework to evaluate the maturity of in-situ data provisioning to serve EO validation activities to identify current gaps and development needs for the RI.

The proposed framework is based on the general satellite data validation requirements for in-situ observations described in Sterckx et al. (2020). Thus, the ideal in-situ data for EO validation should be with fiducial quality, accessible, co-located. timely available, should have sufficient spatio-temporal coverage and include long term records. To further delineate these requirements, we applied parts from the framework by Thorne et al. (2017) that presented a more quantifiable assessment on the maturity of observational capabilities. Their assessment tool included aspects such as the observational data should be well documented, well understood, representative, updated, publicly available and maintains rich metadata. Further, in the construction of the maturity evaluation tool we applied the FAIR principles and requirements for those (how to assess the Findability, Accessibility, Interoperability and Re-usability of data provided (e.g. https://www.go-fair.org/fair-principles/). We applied all the above-mentioned frameworks and further developed them to allow relatively easy but sufficient evaluation for in-situ data provisioning capability to support EO validation data requirements.

The presented evaluation framework on the suitability of in-situ observations to support EO validation activities includes following aspects 1) Metadata maturity, 2) Data findability and accessibility, 3) Data documentation and fiducial quality, 4) Temporal resolution of measurements, 5) Data update frequency, 6) Spatial coverage and 7) Long term records. The evaluation is based on the scores given depending on the response to claims under each aspect. The evaluation is conducted with a simple excel form (Annex 2) and an exemplar result diagram from the evaluation is presented in Figure 4.

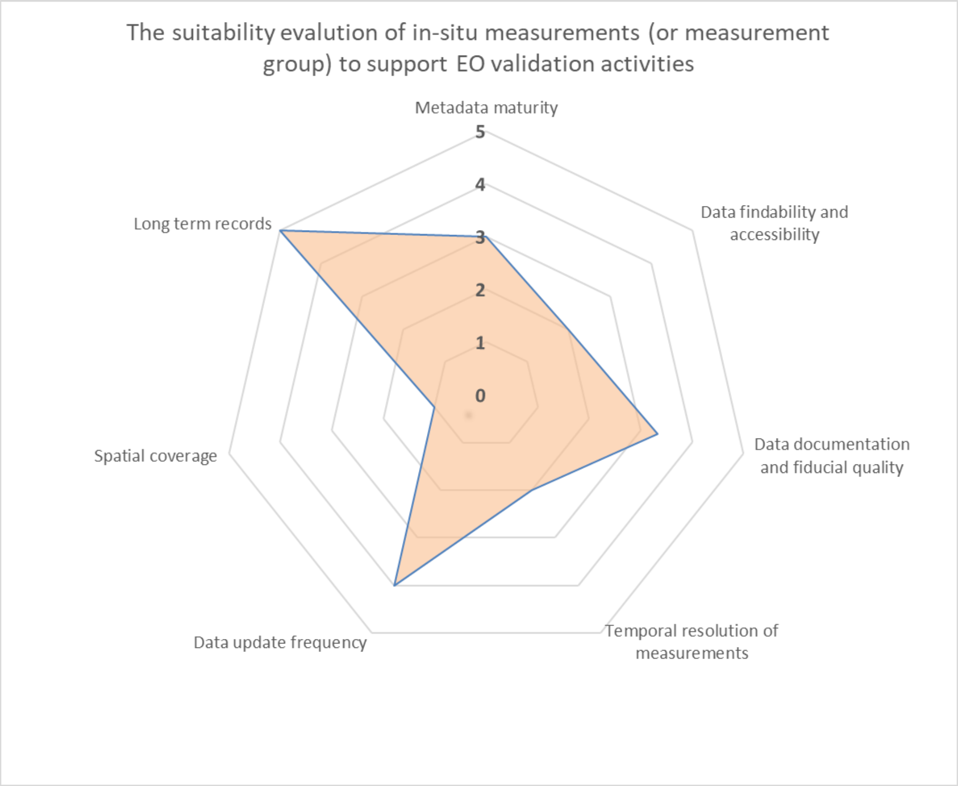

Figure 5. An example on the visualisation on maturity evaluation of in-situ observations to support EO validation activities

5 A look to upcoming public satellite missions relevant for ecosystem monitoring

More than 1400 Earth Observing satellites have been launched by public and private actors since 2000 addressing a variety of application areas (European Patent Office, 2022). Here we take a look to few recent and upcoming public satellite missions with potential relevance for ecosystem monitoring. This review is not complete and e. g. private- and nanosatellite systems are not considered. Collected information is merely aimed to identify the major upcoming satellite mission contributing to global and public research in upcoming years with relevance for the eLTER RI.

