QA4EO-2 Technical Note:
Update process of CEOS LPV Supersites V2

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1. Introduction

Validation of satellite-based land products relies largely on in situ or fiducial reference measurements collected over an ensemble of sites. In the early Moderate Resolution Imaging Spectroradiometer (MODIS) era, the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) Land Product Validation (LPV) subgroup (hereafter called CEOS LPV, https://lpvs.gsfc.nasa.gov/) adopted the Earth Observation Satellite (EOS) Land Validation core sites plus European sites. However, many of these early validation sites were no longer active, and the validation needs and strategy for ground reference sites changed over time. In 2010s, the CEOS WGCV established a CEOS Cal/Val action (CV-12) aimed to evaluate well-characterized supersites with data continuity prospects for validation purposes that allow for testing products, algorithms, and validation strategies through radiative transfer modelling.

In response to this CEOS WGCV (CV-12) action, the CEOS LPV subgroup undertook an assessment to identify CEOS supersites for land product validation considering additional requirements from the Global Climate Observing System (GCOS) Implementation Plan 2016 (GCOS - 200, 2016). For instance, the supersite should be useful to evaluate several land products to ensure consistency among them. Also, it should serve to improve the quality of ground-based reference sites, with agreed measurement standards and protocols. Moreover, the structural knowledge of the canopy would be necessary to facilitate above ground biomass validation and validation through radiative transfer modelling approaches. Hence, the CEOS LPV agreed on the following definition for a CEOS LPV supersite to serve multiple land products validation:

- *Super characterized (canopy structure and bio-geophysical variables) site following well-established protocols useful for the validation of satellite land products (at least 3) and for radiative transfer modeling approaches.*
- *Active, long-term operations, supported by appropriate funding and infrastructural capacity.*
- *Supported by airborne LiDAR and hyperspectral acquisitions (desirable).*

The supersites were primarily selected from well-known and established ecosystem networks such as the National Ecosystem Observatory Network (NEON) in US, the Integrated Carbon Observation System (ICOS) in Europe, and the Australian Terrestrial Ecosystem Research Network (TERN) supersite, even if they are not designed for remote sensing product validation, and from Cal/Val sites nominated by LPV members. After this, the sites were ranked based on how many key variables could be validated with a given site, whether structural information was available for the site, their spatial representativeness, if airborne data was available and if atmospheric and other properties were measured. The sites were also ranked by global region and biome (land cover type), with higher scores assigned to sites located in undersampled regions (e.g., Africa or South America) or biomes (e.g., shrublands, sparse vegetation and bare areas). All this information was combined to come up with a score for each site, and a cut-off was established for accepting a given site. Finally, a list of 55 CEOS LPV supersites was endorsed in 2016.

However, since then many sites have been upgraded with new instrumentation in the framework of recent or on-going activities such as (but not only) Copernicus Ground-based Observations for Validation (GBOV), ESA Land Surace Temperature, Aerosols and Water Vapor (LAW) (https://law.acri-st.fr/home), EU Hyperspectral Radiometer Network (HYPERNETS, https://www.hypernets.eu/), ESA Fiducial Reference Measurements (FRM) projects for land variables (Niro et al., 2021), as well as by Cal/Val activities of new space missions (e.g., Fluorescence Explorer (FLEX)) among others. Moreover, key variables such as spectrally resolved surface reflectance, including those enabling the observation of chlorophyll fluorescence, were not

under consideration in the first CEOS LPV supersite list. In addition, the FRM concept was adopted at CEOS level (Goryl et al., 2023), and a self-assessment matrix has been created to qualify the in situ data in accordance with FRM principles. All these evolutions in the land validation domain needs to be carefully considered to review and update the CEOS LPV supersites to keep it as a useful reference for the land Cal/Val validation community. The objective of this Quality Assurance Framework for Earth Observation follow-on (QA4EO-2) task is to review and update the CEOS LPV Supersite list.

Section 2 reviews the Supersite definition and the list of variables considered. Section 3 describes the explored networks and the available information. Section 4 outlines the ranking methodology, and Section 5 presents the results and the gap analysis. Finally, the conclusions are provided.

2. Supersite Definition

This section revises the CEOS LPV Supersite definition and then summarizes the variables that are included in the analysis.

Minor updates to the Supersite definition have been proposed to better represent the state of the art within CEOS LPV (updates are highlighted in bold).

- *Super-characterized site (canopy structure and bio-geophysical variables) following well-established protocols, useful for the validation of satellite land products (**addressing the needs of at least three product families**) and for radiative transfer modeling approaches.*
- *Active, long-term operations, supported by appropriate funding and infrastructural capacity.*
- *Supported by airborne/**UAV** LiDAR and hyperspectral acquisitions (desirable).*
- ***Adherence to CEOS FRM principles (desirable).***

The following bio-geophysical variables are considered in line with CEOS LPV focus areas, the exception are categorical variables such as land cover or burned areas. Note that Surface Reflectance, Phenology, Evapotranspiration and Gross Primary Productivity were not included in the first supersite version.

- **Surface Reflectance**: Stations providing hyperspectral measurements of surface reflectance data, either in the VIS/NIR domain or in the Sun-Induced chlorophyll Fluorescence (SIF) domain.
- **Surface Radiation**: Albedo and fraction of diffuse radiation.
- **Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FAPAR):** Either LAI and FAPAR measurements, or digital photos useful to estimate those.
- **Phenology:** Either plant phenology observations, or digital photos useful to estimate phenometrics.
- **Soil Moisture (SM)**: Soil moisture measured at different depths.
- **Land Surface Temperature (LST):** LST and emissivity measurements.
- **Above-Ground Biomass (AGB):** It provides AGB measurements or it can be estimated (inventories or from Terrestrial Lasser Scanning (TLS)).
- **Evapotranspiration (ET):** It can be estimated from water vapour fluxes.
- **Gross Primary Productivity (GPP):** GPP and related quantities (Net Ecosystem Exchange (NEE)) are provided or can be estimated from carbon fluxes.

