

Showcasing the potential of the ICOS-Ecosystem network for Cal/Val of spaceborne imaging spectrometers: the Majadas (ES-LMa) site

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Abstract

Vicarious calibration and validation (Cal/Val) of spaceborne imaging spectrometers rely on stable, uniform, and homogeneous pseudo-invariant calibration targets. While this improves the quality of the match between satellite and field properties, the evaluation does not necessarily guarantee the quality of heterogeneous pixels, where the assumptions underlying the atmospheric correction are less likely to be met. Despite these greater uncertainties, it is still necessary to assess the similarity between field and remote-sensing observations across a broad range of conditions for diverse remote sensing applications. In this study we showcase the potential of the Integrated Carbon Observation System (ICOS) Ecosystem network, providing such a wide range of cover types, to support Cal/Val of medium-resolution imaging spectrometers. Las Majadas de Tiétar ICOS station (ES-LMa) was used as a challenging test site to obtain reliable spectral in-situ measurements over vegetation targets for cross-comparison with the Environmental Mapping and Analysis Program (EnMAP) images. In-situ spectral data were acquired within ± 1 hour of two different EnMAP acquisitions on July 2025 over a selected calibration area dominated by senescent grass and surrounded by evergreen holm oaks, located 300 m south of the ES-LMa ICOS tower. Comparison between ASD and EnMAP reflectance factors demonstrated the impact of image off-nadir acquisitions in Cal/Val activities on vegetation targets as well as the susceptibility to atmospheric disturbances of the shortwave infrared bands typically used for the estimation of non-photosynthetic vegetation. Overall, the results prove the potential of ICOS ecosystem sites to complement traditional high-reflectance Cal/Val locations increasing the representativeness of terrestrial targets.

1. Introduction

Vicarious calibration and validation (Cal/Val) of spaceborne imaging spectrometers is fundamental to assess radiometric reliability and consistency throughout their operational lifetime (Pearlshtien et al., 2023). These activities commonly rely on stable, uniform, and homogeneous pseudo-invariant calibration targets (Niro et al., 2021). However, the agreement between satellite and reference data under homogeneous conditions does not necessarily guarantee the quality of heterogeneous pixels, where spatial variability at the sub-pixel level can increase uncertainties (Zhao et al., 2025). This makes it necessary to assess the relationship between field and remote sensing observations under a wide range of conditions, particularly in heterogeneous ecosystems.

Long-term ecosystem monitoring initiatives, as the Integrated Carbon Observation System (ICOS) Ecosystem network, can provide a well-established infrastructure to support remote sensing Cal/Val activities. In contrast to conventional homogeneous calibration sites, ICOS research stations can provide observations of complex ecosystems under changing seasonal conditions, allowing the assessment of satellite observations in a wide range of environmental and phenological stages (Hufkens et al., 2018). These monitoring sites attract scientific activity and regular measurements (e.g., Melendo-Vega et al., 2019) that can support the development and validation of advanced products related with vegetation biochemical and structural variables and dynamics as phenological progress, moisture content and/or illumination conditions, among others, case an impact on the spectral characteristics of the surface (Somers et al., 2011). This explains the growing interest in using

hyperspectral sensors featuring a large number of narrow bands (5-10 nm bandwidth) which could be suitable for detecting subtle absorption features that allow, for example, the discrimination of senescent vegetation from bare soil (Hively et al., 2021). New imaging spectrometers, such as the Environmental Mapping and Analysis Program (EnMAP), and the Earth Surface Mineral Dust Source Investigation (EMIT) offer new opportunities to quantify vegetation properties, phenology and diversity at regional and global scales (Verrelst et al., 2023).