5.1 SWOT (Surface Water and Ocean Topography)

by NASA, CNES

Instrument type: Altimeter/interferometry

Launch year: 2022

Main applications: Ocean surface topography, changes in floodplains and wetlands, freshwater flows, regional shifts in sea level

Web-site: https://swot.jpl.nasa.gov/

Description from the web-site: U.S. and French oceanographers and hydrologists and international partners have joined forces to develop the Surface Water and Topography (SWOT) satellite mission to make the first global survey of Earth's surface water, observe the fine details of the ocean's surface topography, and measure how water bodies change over time. The data will help with monitoring changes in floodplains and wetlands, measure how much freshwater flows into and out of lakes and rivers and back to the ocean, and track regional shifts in sea level. SWOT is being jointly developed by NASA and Centre National D'Etudes Spatiales (CNES) with contributions from the Canadian Space Agency (CSA) and United Kingdom Space Agency. SWOT is scheduled to launch in 2023. https://science.nasa.gov/earth-science/earth-missions-future

5.2 EnNMAP (The Environmental Mapping and Analysis Program)

By DLR

Instrument type: Optical, multi-spectral

Launch year: 2022

Main applications:. Earth ecosystems at global scale with 30m spatial resolution

Web-site: https://www.enmap.org/mission

Description from the web-site: The Environmental Mapping and Analysis Program (EnMAP) is a German hyperspectral satellite mission that aims at monitoring and characterising Earth’s environment on a global scale. EnMAP measures and models key dynamic processes of Earth’s ecosystems by extracting geochemical, biochemical and biophysical parameters that provide information on the status and evolution of various terrestrial and aquatic ecosystems. For more information about the main objectives and the status have a look at the mission page (https://www.enmap.org/)

5.3 Biomass mission

By ESA

Instrument type: P-band synthetic aperture radar

Launch year: 2024

Main applications: forest biomass, carbon stock and fluxes

Web-site: https://earth.esa.int/eogateway/missions/biomass

Description from the web-site: The objective of the Biomass mission is to determine the global distribution of forest biomass by reducing the uncertainty in the calculation of carbon stock and fluxes associated with the terrestrial biosphere.

Selected as ESA's seventh Earth Explorer in May 2013, the Biomass mission will provide crucial information about the state of our forests and how they are changing. The data will be used to further our knowledge of the role forests play in the carbon cycle. Biomass will also provide essential support to UN treaties on the reduction of emissions from deforestation and forest degradation. The Biomass launch is expected around April 2024 and is planned to be a five-year mission.

5.4 PACE (Plankton, Aerosol, Cloud, ocean Ecosystem)

By NASA

Instrument type: Optical, multi-Spectral,

Launch year: 2024

Main applications: phytoplankton, clouds, and aerosols

Web-site: https://pace.gsfc.nasa.gov/

Description from the web-site: NASA’s Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission will study phytoplankton, clouds, and aerosols to provide insights into oceanographic and atmospheric responses to Earth’s changing climate, as well as investigate the diversity of organisms fueling marine food webs. PACE will also continue systematic records of key atmospheric variables associated with air quality and climate, continuing more than two decades of NASA satellite observations of global ocean biology, aerosols, and clouds. One of PACE's primary instruments, the Ocean Color Instrument (OCI), will be the most advanced sensor for observing ocean color in NASA's history, enabling continuous measurement of light at finer wavelength resolution without the blank spots of previous sensors. PACE will launch in 2024. (https://science.nasa.gov/earth-science/earth-missions-future)

5.5 GeoCarb

By NASA

Instrument type: Grating spectrometers

Launch year: 2024

Main applications: key greenhouse gases and vegetation health

Web-site: https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2

Description from the web-site: A new NASA Earth science mission in the early stages of design may achieve a transformational advance in our understanding of the global carbon cycle by mapping concentrations of key carbon gases from a new vantage point: geostationary orbit. Satellites in geostationary orbit travel at the same speed as Earth’s rotation, allowing them to remain over the same place on Earth’s surface at all times.