In addition, the following auxiliary data or information has been assessed:

- **Aerosol Optical Thickness (AOT):** AOT is available if there are Aerosol Robotic Network (AERONET) stations nearby.
- **Structural:** Includes several sources of information related to the vegetation structure, including forest inventories and/or TLS measurements.
- **Airborne/UAV:** hyperspectral optical data or LiDAR collected from airborne or Unmanned Aerial Vehicles (UAV).
- **Meteo properties:** Includes a meteorological station measuring air temperature, air humidity, precipitation, wind speed and direction, soil temperature, and so on.
- **FRM adherence:** if FRM guidelines for traceable uncertainties are accounted for.
- **Upscaling:** if in-situ measurements are upscaled to medium-resolution satellite pixels.
- **Protocol:** relates to the measurement protocol, and if it is specific for validation purposes.
- **Data policy:** if data are freely available or accessible upon request.

3. Explored ecosystem research networks

- **Terrestrial Ecosystem Research Network (TERN)**

TERN is the Australia's multi-scale ecosystem observatory & environmental science research network. TERN measures key terrestrial ecosystem attributes over time from continental scale to field sites at hundreds of representative locations and openly provides environmental monitoring and assessment model-ready data that enable those undertaking environment and ecology research to detect and interpret changes in Australia ecosystems. TERN is structured in three main platforms: TERN Landscapes (remote sensing), TERN Ecosystem Surveillance (soil, flora, and fauna), and TERN Ecosystem Processes (ecosystem function).

TERN Ecosystem Processes (https://www.tern.org.au/tern-observatory/tern-ecosystem-processes/) consists of a network of 16 intensive monitoring sites, known as SuperSites, strategically distributed across Australia to represent key biomes and ecological gradients (Figure 1). These SuperSites are designed to provide long-term, high-frequency observations of ecosystem function at the plot-to-landscape scale, supporting research into carbon, water, and energy fluxes, soil and vegetation dynamics, and biodiversity patterns. Each SuperSite integrates a suite of automated sensors, remote sensing platforms, and regular field surveys to generate time-series data critical for understanding ecological processes, validating Earth observation products, and modelling ecosystem responses to environmental change, following well-stablished protocols (Karan et al., 2015).

Figure 1: Location of 16 TERN Supersites in Australia.

The main data collections of interest for LPV purposes are:

- **Flux data release**, which provides **albedo**, **GPP/NPP** and **ET**. Energy, carbon and water fluxes are primarily measured using eddy covariance towers, forming part of the national Australian and New Zealand Flux Research Network (OzFlux) network (https://www.ozflux.org.au/). These towers provide continuous data on the exchanges of CO_2, H_2O, and energy between terrestrial ecosystems and the atmosphere. Complementary instrumentation includes meteorological stations, soil heat flux plates, and greenhouse gas flux chambers.
- **Field-based surveys** that record Digital Hemispherical Photography (**DHP**) or Digital Cover Photography (**DCP**), from which **LAI** is either directly provided or can be processed if not.
- Phenologycal Camera Network **(PhenoCam) Images** and **Phenology data collections**, related to Land Surface Phenology (**LSP**) and vegetation parameters.

- **SM** is monitored using a combination of capacitance and time-domain reflectometry sensors, as well as Cosmic-Ray Soil Moisture Monitoring Network (**CosmOz)** neutron probes (https://cosmoz.csiro.au/), providing depth-resolved measurements across various soil types and conditions.

Additionally, the vegetation structure is characterized through terrestrial LiDAR (TLS) and airborne/drone LiDAR remote sensing, as well as filed-based measurements of biomass (forest inventory, vegetation structure), canopy height, and species composition. These observations are complemented with long-term vegetation plots and biodiversity transects, enabling detailed structural and functional characterization of each ecosystem. Hyperspectral airborne data and ground calibration data acquisitions are also available.

All data collected through the Ecosystem Processes SuperSites are freely and openly available via the TERN Data Portal (https://portal.tern.org.au/browse/theme).

A total of 16 TERN SuperSites were evaluated. In addition, three additional TERN (ozFlux) sites are selected for validation of remote sensing products in Copernicus GBOV; therefore, these three TERN (OzFlux) sites used in GBOV were also evaluated in this assessment.

- **National Ecological Observatory Network** (**NEON)**

NEON (https://www.neonscience.org/) is a continental-scale ecological observation system funded by the U.S. National Science Foundation. NEON consists of 81 field sites, of which 47 are terrestrial sites distributed across 20 ecoclimatic domains representing the ecological diversity of the United States, including Alaska, Hawaii, and Puerto Rico (see Figure 2). Each terrestrial site includes instrumented towers, soil plots, and a variety of standardized field sampling areas. The network is designed to collect long-term and open-access ecological data to support research on climate change, land use, and ecosystem dynamics at multiple spatial and temporal scales. NEON's consistent observational framework allows for cross-site comparison and national-scale synthesis of ecological patterns and processes (Keller et al., 2008).

Figure 2: Location of 47 NEON terrestrial sites.

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NEON terrestrial sites collect a broad set of data products organized into instrumented and observational collections, as well as airborne remote sensing data collections:

- **Instrumented data products** include **phenology images** (via PhenoCam, for **LSP**) and **carbon** (**GPP**) and **water fluxes** (**ET**) measured via eddy covariance towers, also providing high-frequency observations of Photosynthetically Active Radiation (PAR) and longwave and shortwave radiation (**albedo**), latent and sensible heat fluxes, and auxiliary data such as CO_2 concentration or meteorological variables. Soil measurements include **SM** and temperature at multiple depths, soil CO_2 concentration, and biogeochemical properties.
- **Observational collections** involve field-based sampling of vegetation structure, **DHP**s (useful for **LAI, FAPAR**), **biomass**, **phenology** observations, and species composition, canopy height, and ground cover. These collections are designed using standardized protocols to ensure spatial and temporal consistency across the network, supporting model-data integration and remote sensing validation efforts.
- **Airborne remote sensing and LiDAR** collections are conducted over NEON field sites during peak greenness and provide quantitative information on land cover and changes to ecological structure and chemistry based on airborne spectrometers and LiDAR data. Airborne-based albedo, vegetation indices, LAI/FAPAR and Biomass products are also provided.

