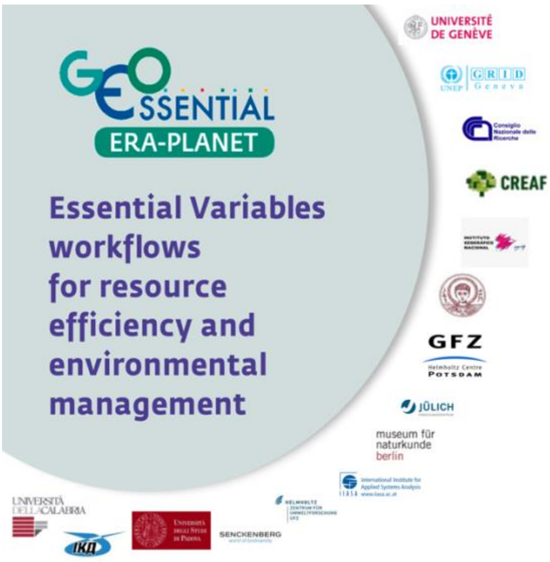

Deliverable 3.3

Report on the existing validation practices for Essential Land Variables (ELVs) derived from Earth Observation

Creator	Bagher Bayat and Carsten Montzka (FZJ, Germany)
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Introduction

Earth observation offers a unique source of information to quantify essential variables (EVs) in land domain and monitor their variations over various scales. Hereafter, we use the term essential land variables (ELVs) to refer to such EVs in this report. The first question popping up for the end-users of ELV products is: *how good/reliable is a specific ELV product derived from earth observation?* Addressing this question is rather challenging and often very specific for a product and/or a ELV. To answer this question properly and to find general characteristics valid for all ELVs, one needs to investigate existing validation practices (standards) for the most important earth observation ELVs products. Although earth observation products offer suitable spatial and temporal coverage, their accuracies and uncertainties should be independently evaluated against in situ reference data before further utilization through standard validation practices. Conducting proper validation is not straightforward either. This deliverable summarizes current earth observation methods, available in situ networks, observations requirements and existing validation practices for ELVs.

Selected ELVs: definitions and importance

An EV is defined by the Global Climate Observing System (GCOS) and endorsed by the United Nation Framework Convention on Climate Change (UNFCCC) as “a physical, chemical, or biological variable or a group of linked variables that critically contributes to the characterization of Earth’s climate”. EV datasets are a sort of empirical evidence which facilitates understanding, quantifying, and predicting the evolution of environmental ecosystems. These datasets can also guide mitigation and adaptation actions, evaluate risks, and enable relating events to underlying causes and justify environmental services [1]. EVs should not be considered as a group of stand-alone variables; they are rather part of a broader concept. There are three main criteria for selecting a variable as an EV as follows:

1. Relevance: the variable is crucial to characterize the system and to monitor its changes
2. Feasibility: Obtaining the variable at the global scale is operationally feasible using an understood scientific approach
3. Cost-effectiveness: Generating and archiving the variable in the desired scale and accuracy is affordable

Nowadays, progress in earth observation and satellite technology makes it possible to obtain the majority of EVs and quantify their spatio-temporal variations. In this report, we focus on exploring some of the most important and widely-used terrestrial EVs, called ELVs, retrievable from earth observation data, available in situ measurements, their challenges and validation practices. Table 1 briefly presents the selected ELVs, their definitions, and importance.

Table 1. The selected ELVs, their definitions, and importance

ELVs	Abbr.	unit	definition	importance	reference
Leaf Area Index	LAI	[m^2 m^{-2}]	LAI is defined as one-half the total green leaf area per unit ground surface area. This describes the amount of ecosystem canopy leaf material.	LAI is a key variable controlling canopy photosynthesis, evapotranspiration, respiration, and rain interception. It is needed in the majority of hydrological and land surface models as an input to consider vegetation-atmosphere interactions.	[2], [3]
Land Surface Temperature	LST	[K]	LST is defined as the accumulated radiometric temperature of the surface elements located in the sensor's field of view.	LST is a key variable for understanding land surface processes and land-atmosphere exchanges and interactions. It is used extensively to constrain land surface energy budgets and climate models' parameters.	[4], [5]
Evapotranspiration	ET	[mm day^{-1}]	ET is defined as the sum of evaporation from soil, plant (known as transpiration) and ocean surface to the atmosphere.	ET is a key component of the surface energy balance and the water cycle. ET is essential for environmental research, water resource management, and sustainable development of agriculture.	[6]
Soil Moisture	SM	[m^3 m^{-3}]	The volumetric SM is defined as the ratio of the volume of the water to the total volume including dry soil, air, and water of a soil sample. Here we refer to surface SM (up to 5 cm soil depth)	SM is a key variable in the atmospheric water cycle and, therefore, very important for understanding land-atmosphere interactions. This variable is needed to quantify hydrological, environmental, and land surface processes.	[7]
albedo	α	[-]	α is defined as the ratio of the land surface reflected radiant flux to the total incident flux.	α is a key variable controlling the surface radiative energy budget and has a crucial role in the partitioning of incoming total energy between the atmosphere and the surface.	[8]
emissivity	ε	[-]	ε is defined as the ratio of actual emitted radiance to the one that would be emitted from a blackbody (which consider being a perfectly emitting surface) at the same thermodynamic temperature.	ε is a key variable to accurate and reliable temperature measurements and for heat transfer computation. For instance, ε is needed for translating brightness temperature observations into LST products.	[4], [5]
Fraction of Absorbed Photosynthetically Active Radiation	fAPAR	[-]	fAPAR is defined as the fraction of photosynthetically active radiation (PAR; solar radiation reaching the surface in the 0.4-0.7µm spectral region) that is absorbed by vegetation.	fAPAR is linked to ecosystem statue and functioning. It has an essential role in carbon balance estimation and, therefore, is a crucial input for vegetation photosynthesis and productivity models.	[9]