5.6 FLEX (The FLuorescence Explorer)

By ESA

Instrument type: Imaging spectrometer

Launch year: 2025

Main applications: Global photosynthetic activity, plant health and stress

Web-site: https://earth.esa.int/eogateway/missions/flex

Description from the web-site: The FLuorescence EXplorer (FLEX) mission will provide global maps of vegetation fluorescence that can reflect photosynthetic activity and plant health and stress. An imaging spectrometer in the red-near infrared to pick out plant fluorescence. FLEX is expected to be launched in 2025, with a three and a half year design lifetime.

5.7 Libera

By NOAA

Instrument type: Radiometer

Launch year: 2027

Main applications:

Web-site: www.nasa.gov/press-release/nasa-selects-new-instrument-to-continue-key-climate-record

Description from the web-site: Libera, slated to launch on NOAA's Joint Polar Satellite System-3 (JPSS-3) satellite in December 2027, will continue more than 40 years of recording the balance between solar radiation entering Earth's atmosphere and the amount absorbed, reflected, and emitted. The radiation balance is essential to understand climate warming and cooling. Development of the NASA-funded instrument is being led at the University of Colorado, Boulder, Laboratory for Atmospheric and Space Physics. Libera, named for the Roman goddess of agriculture, will measure the radiation budget alongside the Clouds and the Earth's Radiant Energy System (CERES) instruments currently operating on NASA and National Oceanic and Atmospheric Administration (NOAA) satellites. (https://science.nasa.gov/earth-science/earth-missions-future)

5.8 List of Copernicus high priority candidate (not confirmed) missions

Several interesting satellite missions relevant for ecosystem monitoring are still on the candidate level. Here is one list of Copernicus high priority candidate mission (acquired 30.11.2022 from https://climate.esa.int/en/evidence/esa-missions-relating-climate/#future-missions-for-climate)

- CO2M: a relatively high spatial-resolution imaging spectrometer to track individual sources of CO_2, and discriminate between anthropogenic and natural sources of the gas.
- CHIME:
  Copernicus Hyperspectral Imaging Mission for the Environment, planned 2028, Multispectral (visible, near, shortwave infra)
  A hyperspectral imager to return detailed information on the health of plants, coastal mapping and land-cover mapping. To provide routine hyperspectral observations through the Copernicus Programme in support of EU- and related policies for the management of natural resources, assets and benefits.

- LSTM: A thermal infrared radiometer to measure land-surface temperature and rates of evapotranspiration in unprecedented detail.
- CRISTAL: An altimeter to measure the height of Earth's ice fields - it will map sea-ice thickness and snow depth, as well as ice elevation on land.
- ROSE-L: An L-band radar to observe ice but many other targets as well, including forests, different crop types, and soils.
- CIMR: A microwave radiometer to measure sea-surface temperature, salinity, and sea-ice concentration.

6 Proposed roadmap for the eLTER RI

Here we have identified general steps for the eLTER RI construction phase required to develop research infrastructure to be able to serve the validation processes of the main EO data providers. As the main EO data providers, we denote the major organizations and their programs providing Earth Observation data products and especially the Copernicus program. All the recommendations are subjected to further discussion, comments and decision from the eLTER RI's lead.

The identified key-steps for the required development are:

Step 1. Identification of eLTER SO's relevant for the main EO data product validation processes

Step 2. Defining the EO cal/val requirements for the LTER SOs

Step 3. Defining the requirements for the eLTER RI development

Step 4. Development of the organization and technical capability of the eLTER RI

Step 5. Uptake of eLTER SO data in the cal/val processes of the main EO data providers

Step 6. Operational data provision of eLTER RI integrated to the validation processes of the main EO data provider

From the recommendations above, the steps 1 and 2 are already included in the eLTER Plus WP3 and WP4 work. Step 3 tasks can potentially be re-planned as a joint action performed under the eLTER Plus WP4 (eLTER Information Clusters populated from multiple sources). In addition, nexus and joint actions should be planned with other eLTER Plus WPs, especially WP11 (ICT service piloting and dissemination of data products) and WP3 (Interoperability of eLTER Standard Observation variables – the user perspective). The resources for the partners needed to commit to this task can potentially be re-allocated from the current eLTER Plus project tasks.

The development of the organizational and technical capability of the eLTER RI to be able to serve major EO data providers with validation data (steps 4 and 5) and operational data provision (step 6) require a dedicated work plan, aims and funding to be completed successfully. Noteworthy is that for the steps 4-6, also a systematically maintained plan for updating the in-situ requirements together with the data users should be included in the development.