All NEON data products are freely and openly available through the NEON Data Portal, users can access, use, and redistribute the data without restriction; the network also adheres to FAIR data principles to ensure data are findable, accessible, interoperable, and reusable. A total of 47 NEON stations were evaluated.

- **Integrated Carbon Observation System** (**ICOS)**

ICOS (https://www.icos-cp.eu/) is an European infrastructure (170 stations, see Figure 3) with the objective to observe the levels of greenhouse gas emissions to predict climate change and mitigate its consequences, covering three key domains: Atmosphere, Ecosystem and Ocean. The ICOS Ecosystem observations network, coordinated by the Ecosystem Thematic Centre (ETC), adheres to the monitoring principles of the Global Climate Observation System (GCOS) and Global Terrestrial Observing System (GTOS). Sampling design at ICOS ecosystem stations include the identification of key components for greenhouse gases observations in terrestrial ecosystems combined with the careful consideration of the requirements from multiple data user categories (Franz et al., 2018).

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Figure 3: Location of the ICOS Ecosystem network stations.

The stations are typically mounted on towers distributed across different countries and ecosystems (forests, croplands, shrublands, etc.) equipped with the following instrumentation:

- Stations typically possess an eddy covariance system which measures the turbulent fluxes and energy between the ecosystem and the atmosphere (carbon and water exchanges (**GPP and ET**), wind speed and direction, etc.)
- Meteorological sensors which measure auxiliary variables for fluxes corrections and modeling (air temperature and humidity, precipitation, shortwave radiation, longwave radiation, net radiation, barometric pressure, etc.). The **albedo**, derived from shortwave radiation components is available for most of the stations.
- Soil sensors (to measure **SM**, soil temperature, soil heat fluxes, etc.).
- Ancillary instruments which are not presents in all the stations (Photosynthetically Active Radiation, **LAI** measurements, **Phenology** observations, **AGB** measurements, etc.).

The **Ecosystem Final Quality (level 2) Data Product** is the fully quality-controlled dataset that was used in this assessment. The data is provided half hourly, except for ancillary instruments, which provides sporadic data. All the ICOS data are open access and free to use for educational, scientific and policy purposes. The Ecosystem Final Quality (level 2) Data Product release 2024-1 includes 80 sites (i.e., level 2), of the total 111 ICOS ecosystem stations, which were reviewed in this assessment. They typically provide measurements (or can be estimated) of **Albedo, LAI, ET, GPP, AGB, and SM.**

In addition, several parallel activities are also taking place at some ICOS sites, including GBOV (see below), FLEX Cal/Val, 3D structural characterization, among others, allowing to complement ICOS sites with LST, TLS, or Hyperspectral reflectance data. As a remarkable example, ESA and Finnish Meteorological Institute (FMI) have recently agreed to establish an Earth observation Cal/Val supersite at ICOS Sodankylä (https://en.ilmatieteenlaitos.fi/sodankyla-supersite) site, which also serves as a test bed for several recently proposed satellite missions.

- **Ground-Based Observations for Validation** (**GBOV**)

GBOV (https://gbov.land.copernicus.eu/) is an initiative of Copernicus Land Monitoring Service (CLMS) to enhance validation of satellite land products providing long-term observations from

operational ground-based monitoring networks (i.e., data is mainly brokered from multiple networks). The main objectives are: i) to collect multi-year ground-based observations over stations from international networks (e.g., ICOS, NEON, TERN, OzFlux, Surface Radiation Budget Network – Surface Radiation Budget Network - SurfRad, AERONET, Baseline Surface Radiation Network - BSRN, U.S. Climate Reference Network - USRCN, etc.); and ii) to upgrade sites with new instrumentation or stablish new sites to close thematic or geographics gaps and maintain the database for reference measurements and upscaled products.

Figure 4: Location of CLMS GBOV sites.

GBOV in-situ measurements are provided to validate seven core land products:

- Top of Canopy Reflectance (TOC-R).
- Surface **Albedo**.
- **SM**.
- **LST**.
- **LAI**.
- **FAPAR**.
- Fraction of Vegetation Cover (FCOVER).

In-situ measurements are available, together with their associated uncertainties for some variables, and accompanying documentation, including collection protocols, which generally follow those of the original networks. Moreover, GBOV delivers upscaled products matching medium resolution (300m) satellite products.

A total of 146 GBOV sites (Figure 4) were evaluated based on the dataset (reference measurements adn upscaled products) downloaded in April 2025. The TERN, NEON, and ICOS sites included in the GBOV service were updated with complementary GBOV data (when available) and with upscaled land products products. For example, NEON sites provide only DHP data over vegetation sites (i.e., LAI can be estimated, but not directly provided), whereas GBOV processes the NEON DHP data to provide estimates of LAI and FAPAR (among others), in addition to the upscaled products. Similarly, GBOV provides LST in some ICOS stations. Consequently, those sites are complemented with GBOV information. The remaining GBOV sites, those not belonging to TERN, NEON and ICOS networks, were evaluated individually.

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- **Complementary Initiatives**

In addition to the main TERN, NEON, ICOS, and GBOV networks, other complementary initiatives were assessed with the aim of identifying *match-up sites* (i.e., sites that coincide with those of the main networks) to enhance them with additional instrumentation and measurements. The following initiatives were assessed:

The **Fiducial Reference Measurements for Vegetation** (FRM4Veg, https://frm4veg.org/) is a project managed by ESA with the objective of stablishing the protocols required for in-situ measurements of vegetation-related parameters with traceable uncertainties (FRM compliant) to support the validation of Sentinel-2, Sentinel-3 and PROBA-V products. The measured variables include **FAPAR,** Canopy Chlorophyll Content (CCC), **Surface Reflectance**, **LAI** and FCOVER, accompanied by the uncertainty budget. UK-Wytham Woods site, already assessed as part of GBOV, was complemented with FRM4Veg data (i.e., FAPAR, LAI, surface reflectance, UAV data, and FRM-compliant protocols).