Photosynthesis [Gross Primary Production]	GPP	[μmol m^{-2} s^{-1}]	GPP is defined as the total photosynthetic carbon uptake by vegetation in the ecosystem.	GPP is an important variable in the global carbon cycle and, therefore, is crucial for quantifying land-atmosphere CO$_2$ exchange.	[10]
land cover	LC	[-]	LC is defined as the observed (bio)-physical coverage of the ground surface. LC includes vegetation and non-vegetated classes (e.g., man-made features, bare soil, rock, inland water bodies).	LC information is essential to parametrize climate, water and carbon models at various scales from local, to regional and global-scale by assigning physical attributes to different classes of LC. Moreover, it can be used to address land management aspects, for instance, to identify the areas suitable for conservation practices.	[11], [12]
total biomass	Bt	[kg]	Bt is defined as the total above-ground standing dry mass of live or dead matter from tree or shrub (woody plant) life forms.	Bt is a key variable for increasing the accuracy (and therefore decreasing the uncertainties) in the global carbon cycle monitoring. Moreover, this is an important parameter for forest management and climate mitigation.	[13]
snow cover	Extent (SE)	[m^2]	SE 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. Here unique implies that the projected area from two vertically superimposed snow-covered surfaces is only counted once.	Snow is a key component of the water cycle and climate system on a global scale. It has significant impacts on the radiation and energy and water balance and, therefore, changes in SE may result in larger climate fluctuations. Reliable information on SWE at the global level is needed for considering freshwater variations and energy budgets components in weather and climate simulations.	[14], [15]
	Snow water equivalent (SWE)	[mm]	SWE is defined as the depth of water resulting from the mass of snow melting.		

Earth observation products for ELVs

High spatio-temporal variability of land surface (biophysical and optical) properties originate in complex interconnections between a wide range of aspects from geological to atmospheric conditions so that there is no single theory to explain such variations over time. This is where satellite-based remote sensing observations can contribute to capturing a synoptic overview of the variations in space and time. In this section, we review the status of such observations, challenges, gaps and target requirements established for future products.

Current status

Satellite observations offer indirect valuable spatial measures of ELVs. This is essential since in situ observations, currently, can only provide information for limited coverage. However, satellite products exhibit differences comparing with other satellite products or measured in situ data. To understand and resolve such differences, one needs to investigate the current status of ELVs products derived from satellite observations as an important starting point. This can pave the way for making progress towards upcoming satellite missions for planning more efficient products and to ensure their accuracy and reliability. Table 2 presents the ELVs observations, their resolutions, standards, and main resources.

Table 2. The ELVs observations, their resolutions, standards and main sources (mainly adapted from [16], [17])

ELVs	Observation method[1]	Spatial resolution	Applicable standards	Sources of data	Important databases[2]
LAI	VNIR, multi-spectral, multi-angular and LiDAR	30 m - 1 km	N/A	Copernicus Climate Change Service, Copernicus Global Land Service, NASA/LPDAAC, EUMETSAT CM SAF, EUMETSAT LSA SAF	http://land.copernicus.vgt.vito.be/PDF/portal/Application.html#Home https://lpvs.gsfc.nasa.gov/producers2.php?topic=LAI
LST	TIR	90 m - 1 km	N/A	Copernicus Global Land Service, NASA/LPDAAC, ESA DUE GlobTemperature, EUMETSAT LSA SAF	http://land.copernicus.vgt.vito.be/PDF/portal/Application.html#Home http://data.globtemperature.info/
ET	VNIR, TIR	30 m - 1 km	N/A	GLEAM, NOAA, EUMETSAT LSA SAF, NASA	http://www.fluxcom.org https://www.gleam.eu https://ladsweb.modaps.eosdis.nasa.gov/search/order/2/MOD16A2-- https://data.csiro.au/dap/landingpage?pid=csiro:17375&v=2&d=tr http://landflux.org/Data.php http://eeflux-level1.appspot.com/ https://ldas.gsfc.nasa.gov/gldas/
SM	Microwave radiometers, scatterometers and synthetic aperture radars in 1–10 GHz range (L, C and X-band), complemented by medium resolution optical and thermal sensors	1 - 25 km	WMO (2008(b))	ESA CCI Soil Moisture Copernicus Climate Change Service	http://www.esa-soilmoisture-cci.org/ https://climate.copernicus.eu/ https://www.nasa.gov/smap https://www.esa.int/Our_Activities/Observing_the_Earth/SMO

[1] This refers to the widely-used satellite-based approach

[2] The list is only the most important available databases and, therefore, does not claim to be complete

α	VNIR, SWIR	30 m - 1 km	N/A	Copernicus Climate Change Service, Copernicus Global Land Service, NASA/LPDAAC, EUMETSAT CM SAF, EUMETSAT LSA SAF	https://modis.gsfc.nasa.gov/data/dataprod/mod43.php https://cds.climate.copernicus.eu/#!/home
ε	TIR	90 m - 1 km	N/A	Copernicus Global Land Service, NASA/LPDAAC, EUMETSAT LSA SAF	http://land.copernicus.vgt.vito.be/PDF/portal/Application.html#Home http://data.globtemperature.info/
fAPAR	VNIR	30 m - 1 km	N/A	Copernicus Climate Change Service, Copernicus Global Land Service, NASA/LPDAAC, EUMETSAT CM SAF, EUMETSAT LSA SAF	https://cds.climate.copernicus.eu/
GPP	VNIR, LiDAR	30 m - 1 km	N/A	NASA, EUMETSAT LSA SAF, Copernicus global land service	http://www.fluxcom.org/CF-Products/ https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD17A2/#chart https://navigator.eumetsat.int/product/EO:EUM:DAT:MSG:LSA-411 https://modis.gsfc.nasa.gov/data/dataprod/mod17.php https://land.copernicus.eu/global/products/dmp
LC	VNIR	30 m - 1 km	No agreed standards but see GLCN (2014), GOFC-GOLD (2015a), and LCCS/LCML	ESA LC-CCI, NGCC	http://www.esa-landcover-cci.org/ https://modis.gsfc.nasa.gov/data/dataprod/mod12.php https://land.copernicus.eu/global/products/lc http://www.gofcgold.wur.nl

Bt	C-band SAR data (ESA Envisat), L-band SAR data, LiDAR	50 km	GOFC-GOLD (2015a) GOFC-GOLD (2015b) GFOI (2013) IPCC (2006)	No global data center	www.globbiomass.org http://lucid.wur.nl/ https://www.globalforestwatch.org/
SC	VNIR, microwave, LiDAR (Snow extent)	30 m - 1 km	WMO (2008(b)) IGOS (2007)	Data centre: NSIDC NRCS SNOTEL NASA JPL	http://nsidc.org/data/ http://www.cryoland.eu/
	Passive microwave (Snow water equivalent)	1 – 25 km			

Target requirements

Defining target requirements is a process of balancing technical possibilities of the sensor system and platform with an optimum benefit of the observation on the application. GCOS proposed target requirements for satellite observations in terms of their spatial resolutions, temporal resolutions, accuracy, and stability. These requirements are presented in Table 3. All these requirements given in Table 3 are indicative that provides a basis for further discussions. The requirements are usually discussed in the scientific community with the close collaboration of GCOS and will be updated if necessary. The main assumption of these target requirements is that the maximum benefits of the derived EVs products for climate applications would be reaped in case of meeting the requirement. These requirements have been defined for global products.