Standardized in-situ measurements and field protocols have been developed to support the validation of EnMAP satellite observations and derived products (Brell et al., 2023), and recent global validation activities have demonstrated the quality of EnMAP data across different surfaces and geographical regions (Brell et al., 2026). However standard operational atmospheric corrections can under-correct or introduce noise artifacts in the shortwave infrared region (SWIR $\sim$ 2000nm) if CO₂ and water vapor overlapping absorptions are not accurately modeled (Lau, 2004). This can have a significant impact on highly relevant applications such as the monitoring of senescent vegetation as recent studies have evaluated optimal band configuration in the shortwave infrared region above 1800nm for future satellite missions (Lamb et al., 2022) with the objective of improving ligno-cellulose absorption features and improve the estimation of crop residues. These studies highlight the importance of assessing the effects of bandwidths, atmospheric impacts and sensor signal-to-noise ratios on the ability of SWIR-derived indices to measure senescent plant material (Hively et al., 2021).

Observations geometry is also a relevant factor to consider in satellite Cal/Val activities. While near nadir observations are typically preferred to minimize atmospheric path length,

directional reflectance complexities, and adjacency effects, these ideal observation conditions may not be always feasible. Further research is needed on the effects of off-nadir observations and to determine the acceptable range, considering the characteristics of the reference target/cover. This is particularly relevant for EnMAP, which allows across-track $\pm 30^\circ$ off-nadir observations (Brell et al., 2026), making viewing geometry an important factor to consider when assessing the consistency of EnMAP and field measurements in heterogeneous ecosystems.

The main objective of this study was to evaluate the potential of the ES-LMa ICOS ecosystem station to support the assessment of EnMAP L2A reflectance factors quality in a heterogeneous Mediterranean tree–grass ecosystem. The specific objectives were: (i) testing the official EnMAP Cal/Val protocol in a complex ecosystem, (ii) analyzing the impact of image off-nadir acquisition over vegetation targets, and (iii) demonstrating the performance of grasslands as a Cal/Val target to analyze the performance of SWIR bands for key specific applications, such as monitoring senescent vegetation.

2. Methods and material

2.1 Study area

The Majadas de Tiétar research site (ES-LMa), an associated ecosystem station that belongs to the ICOS network, where field spectroscopy campaigns are performed regularly, was selected for this pilot study. The site, located in western Spain ($39^\circ 56' 26''\text{N}$, $5^\circ 46' 29''\text{W}$), is also part of the global Aerosol Robotic Network (AERONET) as it features a sun photometer, continuously monitoring aerosol optical depth and column water vapor, useful for validating parameter estimates in the atmospheric correction of satellite images. ES-LMa is representative of a Mediterranean open woodland (i.e. savanna-like or tree-grass ecosystem, locally known as *dehesas*) dominated by holm oaks with very low tree density ($\sim 20\text{--}25$ trees ha^{-1} , $\sim 20\%$ canopy cover) and a seasonally productive, dense ($>90\%$ vegetation fraction cover), and highly diverse herbaceous understory characterized by a strong phenological pattern closely linked to the annual rainfall cycle. The climate is Mediterranean, characterized by a marked summer drought with mean annual precipitation of $\sim 650\text{--}670$ mm, concentrated mainly between late autumn and spring. Topography shows low relief and generally smooth terrain, with elevations in the study area ranging from 265 to 268 m.

2.2 In-situ data

We performed two Cal/Val campaigns simultaneous to Environmental Mapping and Analysis Program (EnMAP) imaging spectrometer overpasses on July 3 and July 22, 2025. In-situ data were acquired using a full range (350–2500 nm) ASD FieldSpec™ 4 spectroradiometer (Analytical Spectral Devices Inc., Boulder, CO, USA) within ± 1 hour of each EnMAP overpass, under clear-sky conditions. The selected calibration area is a forest clearing dominated by senescent grass and surrounded by evergreen holm oaks, which is located 300 m south of the ICOS tower (Figure 1b,d). Following the EnMAP field guide for Cal/Val in-situ measurements (Brell et al., 2023), the area was divided into transects, each 15 meters apart, following EnMAP path orientation ($\sim 8^\circ$ from true North). In this case, the spatial layout was slightly modified to adapt it to the size and shape of the calibration area. As shown in Figure 1c, four 90-meter transects, two 60-meter transects, and two 30-meter transects were measured, instead of the eight 90-meter transects representing a 3×3 pixel (90×90 m) neighborhood recommended

in the EnMAP field guide. Beside this, the same sampling layout, measurement protocol and instrumental settings proposed by Brell et al. (2023) were used in the two campaigns. Ten ASD spectra were collected every 30 meters while walking the transects, and a 99% diffuse calibrated reflectance Spectralon® white reference panel (Labsphere Inc., North Sutton, NH, USA) was measured at the start and end of each full 90, 60 or 30 m transect.