The **PhenoCam** network (https://phenocam.nau.edu/webcam/) provides near-surface remote sensing of **canopy phenology**, installing automated digital cameras to monitor vegetation phenology across diverse ecosystems. the green chromatic coordinate (GCC) index is obtained from digital cameras as the relative brightness of the green channel normalized against the overall brightness of red, green and blue channels. Then, phenological transition dates (as start and end of the green-up and senescence phases) are derived from GCC index. More than 1300 sites are available, and 53 of them coincide (match) with the candidate supersites from TERN, NEON, ICOS and GBOV networks, thereby enriching these sites with PhenoCam information.

The **Phenological Eyes Network** (PEN, http://www.pheno-eye.org/) is a ground-based network for in-situ ecological observations for validating terrestrial remote sensing vegetation phenology across different biomes (from Arctic to tropical ecosystems). The stations are equipped with automatic Digital Fish-eye Camera, which captures daily or hourly imagery of canopy and sky for continuous monitoring of phenological changes. 45 stations were available but only one of them coincides with the candidate supersites list: the GBOV Fuji Hokuroku site. Thereby, the GBOV Fuji Hokuroku site was complemented with digital camera form PEN.

AErosol RObotic NETwork (AERONET, https://aeronet.gsfc.nasa.gov/), is a ground-based remote sensing network stablished by NASA and other calibration centers and collaborators. The main objective is to support satellite aerosol retrievals, climate research, air quality studies and validation of atmospheric models. It provides globally distributed observations of spectral **Aerosol Optical Depth (AOD)**, inversion products, and precipitable water in diverse aerosol regimes. AERONET provides data in more than 1300 stations. AERONET network has been used to identify whether aerosol information is available for the considered candidate supersites, in order to complement them with AOD information. For each candidate supersite, AOD measurements are available if an AERONET station lies within 25 km of the site. A total of 91 candidate supersites meet this criterion.

Radiometric Calibration Network (RadCalNet, https://www.radcalnet.org/#!/) is a global network of terrestrial test sites designed for the radiometric calibration and validation of Earth-observation optical sensors. It is a multi-agency effort, developed under CEOS auspices and coordinated at CEOS WGCV level. RadCalNet collects **surface reflectance measurements** that are processed into top-of-atmosphere reflectance products with traceable uncertainties. The network's data are used for generating top-of-atmosphere reflectance over well-characterised sites (e.g., Railroad Valley Playa, USA; La Crau, France; Gobabeb, Namibia; Baotou, China) that satellite sensors can use for inter-sensor consistency, calibration updates, and monitoring of radiometric stability. The NA-Gobabeb site, part of GBOV, was complemented with RadCaNA-lNet surface reflectance data.

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The **Programme for Monitoring of the Greenland Ice Sheet** (PROMICE, https://promice.org/) together with the Greenland climate network provides measurements for improving the understanding of ice-sheet response to climate change. The network has automatic weather stations and provides shortwave and longwave radiation data around 52 stations. Three PROMICE stations coincide with ICOS candidate supersites, allowing these ICOS sites to be complemented with additional PROMICE observations.

The **FLuorescence Explored Calibration and Validation** (FLEX Cal/VAL) initiative, as part of FLEX mission is a network of sites equipped with the fluorescence box (FloX) system, a ground-based automated spectroradiometer designed to continuously measure vegetation solar-induced chlorophyll fluorescence. A total of 56 stations were proposed in FLEX Cal/Val context[1]; several are currently equipped with FLoX system and others are planned to be equipped in the future. A total of 10 of these stations coincide with candidate supersites (e.g. NEON or ICOS sites), which were consequently complemented with FloX hyperspectral data.

The **Hyperspectral Radiometer Network** (HYPERNETS, https://hypernets.eu/network/) is a network of automated hyperspectral radiometers, which provides water and land surface high-quality and traceable measurements of reflectance. It aims to provide reference data for validating surface reflectance products of any multi- and hyperspectral sensor in the VNIR-SWIR range. The stations are equipped with the Hyperspectral Pointable System for Terrestrial and Aquatic Radiometry (HYPSTAR) radiometer, covering from 380 to1680nm for land. Currently there are nine land stations, which were analyzed to complement candidate supersites data. Three candidates (UK-Wytham Woods, NA-Gobabeb, BE-Lonze) were upgraded with HYPERNETS hyperspectral surface reflectance information.

The **American Flux Network (AmeriFlux**, https://ameriflux.lbl.gov) is a network of sites which aims to provide long-term flux measurements across North, Central and South America, representing major climate and ecological biomes (tundra, grasslands, savanna, crops, forests). At each station, eddy covariance techniques capture high-frequency data on the exchanges of carbon dioxide, water vapor and energy between ecosystem and atmosphere. With the information provided, **albedo, gross primary production and evapotranspiration** can be estimated.It should be noted that AmeriFlux and the NEON program have joined forces for flux data, and the data from the 47 NEON flux towers are now available through the AmeriFlux portal. Therefore, we focus here on regions outside U.S., which is already very well represented by NEON stations. From more than 240 AmeriFlux stations, we retained eleven as candidate supersites, as they are currently active and located in undersampled region, either in South America or Canada.

In addition to that, few other candidates' sites were reevaluated coming from the previous CEOS LPV supersite v1 list, including Environmental Monitoring Network (**Enviro-Net,** https://www.enviro-net.org/) sites in America, **CA-Mer Blue** supersite (https://merbleue-lpv.geog.mcgill.ca/) in Canada, and Karlsruhe Institute of Technology (**KIT)** stations (https://www.imkasf.kit.edu/english/skl_stations.php) for LST, or those from the EU **RemoTrees** project (https://sites.google.com/fmach.it/remotreesproject/) for the collection of several forest variables from Internet of Things technologies.