Target requirements are formulated in Table 3 under the headings of spatial resolution, temporal resolution, accuracy, and stability. These terms are briefly defined as follows:

1. The spatial resolution defined as the sampling distance of the observations which usually is represented in gridded forms (pixels) for the satellite data.
2. Temporal resolution defined as the needed interval between two successive instances of observation.
3. Accuracy is defined simply as the closeness of agreement between observation values and the true values. Since true values are not known, users are provided with observation values which are estimations of true values, and data producers may also report estimation of their observation values. Observation uncertainty might be evaluated by the end-users' own validation activity as well. Accuracy values given in Table 3 are overall levels of the uncertainties of observation values.
4. Stability defined here as a requirement on the extent to which the error of observation remains constant over a long period (of a decade or more). Stability values given in Table 3 are usually the maximum acceptable change in systematic error per decade.

Table 3. Global target requirements for ELVs products derived from earth observation (mainly adapted from [18])

ELVs	Spatial resolution (m)	Temporal resolution	Accuracy	Stability
LAI	250	2-weekly averages	Max (20%; 0.5)	Max (10%;0.25)
LST	1 km	1 h	1 K	<0.1K/decade
ET	25 km (goal 1 km)	Sub-daily	<10%	Better than 1%
SM	25 km	Daily	0.04 m^3 m^{-3}	0.01 m^3 m^{-3} year^{-1}
α	1 km	Daily to weekly	Max (5%; 0.0025)	Max (1%; 0.0001)
ε	1 km	1 h	-	-
fAPAR	250 m	2-weekly averages	Max (10%; 0.05)	Max (3%; 0.02)
GPP	GCOS does not specify requirements	GCOS does not specify requirements	GCOS does not specify requirements	GCOS does not specify requirements
LC	250 m (Moderate-resolution maps)	1 year	15% (maximum error of omission and commission in mapping individual classes), location	15% (maximum error of omission and commission in mapping individual classes), location

			accuracy better than 1/3 IFOV with target IFOV 250 m	accuracy better than 1/3 IFOV with target IFOV 250 m
	10 – 30 m (high-resolution maps)	5 years	5% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 10-30 m	5% (maximum error of omission and commission in mapping individual classes), location accuracy better than 1/3 IFOV with target IFOV 10-30 m
Bt	500 m- 1km averages based on 100-200 m observation	Annual	<20% error for biomass values > 50t ha$_{-1}$ <10% error for biomass values <= 50t ha$_{-1}$	10%
SC	1km; 100m in complex terrain (Snow extent)	daily	5% (maximum error of omission and commission in snow area); location accuracy better than 1/3 IFOV with target IFOV 100m in areas of complex terrain, 1km elsewhere	4% (maximum error of omission and commission in snow area); location accuracy better than 1/3 IFOV with target IFOV 100m in areas of complex terrain, 1km elsewhere
	1 km (Snow water equivalent)	daily	10 mm	10 mm

Adequacy/inadequacy of current observations

LAI

There are a considerable amount of LAI products produced by space agencies and other data providers at various spatio-temporal resolutions covering a part of the whole globe. Nowadays, about ten years of LAI products are available with spatial resolutions in the range of 1 to 2km and temporal resolutions of daily, weekly, ten days and monthly. Discrepancies in these products originate from differences in definitions, concepts, retrieval methodology, and input data quality. There are few considerations to increase the consistency of the products, to improve the accuracy and reliability of current and forthcoming LAI products as follows:

1. More research should be conducted to understand, quantify, and reduce large systematic biases among various LAI products.
2. Delivering LAI products at a resolution of 100 to 300 m is feasible. However, this needs to be generated operationally from earth observations (e.g., MODIS, MERIS, MISR, etc.) through efficient approaches and models. Therefore, data providers should figure this out effectively beside continuing to generate current LAI products with more emphasize on traceability and clarity for the end-users.

3. More close collaboration is required between LAI products providers, modelers and end-users to ensure that in operational procedures, the model structure, assumptions, definitions, and requirements are utilized in a correct way in order to meet the needs of end-users applications.
4. Detailed documentation is required in which available LAI products, their definitions, production assumptions, adopted approach and implemented models are described clearly. This can help better understanding of products differences and proposing simple methodologies to convert one into another. In addition, further details of assumed spectral properties, vegetated canopy characteristics, illumination condition in the generation of LAI products might be useful for end-users interpretations.
5. Re-processing of available products in order to set a long-term time series by data-providers is of great importance which can be of interest of many end-users for different applications. Moreover, extending LAI records into the past (e.g. dating back to mid-eighties) while considering compatibility, consistency and reliability need more efforts for both modelers and data providers.
6. Developing new, fast, efficient and accurate retrieval algorithms as computer models is always needed and should be done by the scientific community to improve the LAI products in which all the end-users requirements are met.

LST and ε

Earth observation LST products are generated based on land-surface energy balance theory. LST can change rapidly since land surface thermal inertia is relatively low. Thermal emission at infrared wavelength is usually utilized to generate LST products. Interpretation of a LST product is challenging because of land surface variable angular emissivity and complex structure as well as topography of the land surface. There are some considerations regarding LST products as follows:

1. Majority of current observations of satellite LST and emissivity products have a satisfactory spatial resolution of 1 – 2 km. This is quite adequate for environmental monitoring applications.
2. The temporal resolution of LST products still remains challenging since LST changes in the environment can vary from hours to years. Geostationary satellites can offer suitable and adequate products and capture the full diurnal cycle, of course in clear atmospheric conditions. To overcome cloudy situations, making use of combined infrared-microwave observations show already good results.
3. Relatively long time series of LST products at the global scale are available from AVHRR and geostationary observations since 1983.
4. Global LST products with acceptable accuracy (1 K) can be obtained from MODIS, ASTER, and AATSR covering various surface types.
5. Intercomparison of various sensor products needs to be executed to find out the most reliable products.