In addition, we recommend establishing a guidance group for the development with representativeness at least from the Copernicus In-situ component lead by EEA, relevant subgroups of the CEOS calibration & validation workgroup, GBOV (Ground-Based Observations for Validation as part of the Copernicus Global Land Service), ESA and from the lead of eLTER RI.

The identified steps are presented in the Fig. 6, with proposed time scale for the development

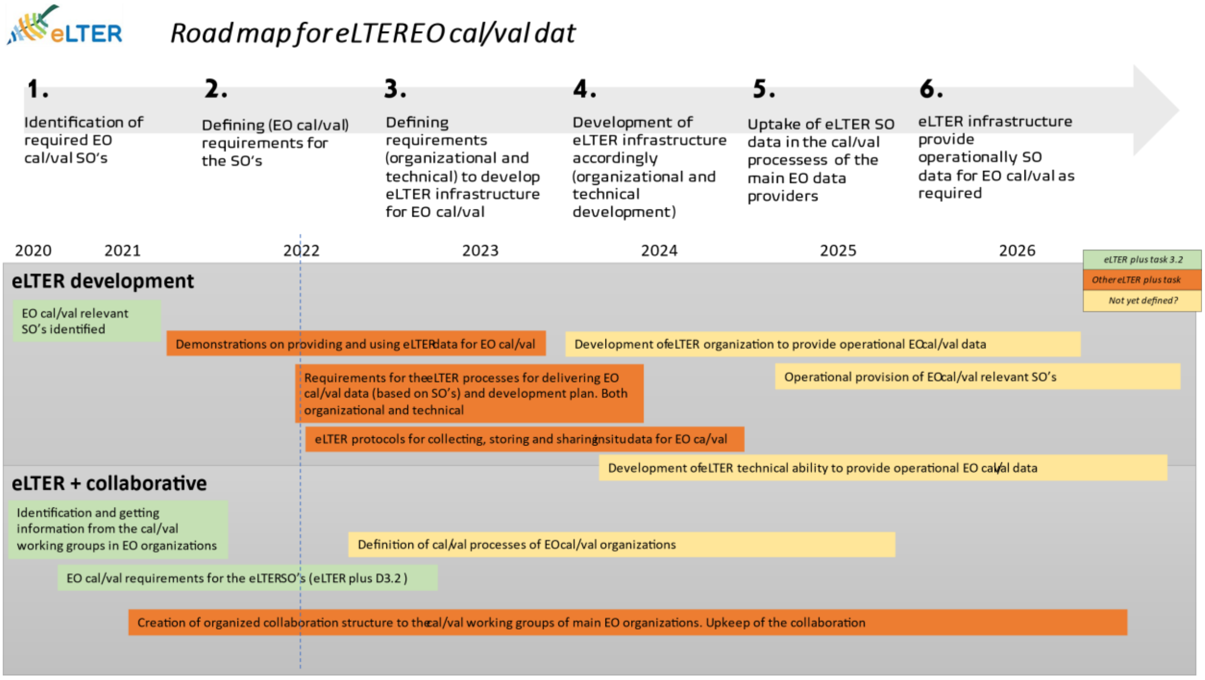

Fig 6. Proposed road map and key steps for the eLTER RI development to be able to serve the validation processes of the main EO data providers

7 Summary

The purpose of this document is to advance and define requirements for the eLTER RI to be able to serve validation processes of the major Earth Observation (EO) data providers. Here we described the general requirements for in-situ data and identified current eLTER Standard Observations (SOs) that are mostly needed in the calibration and validation processes of the main EO data providers.

We also gave a view to the current validation protocols and tools used in the cal/val processes as well as described a framework to evaluate the maturity of in-situ observations for EO validation. Finally, we identified key steps for the eLTER RI required to develop research infrastructure activities to be able serve these validation processes.

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Annex 1

Here we list variables identified relevant for the calibration and validation of Earth Observation products, but which are not included in the current list of eLTER standard observations (Zacharias et al., 2022). The list of eLTER RI SO's is, however, planned to be evaluated and updated regularly according to the user needs. Therefore, variables from the following table can be included if requested by the EO community.

Table A1: List of variables relevant for the calibration and validation of Earth Observation products and which are not included in the current list of eLTER standard observations.