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[1] flex-level-2b-calibration-validation-plan

3. Metadata information for each site

The first tab of the CEOS LPV supersite v2 excel file presents detailed metadata information for each proposed supersite. This metadata information for each site includes the relevant information for each station:

- Name.
- Country.
- Acronym.
- Network affiliation.
- Geographic coordinates (latitude and longitude).
- Land cover (network), info provided by the main network.
- Land cover, based on the Climate Change Service (C3S) Land Cover V2.1 2021 dataset.
- Main biome type, aggregation of C3S Land Cover V2.1 2021 classes.
- Site Homogeneity, provided in four levels, describes the degree of homogeneity around the station, considering its suitability for validating products at decametric, hectometric, and kilometric resolutions.

Figure 5 presents Google Earth views of 2 km × 2 km areas from different proposed supersites, illustrating the different levels of spatial homogeneity: 0) homogeneous in a diameter < 100m; 1) homogeneous in a diameter 100m≤d<500m; 2) homogeneous in a diameter 500m≤d<1km; and 3) homogeneous in a diameter d≥1km.

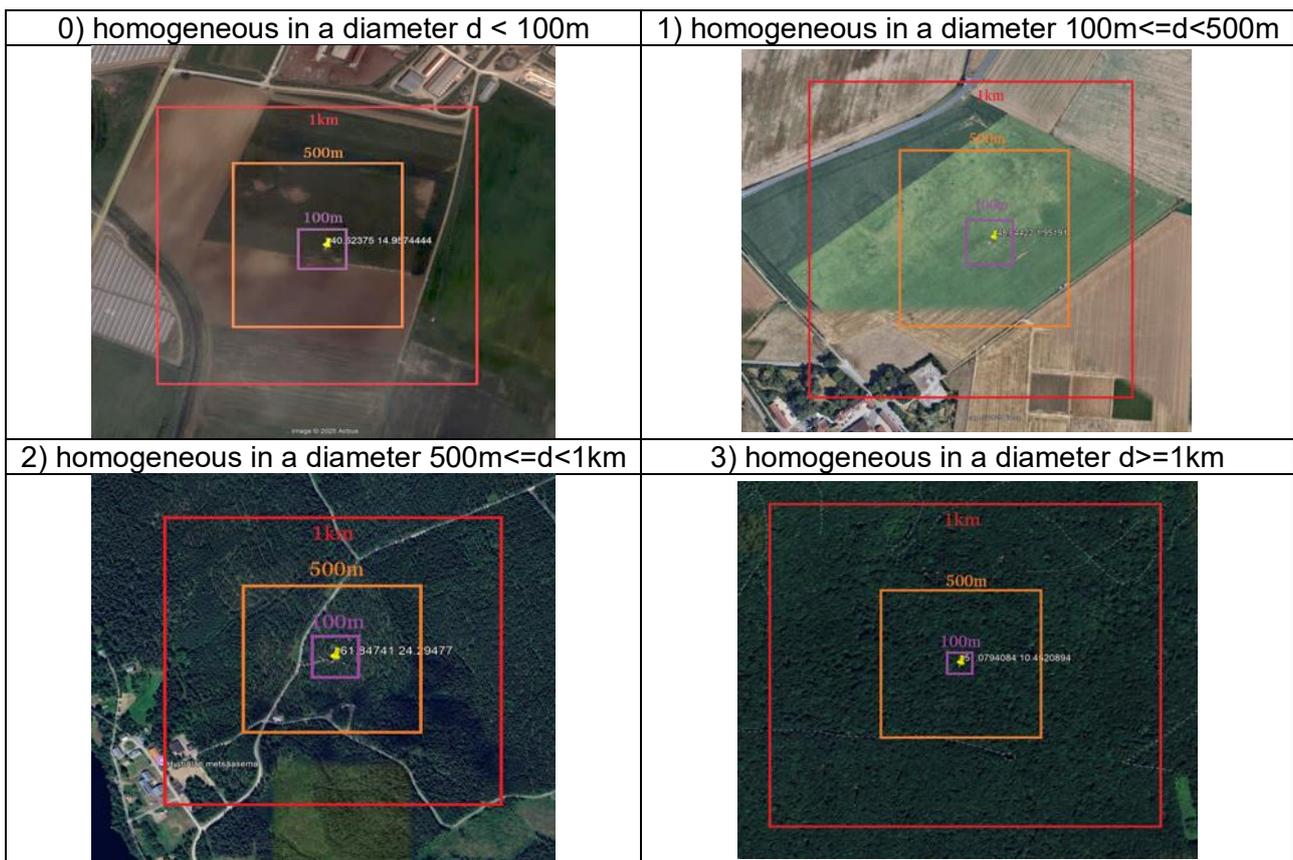| 0) homogeneous in a diameter d < 100m	1) homogeneous in a diameter 100m<=d<500m
2) homogeneous in a diameter 500m<=d<1km	3) homogeneous in a diameter d>=1km

Figure 5: Google Earth view of different proposed supersites illustrating different levels of homogeneity: 0) Borgo Cioffi (IT-BCi), 1) Grignon (FR-Gri), 2) Hyytiala (Fi-Hyy), 3) Hainich (De-Hai)

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The metadata also documents the availability of in situ data for each considered variable. For each variable, the dataset specifies whether data are provided, can be estimated (e.g. from digital camera), or are not available, a different code is used for each case. The value assigned to each field during the ranking is also included in the metadata.

- Considered variables with data availability:
    - Hyperspectral bidirectional reflectance factors (BRF).
    - Surface Albedo.
    - Leaf Area Index (LAI) / Fraction of Absorbed PAR (FAPAR).
    - Phenology.
    - Soil moisture
    - Land surface temperature (LST).
    - Above-ground biomass (AGB).
    - Evapotranspiration (ET).
    - Gross Primary Productivity (GPP).