ET

There are a variety of ET products estimated from optical and thermal remote sensing observations. For instance, daily ET products are available from MODIS observations with global coverage, spatial resolution from 250 m to 1 km since 2000. Moreover, much higher resolution of ET products (at 30 m) are available from Landsat TM, ETM and OLI observations with a temporal resolution of 16 days. There are some considerations for the use of these ET products:

1. Global estimation of ET from earth observation data is challenging mainly due to the large land surface heterogeneity, topographic complexity, and dependence of water availability on climate condition. Multiple algorithms have been applied to generate ET products at the regional and global scale. Validation of these products and inter-comparison of them are of great importance to find out the most reliable products.
2. Improved temporal scaling procedures are needed to convert instantaneous estimations to daily or longer time periods. Developing new algorithms for such conversion is still required.
3. ET target requirements, validation, and calibration protocols have not investigated properly yet. Collaboration between data providers, experts, and the scientific community is of an urgent need for further investigation.

SM

SM is probably the most heterogeneous variable that varies on a small scale based on soil properties, drainage patterns, topographic conditions. However, earth observation products can only provide an average of this variable over relatively large-scale areas. This even can be more complicated due to the vegetation contributions in the signal. There are few considerations for the use of these products:

1. Linking moderately small (local) in situ SM measurements to relatively coarse scale satellite observations needs a scaling procedure which has not been defined by internationally accepted calibration and validation standards.
2. Valuable soil moisture information is available from many microwave satellite observations at a spatial scale of tens of kilometers. However, the full potentials (capacities) of these observations have not exploited yet, because of the requirement of higher spatial resolution SM information (at the sub-km scale). Therefore, scientific communities and modelers currently propose, test and develop robust methods to downscale soil moisture observations.
3. Currently, there are adequate soil moisture observations (e.g., NASA’s Nimbus-7, TRMM TMI, AMSR-E, Windsat, SMOS, Sentinel-1) making it possible to build a long-term soil moisture records covering the period of 1970 – 2019.
4. Passive microwave instruments offer valuable SM products. However, their capability is limited since there is significant radio frequency interference (RFI) in some parts of the globe. RFI has been reported e.g. at C-band (AMSR-E/AMSR2) for the USA and EU as well as for L-band (ESA SMOS)over the middle East and Asia making the observations unusable.

5. The first time series of soil moisture products based on combining active and passive datasets are available. However, more research is needed to explore a new approach for combining satellite soil moisture datasets with ground measurements.
6. C-band SAR systems (e.g.Sentinel-1) can play an important role to generate soil moisture maps for low vegetation regions on a global scale. However, to get continuous maps also under forests L-band or even P-band SAR observations are currently investigated.

α

Hemispherical-conical spectral reflectance observations are available from the early 1980s. Some of these observations have been employed to retrieve albedo products. However, a coherent effort is needed to ensure reasonable accuracy and temporal coverage. There are some considerations for earth observation albedo products as follows:

1. Albedo products generated by various space agencies should still be validated extensively. Much effort should be made for albedo products intercomparisons and benchmarking.
2. The accuracy, reliability, and stability of albedo products might be improved by the existence of a high-quality dedicated sensor which can offer traceability to international standards.
3. Land surface albedo products make it possible to monitor subtle changes in the ecosystem over time. Therefore, it is important that current and future archives of albedo products be preserved and accessible on a continuing basis.

fAPAR

The fAPAR products are generated from satellite observations by space agencies and data providers on a global scale. About 10 years of fAPAR products are available with a typical spatial resolution of 1 to 2 km (finer resolution products (of 250 – 300 m) may be available at regional scale) and temporal resolution of daily, weekly, ten days and monthly. To produce these fAPAR products, physical radiative transfer models are inverted against satellite reflectance observations in not only PAR range but also in NIR/SWIR bands (to account for background contribution) and blue bands (to account for atmospheric influence). Comparing various fAPAR products demonstrates discrepancies originating from differences in definitions, concepts, retrieval algorithms and the quality of input datasets. There are some considerations to improve the reliability and value of current and forthcoming fAPAR products as follows:

1. More research is needed to investigate total biases among current products and, therefore, reduce large systematic biases to deliver more reliable products explaining seasonal variability.
2. The fAPAR products with a finer spatial resolution of 100 to 300 m are feasible (e.g., from MODIS, MISR, MERIS). However, this is not generated operationally for the whole globe and, therefore, much efforts are required by data providers to move towards these products.

3. In some climate models, the users need to have separated fAPAR values for both direct and diffuse incoming radiation with respect to the sun position. To the best of our knowledge, currently, there is no institution/data provider offering such products.
4. More efforts are required to well document fAPAR datasets in order to make them easy for users to understand. Detailed information on the retrieval methods, assumptions, adopted models, spectral data properties, architectural structure, illumination conditions are among the important ones that can be of users' interest.
5. Long-term time series data is important to detect fAPAR (small) trends from its interannual variability. Therefore, data providers should consider this and try to schedule re-analysis and re-processing of available archives to generate consistent products and save them as a long-term fAPAR database.

GPP

Several GPP products have been generated from earth observation data and modeling approaches over a long period. For instance, daily MODIS GPP products are available with a spatial resolution of 500 m since 2000 and BESS GPP products with a spatial resolution of 1 km and temporal resolution of 8-day are produced and available from 2001. However, there is inconsistency in the performance of these GPP products. Therefore, there are some considerations for using earth observation GPP products as follows:

1. GPP validation and accuracy assessment are not straightforward because of the lack of representative in situ measurements. Although measured GPP at FLUXNET sites provides a good opportunity for earth observation product assessment, this tower information may not be considered as representative for all possible biomes and climatological regimes.
2. Linking moderately small (local) in situ GPP measurements to relatively large satellite observations is challenging.
3. Land Product Validation (LPV) subgroup of Committee on Earth Observation Satellite (CEOS) working group on validation has not investigated GPP target requirements, validation, and calibration protocols yet, to the best of our knowledge. Collaboration between data providers, experts, and the scientific community is of an urgent need for further investigation.