The ASD raw data was pre-processed with the ViewSpec Pro software version 6.0 (Analytical Spectral Devices Inc., Boulder, CO, USA) to obtain absolute reflectance factors and checked to ensure consistency and plausibility of the measured spectra as recommended in Brell et al. (2023). These measurements were delivered to the EnMAP team in charge of the mission validation and were incorporated to the external dataset use in the quality assessment framework described in Brell et al. (2026). An Apogee SQ-500 full-spectrum quantum sensor (Apogee, Logan, UT, USA) was installed north of the Cal/Val area, nearby the white reference panel to real-time monitoring of illumination conditions during the measurement window (Figure 1e). Additionally, the ES-LMa station is equipped with a CIMEL CE318-T sun photometer (Cimel Electronique, Paris, France) that continuously acquire high-accuracy measurements of Aerosol Optical Thickness (AOT) and water vapor providing relevant information on precise atmospheric conditions at the time of EnMAP overpass which are critical in the validation of L1B Top of Atmosphere (TOA) radiance products. This data is openly available through the AERONET web portal (AERONET, 2026).

2.3 EnMAP acquisitions

EnMAP is a German satellite mission conceived to provide high-spectral resolution observations of biophysical, biochemical and geochemical variables in the spectral range of 420–2450 nm with 30 m ground spatial resolution and 30 Km maximum swath width. It carries on board a Hyperspectral Imager (HSI) that maps the Earth's surface in 224 spectral bands. In this validation exercise, we evaluated the quality of two EnMAP L2A images acquired in July 2025 simultaneously with the field data and freely accessible through the official EOWEB GeoPortal (DLR, 2026). The L2A products provide atmospherically corrected Bottom-Of-Atmosphere (BOA) surface reflectance using the Python-based Atmospheric Correction (PACO) (de los Reyes et al., 2023). The first image acquired on July 3, was specifically scheduled to coincide with a scientific campaign at Las Majadas de Tiétar site that included the acquisition of hyperspectral data using spectroradiometers and cameras mounted on drones in the context of the SensOFOREST project (SensOFOREST, 2024). The second image acquired on July 22 was part of the EnMAP Foreground Mission's regular programming over the ES-LMa site. Both images were acquired under similar environmental and atmospheric conditions, although the observation geometry differed significantly in terms of the off-nadir angle (Table 1), which allowed us to study the effect of this parameter in the validation experiment.

Date (mm/dd/yyyy)	Time (UTC)	Off-nadir Across (°)	Off-nadir Along (°)	AOT
07/03/2025	11:57	-14	-0.9	0.237
07/22/2025	11:50	-0.4	-0.2	0.165

Table 1. Acquisition date, time and off-nadir angle for the EnMAP images used in the study, and Aerosol Optical Thickness (AOT) measured by the CIMEL sun photometer in the study site at the time of the satellite overpass (Source: AERONET, 2026)