- A number of auxiliary data were also evaluated and described in the metadata:
    - Aerosol optical thickness (AOT).
    - Structural measurements: availability of detailed canopy structure representation (TLS, inventories).
    - The availability of proximal remote sensing information (UAV, airborne).
    - Meteorological observations.
    - Adherence to FRM principles or at least if associated uncertainties are available.
    - Upscaled ground based maps.
    - Availability of measurements protocols and if they are specific for validation.
- Data policy, if data is free or requires permission.
- Contact, main contacts
- Data access, URL to the data.

4. Ranking methodology

To establish a consistent and transparent ranking of candidate Supersites, a scoring system was defined based on the availability, quality, and representativeness of in situ measurements. A score was assigned to each criterion according to its relevance for satellite product validation, with higher scores reflecting greater robustness and completeness of the observations. Table 1 summarizes the criteria, the range of values for each parameter, and the corresponding scores applied in the ranking procedure.

The first criterion considered in the ranking is **site homogeneity**, since the representativeness of ground measurements strongly depends on the spatial consistency of the surrounding land cover. Homogeneity scores range from 0.5 (homogeneous within a diameter <100 m) up to 2 (homogeneous within a diameter ≥1 km), giving higher ranking to stations useful for validation of satellite products at different resolutions.

The second criterion includes **data availability for core variables** relevant for satellite product validation, namely BRF, albedo, LAI/FAPAR, phenology, soil moisture, LST, AGB, ET, and GPP. For each of these variables, the scoring scheme assigns the highest value (1.5) when measurements are available, and a lower ranking value (0) if there is no data. 1 point is given when the variable can be estimated (but further processing is needed, e.g., digital hemispherical photos are available, but not LAI values, in NEON stations). The maximum score for this criterion (when all data are available) is 13.5 points.

Finally, the third criterion includes the **auxiliary variables or relevant information** for validation. These comprise proximity to AOT stations, provision of structural or airborne/drone data, meteorological observations, adherence to FRM principles, availability of upscaling maps, application of measurement protocols, and data policy. Although these criteria carry lower weights (typically between 0.25 and 1), they provide valuable information that enhances the reliability, usability, and openness of the data provided by each station. Higher weights were assigned to FRM-compliant sites and to those with well-characterized structural information (TLS). It should be noted that up to 2 additional points were assigned by its relevance to undersampled geographical regions (Africa, Asia, South America), and 1 points to undersampled biomes (bare soils and sparsely vegetated areas), which only affects few sites. The maximum score for this criterion is 8.5 points.

The maximum possible score for a supersite is 24 points, or 21 when excluding the points related to its relevance by biome or geographical region (affecting only few sites). A total of 230 candidates were evaluated and ranked.

Table 1: Ranking score assigned to each parameter.

Parameter	Value	score
Homogeneity	0: Homogeneous in a diameter d < 100m	0.5
	1: Homogeneous in a diameter 100m<=d<500m	1
	2: Homogeneous in a diameter 500m<=d<1km	1.5
	3: Homogeneous in a diameter d>=1km	2
BRF (hyper)	0: It does not provide BRF data	0
	1: It provides hyperspectral data	1
	2: It provides spectral data for fluorescence estimation	0.5
	3: It provides hyperspectral wider range (VNIR/SWIR) and fluorescence range	1.5
Albedo	0: It does not provide Albedo data	0

	1: It provides albedo data, but not diffuse information	1
	2: It provides both, albedo data and diffuse information	1.5
LAI/FAPAR	0: It does not provide LAI/FAPAR data	0
	1: It provides Digital Hemispherical Photos	1
	2: It provides LAI/FAPAR measurements	1.5
Phenology	0: It does not provide phenology data	0
	1: It provides camera photos	1
	2: It provides phenological measurements	1.5
Soil Moisture	0: It does not provide soil moisture data	0
	1: It provides soil moisture data	1.5
LST	0: It does not provide LST data	0
	1: It provides only LST	1
	2: It provides both, LST and emissivity data	1.5
AGB	0: It does not provide AGB data	0
	1: AGB can be estimated	1
	2: It provides AGB	1.5
ET	0: It does not provide ET data	0
	1: ET can be estimated	1
GPP	0: It does not provide GPP data	0
	1: GPP can be estimated (CO_2 fluxes)	1
	2: It provides GPP data and/or others (NEE,…)	1.5
AOT	0: There is not a station of AOT near (<25km)	0
	1: There is a station of AOT near (<25km)	0.25
Structural	0: It does not provide structural data	0
	1: It provides Terrestrial Laser Scanning (TLS)	1
	2: It provides forest inventory	0.5
	3: It provides both, TLS and forest inventory	1.5
Airborne /drone	0: It does not provide airborne or drone data	0
	1: It provides LIDAR data	0.5
	2: It provides airborne/drone data	0.5
	3: It provides both LIDAR and airborne/drone data	1
Meteo	0: It does not provide meteo data	0
	1: It provides meteo data	0.25
FRM concept	0: Measurements does not provide uncertainties	0
	1: Measurements provides uncertainties, but only partially accounted for (at least in one variable)	0.25
	2: Measurements provides uncertainties with adherence to FRM (at least in one variable)	1
Upscaling	0: It does not provide upscaling maps	0
	1: It provides upscaling maps (at least in one variable)	0.25
protocol	0: Measurements are taken without a protocol	0
	1: Measurements are taken with a protocol, but not specific for validation	0.25
	2: Measurements are taken with a protocol, which is specific for validation	0.5
data policy	0: Under request	0
	1:Open access	0.5