LC

Data providers and the research community are working together closely to generate reliable land cover maps. The generated land cover products have a resolution of 250 m to 1 km. Similar to other earth observation products, the lack of compatibility between various land cover products make it challenging to quantify climate-induced or anthropogenic changes in land cover. Different approaches have been adopted for extracting land cover from satellite images. For instance, centralized processing by means of a single method of image classification (e.g., MIDLAND, GlobCover) and a distributed method by means of a network of experts who apply the regionally specific algorithm (e.g., GLC2000). Using the above-mentioned approach has a big advantage of producing consistent products. However, it may not produce optimum results for all regions and land-covers. Therefore, automated land cover extraction for the purpose of change detection still remains as a hot research topic. Important considerations to have better land cover products are as follows:

1. It is necessary to follow internationally-agreed standards (i.e., the one agreed by the UN/ISO framework) for adopting a classification system and the associated product legends. Moreover, making use of existing initiatives, for instance, the FAO land cover classification system or IGBP legend system, can be of great help for land cover products legend harmonization and translation. The use of new FAO land cover meta language (LCML) is also encouraged for the sake of strengthening the process of harmonization and legend translation.
2. Metadata, including a description of thematic and spatial accuracy for each class, must accompany the global land cover products. To this end, one can utilize CEOS WGCV-proposed validation protocols. Accuracy assessment following these available protocols is based on a sample of high-resolution (1-30 m) remote sensing observations which itself needs to be validated.
3. To have better monitoring of land cover changes at the global scale, it is proposed to generate detailed land cover products from satellite high-resolution observations (at the spatial resolution of 10 - 30 m) with the global coverage. These products are required at least every five years. This is feasible and has already been tested regionally by means of Landsat, Sentinel-2 and SPOT HRV. However, data providers and space agencies should assure the availability of earth observations with 10 – 30 m resolution for operational monitoring at the global scale.
4. Proper earth observation archives such as the Landsat, SPOT and Argos/Corona should be easily and systematically accessed and suitable observations selected to be used for reconstructing early land cover products
5. Synergistic use of various satellite data and integration of these data with in situ measurements can assist obtaining a higher quality of land cover products.
6. Although high resolution (about 30 m) land cover maps are available for specific regions (e.g., CORINE for Europe, EOSD for Canada, PRODES for the Brazilian Amazonia), specific arrangements needed to ensure feasible operational setting for a global generation of such products.

Bt

Regional biomass products have been produced from passive optical sensors (e.g., Landsat, MODIS) and active sensors (lidar and radar). However, these earth observation data provides different biomass information.

Passive optical sensors can provide indirect information about biomass and, therefore, other supplementary environmental and forest data are still required. This approach is applied with reasonable accuracy, for instance, in Sweden, where there was lots of supporting data. However, it is not extended to cover the whole globe.

In addition, various active methods have been applied to estimate biomass products from earth observation data. For instance, L-band backscatter observed by the JAXA Daichi (ALOS) could provide biomass information (up to 60-80 t ha$_{-1}$) in African miombo forests. Furthermore, information derived from Envisat C-band data correlated well with biomass data in the boreal and temperate forest. To improve biomass estimation from earth observation data, probably low-frequency radar combined with lidar data is a good candidate. In general, there are some considerations for biomass products as follows:

1. Regional biomass products generated from earth observation data need to be assessed to flag their quality and better document the adopted approach.

2. Large differences reported between various biomass products extracted from passive and active observations, especially over tropical regions.

3. Making use of earth observation data from multiple sensors to better estimate biomass products is a promising approach. However, quantitative methods need to be developed by the research community for this purpose.

SC

Currently available observations of historical remote sensing provide adequate data to produce needed SC products at the global scale for the past 20 – 30 years. The USA national snow and ice data center (NSIDC) provides snow cover extent products at the global scale with a temporal resolution of weekly for the period 2000 to the present. This product obtained from combined use of optical (MODIS) and passive microwave (SSM/I) earth observation data. Moreover, NASA EOS provides snow water equivalent products derived from AMSR-E observations since 2002. There are some considerations regarding snow cover products as follows:

1. National archives should have a clear agreement for making all data available online and easy to access databases.
2. Current and planned passive microwave observations at low to moderate-resolution (e.g., 5 km to 20 km) provide an adequate source of data to estimate snow water equivalent for the case of shallow snowpacks in simple topographic conditions. However, there are still some limitations for estimating snow water equivalent for the case of deep snowpack and topographically complex areas from low-resolution passive microwave observations. This demonstrates the need to improve retrieval algorithms and develop higher resolution sensors for complex terrains.
3. To increase the reliability and accuracy of snow cover products, it is suggested to have not only more spectral narrower and better-calibrated bands but also to cover a greater dynamic range. This is important for space agencies who are designing new sensors.
4. Making use of multi-sensor observations (optical, microwave and in situ) can result in spatial and temporal consistency for the snow cover products at the global scale. This should be considered by the research community and data providers to move towards

this direction. There are few good examples available for the use of the multi-sensor approach for producing snow cover products. For instance, the NOAA/NWS national operational hydrologic remote sensing center has applied a novel multi-sensor snow analysis approach for the USA and generated snow cover products from 2003.

In-situ observations networks for ELVs

Current status

Continues and representative measurements of ground ELVs in situ networks are of great importance mainly for validation purposes of ELVs derived from satellite data. Moreover, long-term records of data in situ networks themselves could reveal ecosystem response (as trends) to environmental and climate changes. Much effort has been made to establish new in situ stations and/or extend currently available and active in situ networks with the aim of reaching global coverage. Table 4 present the main in situ networks and databases currently operational for the selected ELVs.

Table 4. Important repositories/databases for selected ELV

ELVs	In-situ reference data sets	Important databases[3]
LAI	BELMANIP-2 and DIRECT data sets within the On Line Interactive Validation Exercise (OLIVE) platform, ImagineS, NEON (US Only), ICOS (Europe), EnviroNet	http://calvalportal.ceos.org/web/olive/site-description http://fp7-imagines.eu/pages/services-and-products/ground-data.php https://www.neonscience.org/ https://www.icos-cp.eu/ http://www.enviro-net.org/
LST	JPL reference data, the Surface Radiation (SURFRAD) network, Karlsruhe Institute of Technology (KIT) stations, CEOS /LPV subgroup,	https://calval.jpl.nasa.gov/ https://www.esrl.noaa.gov/gmd/grad/surfrad/ http://www.imk-asf.kit.edu/english/MSA-Validiation.php https://lpvs.gsfc.nasa.gov/LSTE/LSTE_home.html
ET	FLUXNET LandFLUX ICOS	https://fluxnet.ornl.gov/fluxnetdb https://hydrology.kaust.edu.sa/Pages/GEWEX_Landflux.aspx https://www.icos-cp.eu/
SM	The International Soil Moisture Network	https://ismn.geo.tuwien.ac.at/en/
α	In situ operational networks such as BSRN, Surfrad, and Fluxnet, EUMETSAT	https://bsrn.awi.de/ https://www.esrl.noaa.gov/gmd/grad/surfrad/ https://fluxnet.fluxdata.org/ http://savs.eumetsat.int/
ε	Joint Emissivity Database Initiative (JEDI)	https://emissivity.jpl.nasa.gov/