Variable	Definition and method
Land surface temperature [K, °C]	Aggregated radiometric surface temperature based on a measure of radiance. Measured by radiometer or temperature sensors mounted on permanent stations (GBOV, 2018)
Land surface emissivity []	Ratio of the power emitted by an object to the power that would be emitted by a perfect black body having the same temperature as the object. Measured through field experiments, rarely on permanent ground stations (GBOV, 2018)
Direct/diffuse thermal radiation [W m^{-2}]*	Broadband and multispectral thermal infrared radiation in the upwelling and downwelling direction at the surface [4.0 – 25 µ], Upward thermal radiation (W.m-2) (Thermal radiation flux emerging from the ground.) Downward thermal radiation (W.m-2) (Thermal radiation flux incoming from the ground.) (GBOV, 2018), measured with cosine-collector light meter
Surface reflectance or Top of canopy reflectance [] *	Ratio of the reflected to incident radiation; Two types of data are available: a ground albedometer footprint, representing 1 km$_2$, and a 3 x 3 upscaled macropixel computed by satellite images (GBOV, 2020); Protocols by the FRMV project (Origo et al. 2020)
Fire/ burned area	Burned Area is defined as the area affected by wildfires. Active Fire is the location of burning at the time of the observation. Fire Radiative Power is the rate of emitted radiative energy by the fire at the time of the observation Reference data for burned area is generated by Landsat class imagery. Active fires are validated with simultaneous observations with higher resolutions. Validation of radiative power requires coincident unsaturated radiance measurements (https://lpvs.gsfc.nasa.gov/Fire/Fire_home.html)
Surface albedo	Defined as the ratio of the radiant flux reflected from a unit surface area into the whole hemisphere to the incident radiant flux of hemispherical angular extent (Schaepman-Strub et al., 2006). It can be defined for broad spectral regions or for spectral bands of finite width. Good practice guide in Wang et al. (2019).