5. Results and gap analysis

230 candidate sites were ranked following the Table 1 scores. As the maximum score for most sites is 21, a cut off was done in 11 (i.e., sites obtaining more than 50% of maximum score). The **CEOS LPV Supersite V2** dataset includes **92 LPV supersites**, with scores between 18.75 and 11. Their global distribution is shown in Figure 6. Additionally, a separate tab lists **68 candidate sites** with scores from 10.75 to 5, intended to encourage future upgrades to LPV supersite status.
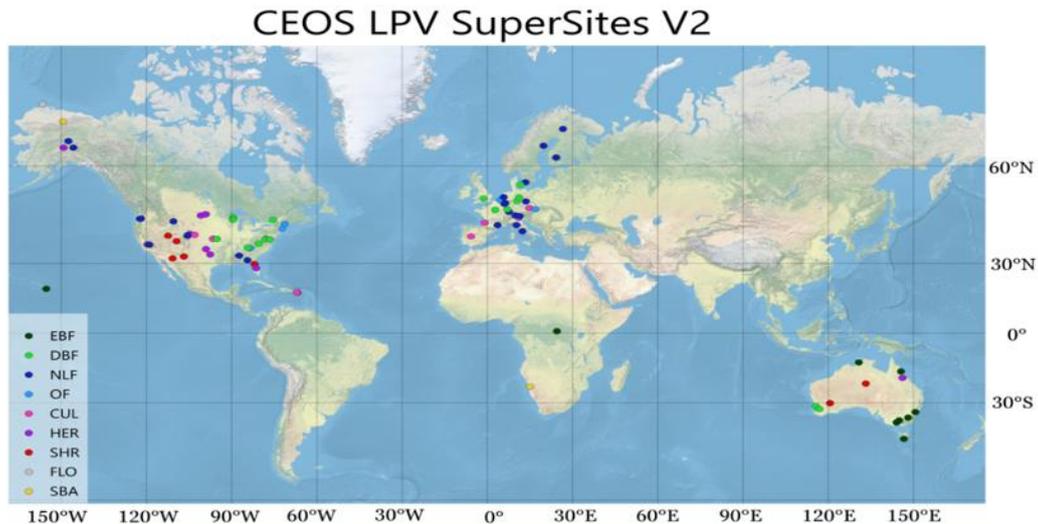

Figure 6: Global distribution of the 92 CEOS LPV V2 proposed supersites.

Figure 7 summarizes the representativeness of the proposed CEOS LPV supersites by biome type (left) and continent (right), compared with global distributions. Forests (mainly Deciduous Broadleaf Forests and Needle-Leaf Forests) and herbaceous areas are oversampled among the supersites, whereas other biomes such as shrublands, cultivated and mainly sparsely vegetated areas are undersampled. As shown in the map, most supersites are located in North America, Europe, and Australia, associated with the three main networks: NEON, ICOS, and TERN respectively. Large gaps remain in V2 over South America, Africa and Asia.
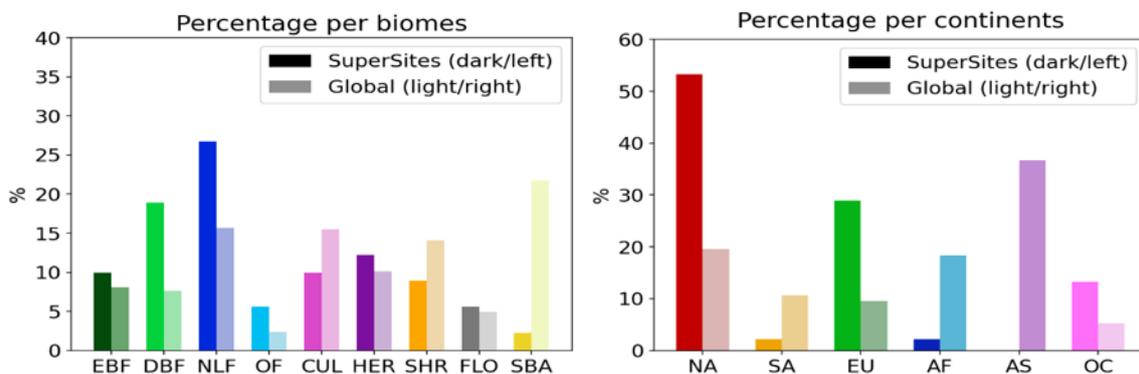

Figure 7: Percentage of CEOS LPV supersites (dark color) per biome type (left) and continent (right), compared with global data (light color). EBF stands for Evergreen Broadleaf Forests, DBF for Deciduous Broadleaf Forests, NLF for Needle-Leaf Forests, OF for Other Forests, CUL for Cultivated, HER for Herbaceous, SHR for Shrublands, FLO for Flooded vegetation sites, and SBA for Sparsely vegetated and Bare Areas. NA stands for North America, SA for South America, EU for Europe, AF for Africa, AS for Asia, and OC for Oceania.

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Figure 8 illustrates the percentage of CEOS LPV V2 supersites that provide measurements of the considered LPV variables. Most of them (>93%) include measurements related to albedo, LAI/FAPAR, AGB, ET, and GPP, while phenology (68.9%) and SM (67.8%) are also provided by a large proportion of supersites. However, hyperspectral surface reflectance (17.8%) and LST (27.8%) require further attention. New activities such as the New Users for a Better ICOS (NUBICOS) project (https://www.icos-cp.eu/projects/nubicos) are expected to enhance the contribution of sites measuring LST over Europe.
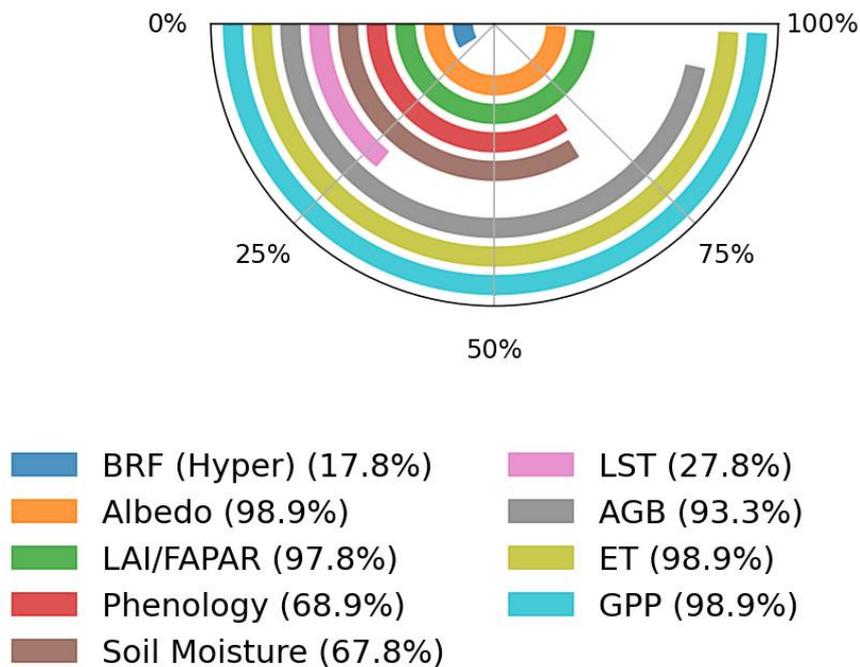