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[3] The list is only the most important available databases and, therefore, does not claim to be complete

fAPAR	OLIVE platform, ImagineS, NEON (US Only), ICOS (Europe), EnviroNet	http://calvalportal.ceos.org/web/olive/site-description http://fp7-imagines.eu/pages/services-and-products/ground-data.php https://www.neonscience.org/ https://www.icos-cp.eu/ http://www.enviro-net.org/
GPP	FLUXNET ICOS	https://fluxnet.ornl.gov/fluxnetdb https://www.icos-cp.eu/
LC	GOFC-GOLD Reference Data	http://www.gofcgold.wur.nl
Bt	ForestGeo, NEON (USA), TERN (Australia), ForestPlots, FLUXNET	https://forestgeo.si.edu/ https://www.neonscience.org/ https://www.tern.org.au/ https://www.forestplots.net/ https://fluxnet.ornl.gov/fluxnetdb
SC	SNOWPEX	https://earth.esa.int/web/sppa/activities/qa4eo/snowpex

Challenges and gaps

Considerable efforts should center on addressing in situ networks challenges and filling their possible gaps. This can play an important role to increase the reliability of ELVs derived from earth observations through direct validation. Some of the main challenges with that in situ networks are facing are as follows:

1. Despite all progress has been made towards having long-term continuity of in situ measurements, there are still large areas without any in situ observations. Even in well-equipped areas, the stations are not spatially well distributed. Therefore, the available in situ networks are not probably adequate and/or representative for the whole globe. More endeavors are needed to expand these networks to have representative samples over different biomes targeting to reach the full geographical coverage.
2. Earth observation products are generated from satellite observations with various spatial resolutions. This makes the direct comparison of these products with local in situ measurement very challenging. Therefore, there are many on-going scientific discussions about the representability of in situ measurements against earth observation products with various resolution. The in situ networks should be consolidated in a way to have more consistency with a spatial resolution of remote sensing observations.
3. Making a global agreement between national organizations who are responsible for in situ data collection on setting an identical measurement principle, a unique standard (protocol) for data measurements, and single (meta-) data repository per each ELV.
4. Current in situ methodologies needs to be evaluated in a variety of biomes, based on GCOS criteria for example, for documenting their accuracy and reliability. To this end, establishing supersites located in various biomes and different locations around the globe can be of a good starting point.
5. The scientific community should propose operational (and of course feasible) methodology to deal with variable-specific measurement issues for in situ networks.

For instance, taking reliable LAI measurements during a windy condition needs more investigation by the scientific community.

6. Some in situ measurements are owned by specific research groups, national meteorological services, and hydrological modelers that are mostly well organized and unique. However, in most cases, this data is not shared outside of the owning body openly or treated nationally/commercially sensitive information. There is a need at national authority's level to encourage those data owners to share such data in an international, standard and traceable repository.

Validation practice

Before proceeding further, it is needed to provide a definition for validation. Based on definition proposed by the working group on calibration and validation Committee on Earth Observation Satellite (CEOS), ISO 9000 and the National Institute of Standards and Technology, validation is " the process of assessing, by independent means, the quality of the data products as derived from the system outputs". There are three key components for such an assessment [3] as follows:

1. Direct validation by means of in situ reference data sets
2. Inter-comparison of products by means of a representative global sample data sets
3. Statistics related to the temporal completeness of products

Status of current validation capacity

Some progress has already been made in validation of ELVs from space agencies driven initial investigations to CEOS on-going variable-specific validation activities. Data providers and space agencies such as NASA and ESA usually conduct some initial validation of their products. CEOS/LPV has also made considerable efforts with the collaboration of the scientific community to conduct ELV validations and establish validation protocols (https://lpvs.gsfc.nasa.gov/).

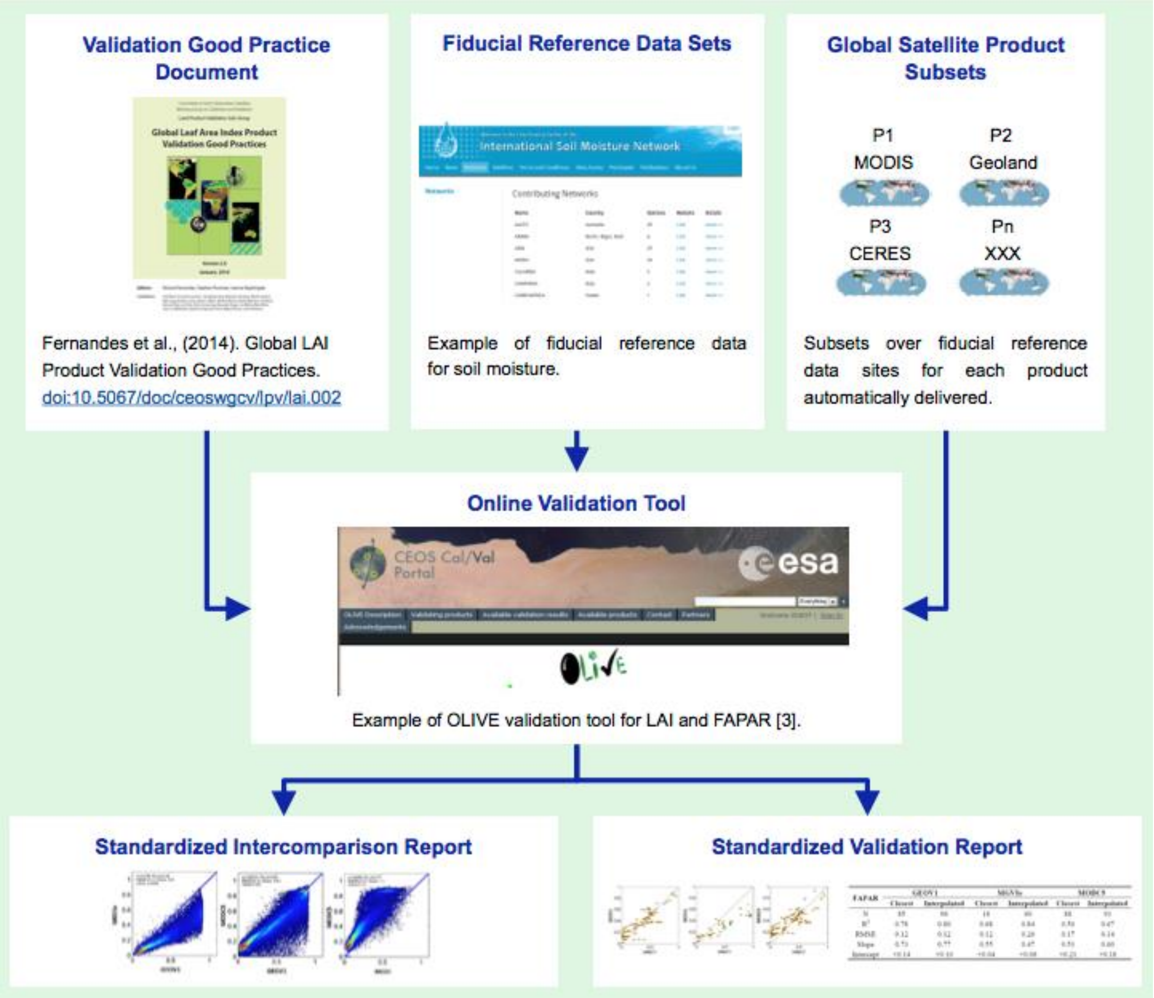
CEOS/LPV intends to standardize intercomparison and validation procedure useable for various satellite products across communities. CEOS/LPV mostly focused on investigating the validation of essential climate and biodiversity variables. Based on CEOS validation hierarchy, there are five main validation stages as described in Table 5.