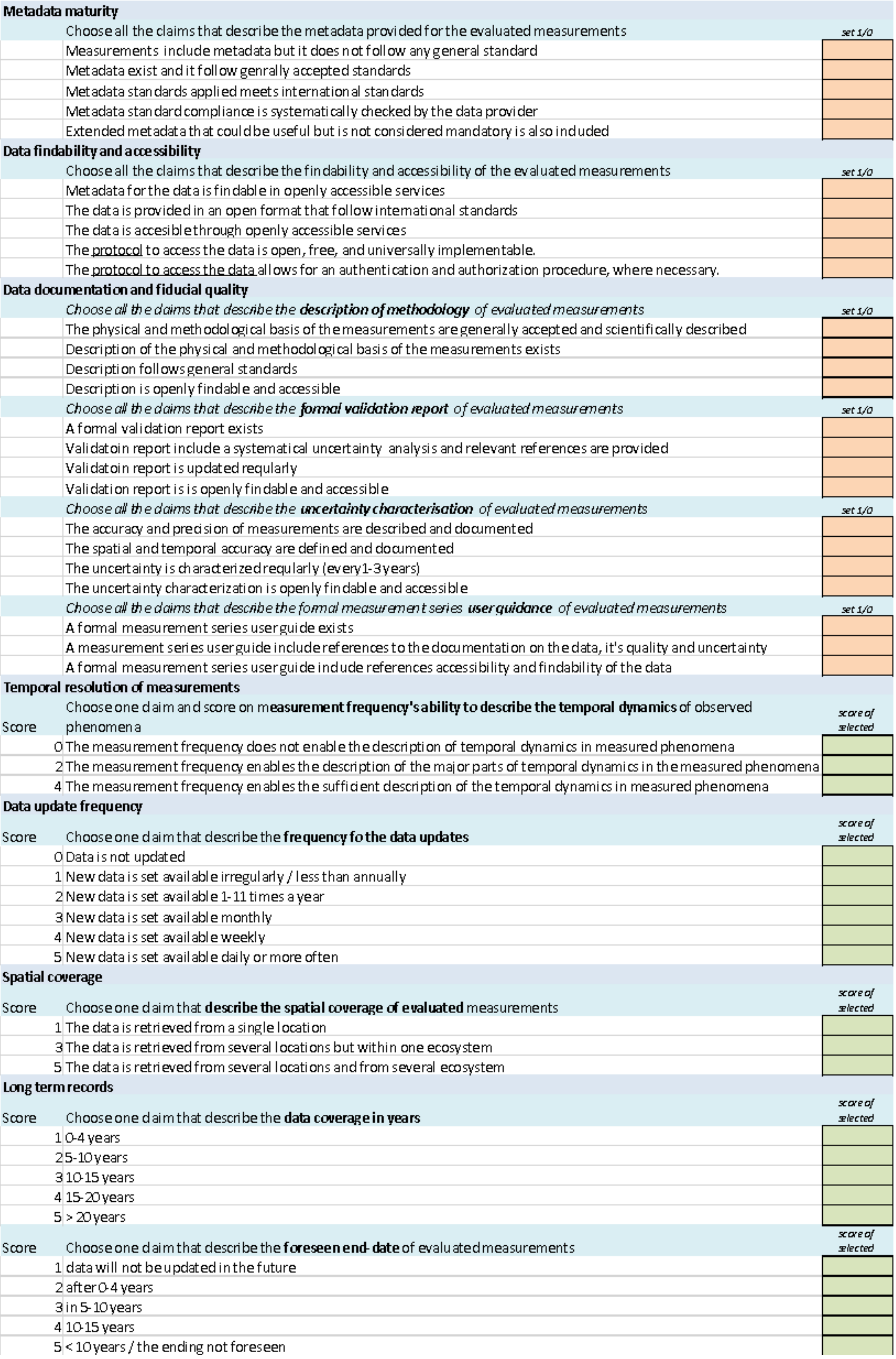
Variable	**Definition and method**
Soil BRF	Hyperspectral Bidirectional Reflectance Factor Schaepmann-Strub et al. (2006), Systematic airborne campaigns over stations every 3 years (GBOV, 2018).
Vegetation structure **	Terrestrial Laser scanning, forest inventories; Airborne Lidar (GBOV, 2018)
Gross and net primary productivity [g C m^{-2} yr^{-1}]	Gross primary productivity is the amount of carbon fixed by plants/ primary producers through photosynthesis per unit time. Net primary productivity is the difference between the GPP and respiration. Derived from Eddy covariance measurements
Canopy Chlorophyll content	Canopy Chlorophyll Content (CCC) is defined as the product of leaf chlorophyll concentration (LCC) and LAI. LCC is expressed as the mass of chlorophyll per unit leaf area, whist LAI is a dimensionless quantity defined as the one-sided leaf area per unit ground area LCC is determined by destructive sampling and laboratory analysis (see Brown et al. 2022).
Habitats and biotopes / vegetation ground measurements	Various ground measures of vegetation type, cover and habitats. Requirement from Copernicus In-situ Information System; Report for Service Component: Global Land Component (GLC) ("The most shared Requirement is "Vegetation Ground Measurements", which is because this is an essential input to the global vegetation and broader Products.")
Atmospheric properties	Aerosol optical depth, Angström exponent Ancillary information for satellite retrievals and atmospheric correction
Direct/diffuse thermal radiation [W m-2]	Broadband and multispectral thermal infrared radiation in the upwelling and downwelling direction at the surface [4.0 – 25 µ], Upward thermal radiation (W.m-2) (Thermal radiation flux emerging from the ground.) Downward thermal radiation (W.m-2) (Thermal radiation flux incoming from the ground.) (GBOV, 2018), measured with cosine-collector light meter;
Plankton pigments (chlorophyll a, phycocyanin)	Laboratory analysis or optical measurements on the plankton pigment concentrations in the water (mg/l)
Water secchi depth / water transparency	Estimations on the water transparency either with optical devices or with traditional secchi disk
Algae blooms	Measures of plankton pigments and/or visual observations on the algae blooms
Total suspended matter	Total suspended matter concentration in the illuminated water column

Variable	Definition and method
Water colour/reflectances	Out-welling reflectance spectra from the water

** Variable described differently or with less detailed methods in eLTER SO's

Annex 2.

An evaluation tool for the maturity assessment of in-situ observations to serve EO validation activities created by applying and further developing frameworks described in Sterckx et al. (2020), Thorne et al. (2017) and https://www.go-fair.org/fair-principles/ .