Figure 8: Percentage of cases providing the main LPV variables in the proposed CEOS LPV supersites.

6. Conclusions

This technical note summarises the process for updating the CEOS LPV Supersites (V2) list. Four main networks were explored (ICOS, NEON, TERN Supersites, and GBOV), in addition to several complementary initiatives (RadCalNet, PhenoCam, AERONET, FLEX Cal/Val, FRM4Veg, AmeriFlux, etc.) to complement previously identified candidates with additional information. A total of 230 candidate sites were identified.

Each site has been assessed according to three main criteria: spatial homogeneity; data availability (BRF, albedo, LAI/FAPAR, phenology, LST, SM, AGB, ET, GPP); and ancillary information (AOT, structural data [TLS], airborne/drone, meteorological, FRM compliance, protocols, upscaling products, and data policy). A ranking methodology was developed with a maximum score of 21 points (plus up to 3 additional points for relevance to fill geographical or biome gaps, assigned to a few sites).

Finally, 98 supersites with a score of 11 or higher (i.e., greater than 50% of the possible maximum score) have been included in the CEOS LPV Supersites V2 list, with complete metadata information. In addition, a separate tab lists 68 candidate sites with scores from 10.75 to 5, intended to encourage future upgrades to LPV supersite status.

The gap analysis reveals that large geographical gaps remain in Africa, Asia, and South America. Regarding data availability, surface albedo, vegetation, and carbon and water fluxes are well represented, whereas surface reflectance and LST require further attention.

CEOS LPV Supersites V2 represents an update of the previous version, refining validation approaches, incorporating new variables such as ET and GPP in line with recent developments in CEOS LPV focus areas, and introducing new criteria such as FRM compliance and upscaled products.

Finally, a revision of the CEOS LPV Supersites list every 4–5 years is recommended to keep it up to date.

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Annex I: Acronym list

AGB	Above Ground Biomass
AmeriFlux	American Flux Network
AOD	Aerosol Optical Depth
AOT	Aerosol Optical Thickness
BRF	Bidirectional Reflectance Factor
BSRN	Baseline Surface Radiation Network
Cal/Val	Calibration and Validation
CCC	Canopy Chlorophyl Content
CEOS LPV	Committee on Earth Observation Satellite Land Product Validation
CLMS	Copernicus Land Monitoring Service
CosmOz	Cosmic-Ray Soil Moisture Monitoring Network
CUL	Cultivated
DBF	Deciduous Broadleaf Forests
DCP	Digical Cover Photography
DHP	Digital Hemispherical Photography
EBF	Evergreen Broadleaf Forests
Enviro-Net	Environmental Monitoring Network
EOLAB	Earth Observation Laboratory
EOS	Earth Observation System
ESA	European Space Agence
ETC	Ecosystem Thematic Centre
FAIR	Findable, Accessible, Interoperable, and Reusable
FAPAR	Fraction of Photosynthetically Active Radiation
FCOVER	Fraction of Vegetation Cover
FLEX	FLuorescence Explorer
FLO	Flooded
FLoX	FLuorescence boX
FMI	Finnish Meteorological Institute
FRM	Fiducial Reference Measurement
FRM4Veg	Fiducial Reference Measurements for Vegetation
GBOV	Ground-Based Observations for Validation
GCC	Green Chromatic Coordinate
GCOS	Global Climate Observing System
GPP	Gross Primary Production
GTOS	Global Terrestrial Observing System
HER	Herbaceous
HYPERNETS	Hyperspectral Radiometer Network
HYPSTAR	Hyperspectral Pointable System for Terrestrial and Aquatic Radiometry
ICOS	Integrated Carbon Observation System
KIT	Karlsruhe Institute of Technology
LAI	Leaf Area Index
LAW	Land Surace Temperature, Aerosols and Water Vapor
LiDAR	Laser Imaging, Detection and Ranging
LSP	Land Surface Phenology
LST	Land Surface Temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NEE	Net Ecosystem Exchange
NEON	National Ecosystem Observatory Network
NIR	Near-Infrared

NLF	Needle-leaf Forests
OF	Other Forests
OzFlux	New Zealand Flux Research Network
PAR	Photosynthetically Active Radiation
PEN	Phenological Eyes Network
PhenoCam	Phenologycal Camera Network
PROMICE	Programme for Monitoring of the Greenland Ice Sheet
QA4EO-2	Quality Assurance Framework for Earth Observation 2
RadCalNet	Radiometric Calibration Network
RemoTree	Remote Tree Monitoring Network
SBA	Sparse and Bare Area
SHR	Shrublands
SIF	Sun-Induced chlorophyll Fluorescence
SM	Soil Moisture
TERN	Terrestrial Ecosystem Research Network
TLS	Terrestrial Lasser Scanning
TOC-R	Top Of Canopy Reflectance
UAV	Unmanned Aerial Vehicle
URL	Uniform Resource Locator
USRCN	United States Climate Reference Network
VIS	Visible
WGCV	Working Group on Calibration and Validation