Table 5. The CEOS Land Product Validation hierarchy (adapted from [3]).

Validation stage	Definition	CEOS defined ELV stage
0	No any validation has been conducted and, therefore, the accuracy of the products have not been evaluated. These products are considered as beta.	N/A
1	Products have been initially evaluated and accuracy has been quantified by using a small (typically < 30) set of in situ (or other suitable reference) samples and	Snow Fire radiative power

	within specific time periods.	
2	Validation has been performed and, therefore, product accuracy evaluated using a significant set of samples (in various locations and time periods). For the validation, in situ measurements or suitable reference data are utilized. Moreover, products spatio-temporal consistency have been assessed over globally representative locations and time periods. Results of such investigations are published in the peer-reviewed literature.	LAI FAPAR Land cover Phenology Burned area
3	Product uncertainties are well quantified from comparison with reference in situ measurements and/or other suitable reference data. Uncertainties are quantified by means of rigorous statistical approach over various locations and time periods representing the whole globe. Moreover, products spatio-temporal consistency have been assessed globally over various locations and time periods. Results of such investigations are published in the peer-reviewed literature.	LST Emissivity Soil moisture Albedo Vegetation indices
4	Validation results of the previous stage (i.e., 3) are updated through a systematic way when new products are released and as the time series expands.	Active fire

In addition, LPV has developed a suitable validation/intercomparison framework aiming to reach validation stage 4 in a straightforward automated way. There are three key components in this framework; (1) a unique protocol, (2) standard reference data and (3) automated subsetting. Ideally, each of these components will be implemented together as an integrated online platform in which quantitative tests are performed regularly. As a result, standardized validation and intercomparison reports will be generated for all products in the validation exercise. The final goal of LPV is to implement such fully automated framework for each of ELV products through online platforms. This automated framework enables processing time series of different ELV products efficiently and generating standardized validation reports. Figure 1 shows an overview of LPV proposed framework for LAI product (https://lpvs.gsfc.nasa.gov/).



Fernandes et al., (2014). Global LAI Product Validation Good Practices. doi:10.5067/doc/ceoswgcv/lpv/lai.002

Example of fiducial reference data for soil moisture.

Subsets over fiducial reference data sites for each product automatically delivered.

Example of OLIVE validation tool for LAI and FAPAR [3].

Figure 1. An overview of LPV proposed framework for LAI product (https://lpvs.gsfc.nasa.gov/).

In parallel, there is a range of on-going activities to perform either direct validation or inter-comparison at local, regional and global scales by the scientific communities. From these validation practices arise three essential components for a validation protocol: (1) products direct validation by means of in situ reference measurements, (2) products inter-comparison over representative samples, and (3) products temporal completeness investigations by means of proper statistics.

Validation requirements

GCOS has proposed five primary criteria for the validation strategy of the desired ELV as follows:

1. **Performing direct validation at the global scale representative of seasonal variations to estimate the desired ELV accuracy**

It is an important step to perform direct validation using reliable reference measurements (e.g., in situ networks) for each ELV. Uncertainty of reference measurements should also be taken into account during the validation procedure. Estimations need to be up-scaled using either high-resolution land cover maps or satellite /airborne observations as two auxiliary sources. This is not always straightforward since there are some regions around the globe in which the measured in situ data is not representative. There are three solutions for this challenge: (1) heuristic estimations using lookup tables, for instance, LAI value of water is known and equal to zero; (2) estimations using biome-specific radiometric relationship; and (3) estimations according to possible max and min range of the desired ELV. In case of a need for gap filling of any reference map, it should be done only in spatial extent (e.g., roads, pathways, streams with have small linear features). Furthermore, the uncertainty of auxiliary sources for the possible use of in situ data scaling should be considered. CEOS LPV subgroup has proposed some protocols for generating reference ELVs maps which should be followed especially in case of interest for doing any comparison with earth observation ELVs products (https://lpvs.gsfc.nasa.gov/).

2. Quantifying the representativeness of the ELV accuracy estimate over time in various area without reference datasets

The main issues with representativeness are; (1) the key assumption for the precision of the accuracy estimate is that the reference data would be globally representative, (2) the comparable spatial extent, and (3) the temporal domain of the comparison.

One can model the precision of the accuracy estimates by means of confidence interval accuracy statistics. Representativeness of accuracy statistics might be investigated in two steps. As the first step, the spatial variation of the desired ELV product accuracy over a subset of a biome by means of various reference data can be assessed. In the second step, if it is recognized that the reference dataset might be a biased sampling at the global scale, a diagnostic of the accuracy statistics of representativeness (of both spatial and temporal) is needed. CEOS has proposed two diagnostics; (1) including areas with similar land covers, desired ELV and seasonal conditions as representative areas, and (2) using areas which have the same agreement compared to a global seasonally continuous ensemble reference.