Metadata maturity		
	Choose all the claims that describe the metadata provided for the evaluated measurements	*set 1/0*
	Measurements include metadata but it does not follow any general standard	
	Metadata exist and it follow genrally accepted standards	
	Metadata standards applied meets international standards	
	Metadata standard compliance is systematically checked by the data provider	
	Extended metadata that could be useful but is not considered mandatory is also included	
Data findability and accessibility		
	Choose all the claims that describe the findability and accessibility of the evaluated measurements	*set 1/0*
	Metadata for the data is findable in openly accessible services	
	The data is provided in an open format that follow international standards	
	The data is accesible through openly accessible services	
	The protocol to access the data is open, free, and universally implementable.	
	The protocol to access the data allows for an authentication and authorization procedure, where necessary.	
Data documentation and fiducial quality		
	Choose all the claims that describe the ***description of methodology*** *of evaluated measurements*	*set 1/0*
	The physical and methodological basis of the measurements are generally accepted and scientifically described	
	Description of the physical and methodological basis of the measurements exists	
	Description follows general standards	
	Description is openly findable and accessible	
	Choose all the claims that describe the ***formal validation report*** *of evaluated measurements*	*set 1/0*
	A formal validation report exists	
	Validatoin report include a systematical uncertainty analysis and relevant references are provided	
	Validatoin report is updated regularly	
	Validation report is is openly findable and accessible	
	Choose all the claims that describe the ***uncertainty characterisation*** *of evaluated measurements*	*set 1/0*
	The accuracy and precision of measurements are described and documented	
	The spatial and temporal accuracy are defined and documented	
	The uncertainty is characterized regularly (every 1-3 years)	
	The uncertainty characterization is openly findable and accessible	
	Choose all the claims that describe the formal measurement series ***user guidance*** *of evaluated measurements*	*set 1/0*
	A formal measurement series user guide exists	
	A measurement series user guide include references to the documentation on the data, it's quality and uncertainty	
	A formal measurement series user guide include references accessibility and findability of the data	
Temporal resolution of measurements		
Score	Choose one claim and score on m**easurement frequency's ability to describe the temporal dynamics** of observed phenomena	*score of selected*
0	The measurement frequency does not enable the description of temporal dynamics in measured phenomena	
2	The measurement frequency enables the description of the major parts of temporal dynamics in the measured phenomena	
4	The measurement frequency enables the sufficient description of the temporal dynamics in measured phenomena	
Data update frequency		
Score	Choose one claim that describe the **frequency fo the data updates**	*score of selected*
0	Data is not updated	
1	New data is set available irregularly / less than annually	
2	New data is set available 1-11 times a year	
3	New data is set available monthly	
4	New data is set available weekly	
5	New data is set available daily or more often	
Spatial coverage		
Score	Choose one claim that **describe the spatial coverage of evaluated** measurements	*score of selected*
1	The data is retrieved from a single location	
3	The data is retrieved from several locations but within one ecosystem	
5	The data is retrieved from several locations and from several ecosystem	
Long term records		
Score	Choose one claim that describe the **data coverage in years**	*score of selected*
1	0-4 years	
2	5-10 years	
3	10-15 years	
4	15-20 years	
5	> 20 years	
Score	Choose one claim that describe the **foreseen end-date** of evaluated measurements	*score of selected*
1	data will not be updated in the future	
2	after 0-4 years	
3	in 5-10 years	
4	10-15 years	
5	< 10 years / the ending not foreseen	

Annex 3.

The eLTER SO's are closely related to the Essential Variables described under several domains including e.g. climate, (ECVs), Biodiversity (EBVs) and Ocean (EOVs) (c.f. Maso et al., 2019). Some of the Essential Variables can be derived by using to the existing Earth Observation products and have been previously assessed (Table x; Böttcher et al., 2020, unpublished).

Table x. Remote sensing enabled Essential variables included in the biodiversity, climate and ocean frameworks (Böttcher et al., 2020, unpublished)

EV	**Essential variable and respective measurements by EO**
EBV	Primary productivity / Gross and net primary productivity and variables that are needed in their calculation/modelling: FAPAR, LAI, above ground biomass (link to ECVs)
EBV	Ecosystem phenology / Ecosystem phenology or land surface phenology (start, max and end of season)
EBV	Taxonomic diversity / Percentage of species which grow or occur together
EBV	Ecosystem distribution
ECV	Snow / Area covered by snow
ECV	Land cover / Maps of high-resolution land cover
ECV	Lake Color/Lake Water Leaving Reflectance
ECV	Ocean Color / Water Leaving Reflectance; Chlorophyll-a Concentration
EOV	Phytoplankton biomass and diversity / Spectral reflectance, harmful algal bloom indices, including Harmful Algal Events
EOV	Ocean color / Water Leaving Reflectance; Chlorophyll-a Concentration
EOV	Sea surface temperature/ Sea surface temperature
EOV	Dissolved organic carbon / aCDOM