3. Quantifying the precision of ELV estimates over time and space on a larger (e.g., globally) representative basis.

ELV precision is related to the variation in ELV estimations under constant in situ conditions. Temporal precision could be assessed using two methods. To account for inter-annual precision, the variation from linearity of midpoints of triplets is proposed [3], [19]. However, spatial precision could be assessed by quantifying the change in the desired ELV in areas with temporally stable ELV patterns while having large spatial variability. Such precision information is not currently available and, therefore, statistics derived from the ensemble of regional correlations between consecutive product time slices are widely used. This approach is utilized for products comparison for the time being until temporally stable areas could be detected.

4. Quantifying inter-annual stability in ELV products for a long-term period

Existing validation studies have been conducted using in situ sites with limited inter-annual measurements. Most of these sites are positioned in flux towers and ecological sites. These sites have usually insufficient spatial ELV sampling and, therefore, make the validation of coarse-resolution earth observation data challenging. It is proposed that inter-annual stability be evaluated by assessing ELV products’ trends in a subsample (e.g., 3 * 3 pixels for LAI case) with vegetation cover during the growing season. More investigation is needed to select appropriate subsamples and adopt suitable trend metrics for quantifying stability.

5. Identifying potential issues with retrieval methods and/or earth observation datasets that may cause biases in ELV

Investigation of current retrieval algorithms is urgently required to not only identify and solve potential issues but also make them efficient, fast and optimize. Making use of physical models for exploiting earth observation data to full extent might also increase the accuracy of the results. The main advantages of these physical-based retrieval algorithms are that they are not site or sensor-specific and, therefore, can easily be applied globally.

Validation good practice

Validation statistics should be reported for visualization of performance and quality of products. Land products validation (LPV) subgroup of CEOS classified the main validation statistics into four classes: (1) total measurements error, (2) bias, (3) precision and (4) completeness [3]. The Joint Committee for Guides in Metrology [20] has defined these statistics as follows:

The total measurement error (uncertainty) consist of both systematic and random measurement errors. In the case of only one product estimate for each mapping unit, the total measurement error corresponds to the accuracy. Bias is the value corresponding to the difference between the product and reference estimates. This is an indicator of the systematic measurement error. Precision is the dispersion of estimates around their expected actual values. This is an indicator of random measurement error. Completeness is the ratio of valid retrievals to an observation domain. Table 6 shows these four validation statistics, the CEOS-LPV recommended validation good practice and common practice.

Table 6. Widely-used validation statistics, proposed good practice and current practice for ELVs.

Validation statistics	Good practice	Current practice
Total measurement error	Scatter plot of the mean or median match-ups	Scatter plot of the mean match-up
	Median and percentiles of absolute residuals, RMSE	Root Mean Square Error (RMSE)
	Box plot of absolute residuals versus ELV	Scatter plot of residual versus ELV
Bias	Median and percentiles of	Mean difference

	residuals	
	Box plot of residual versus ELV	Mean difference versus ELV
	Kendall-Thiel line slope and confidence interval	Ordinary least squares line slope and confidence interval
Precision	Box plot of residuals from Kendall-Thiel Line fit	Residuals of line fit versus ELV
	Median signed anomaly of 95th percentile and 5th percentile	Mean seasonal difference
	Median 3 point difference	Mean 3 point difference
	Spatial rank correlation	Pearson's correlation coefficient
Completeness	Gap size distribution	Relative frequency histograms

Common metrics

There are many statistical metrics used in the literature for validation of retrieved ELV products (for instance, see review [21]). However, few of these metrics are widely-used, quite well-known and accepted by different communities. Table 7 present these validation metrics. Validation metric listed under category 1 in Table 7 quantifies the deviation of ELV products from in situ values. The metric describes the departure of earth observation derived products from the one-to-one line [22]. The primary importance of computing such a metric is that one can demonstrate the simple or squared differences between in situ and product values. Another widely-used validation metric is correlation-based one listed as category 2 in Table 7. This metric is useful since it is bounded (for R^2 between 0 and 1), and, therefore, is independent of the unit of the product. However, these two metrics from category 1 and 2 (i.e., RMSE and R^2, respectively) may not be sufficient tools for validation practices [22], [23]. Additionally, there are some dimensionless metrics adopted in some studies, listed as category 3 in Table 7. The crucial advantage of RRMSE and NRMSE is that the actual error could be quantified without being affected by the data unit.

Table 7. Common metrics used for validation of ELVs.

Statistical Measure	Equation	Unit/Range
(1) Error metrics		
Root Mean Square Error	$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_{product}^{i} - V_{in\,situ}^{i})^{2}}$	Data unit
(2) Correlation-Based metrics		
Coefficient of Determination	$R^2 = 1 - \frac{\sum_{i=1}^{n}(V_{in\,situ}^{i} - V_{product}^{i})^2}{\sum_{i=1}^{n}(V_{in\,situ}^{i} - \bar{V}_{in\,situ})^2}$	0 to 1
(3) Dimensionless Error metrics		
Normalized RMSE	$NRMSE = \frac{RMSE}{Range\ (in\ situ)}$	0 to ∞
Relative RMSE	$RRMSE = 100.\frac{RMSE}{Mean\ (in\ situ)}$	0 to ∞

Conclusion

The most important ELVs retrievable from earth observation data, current observation status, available in situ networks, existing validation strategy, common metrics, and their challenges are shortly described in this report. Satellite data offer a unique tool to capture spatio-temporal variations of ELV products in various scales from local to regional and global coverage. However, not only supplementary measurements are needed to assess the reliability and accuracy of earth observation products, but also reasonable validation practices are of great importance. Many in situ measurement stations are currently active and recording ELVs globally. Moreover, validation good practices, proposed by CEOS LPV, provide a useful protocol to evaluate earth observation products and produce reference datasets. The validation practices aim to quantify ELVs accuracy, precision, and completeness using in situ measurements, reference maps and products inter-comparisons in a uniform procedure. Adequacy/inadequacy of datasets, validation current status, and the best practices are discussed. Although this report summarizes the most important aspects of selected ELVs and validation practices, it is noteworthy to mention that it covers only the minimum common components of ELVs validation studies and, therefore, it might be improved by including more details for each ELV as a separate investigation.

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