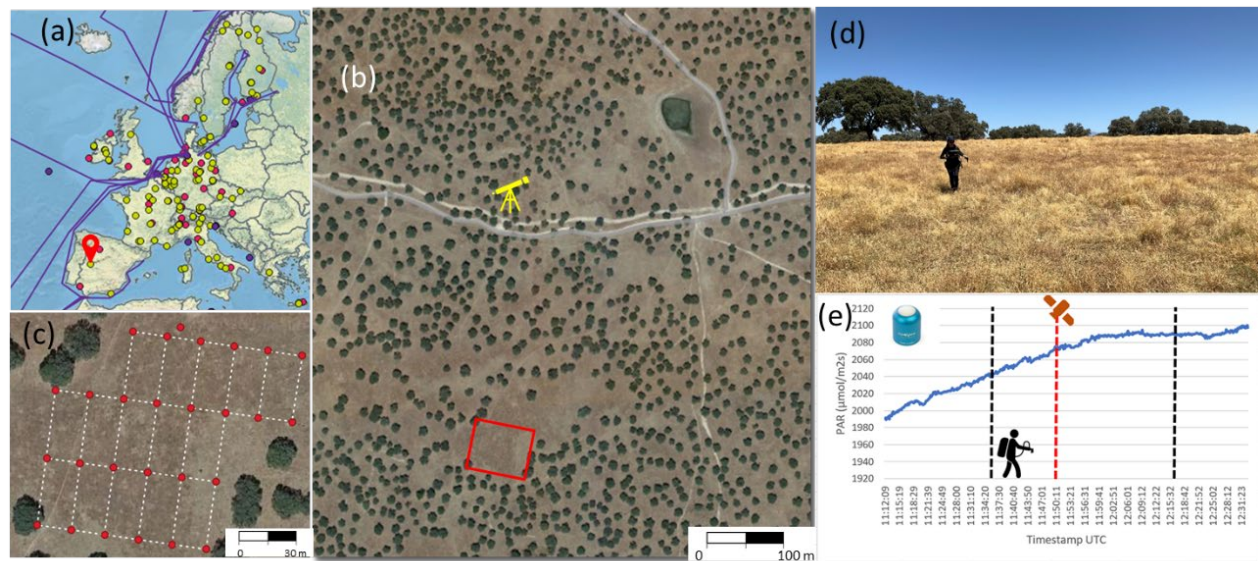


Figure 1. Study site, Cal/Val area and real-time monitoring of illumination conditions: a) location of the ICOS Ecosystem sites (yellow dots) in Europe with Las Majadas de Tiétar (ES-LMa) site highlighted with the red symbol; b) location of the Cal/Val area (red box) and the sun photometer (yellow symbol) in Las Majadas de Tiétar station; c) spatial sampling layout for the Cal/Val campaigns. White dotted lines indicate the sampling transects and red dots the starting and end points of the ten spectra acquired every 30 m with the ASD FieldSpec™ 4 spectroradiometer; d) field photo acquired in the Cal/Val area during the ASD measurements on July 22, 2025; e) photosynthetically active radiation measured with a full-spectrum quantum PAR sensor on July 22, 2025 during the Cal/Val time window (11:12 to 12:31 CEST). Vertical black lines indicate the starting and end time of the ASD measurements and the vertical red line indicate the EnMAP overpass time. Source ICOS station network map: (ICOS, 2026).

2.4 Data analysis

In order to quantify the differences between the EnMAP L2A and the ASD in-situ BOA reflectance measurements, the ASD data were spectrally convolved to the EnMAP spectral configuration using the sensor's spectral response function (SRF) derived from a gaussian function calculated based on the central wavelength and the Full Width at Half Maximum (FWHM) of the sensor. Mean residual between the EnMAP-derived quantity and the corresponding reference measurement were calculated. To ensure spectral consistency, atmospheric water absorption regions were previously removed, retaining 197 spectral bands. Different pixel sampling strategies (central pixel, 2×2 and 3×3 -pixel windows) were implemented to extract the representative EnMAP value from the Cal/Val area to analyze the effect of land cover heterogeneity. The Mean Absolute Error (MAE) of the residuals was calculated as the difference between EnMAP and ASD reflectance for the different sampling strategies.

To analyze potential effects of the single-transect re-optimization plus white reference panel measurement established in the EnMAP protocol, wavelength-dependent BOA reflectance residuals between white reference panel measurements taken with the ASD spectroradiometer at the start and end of the four 90-meter transects (Figure 1c) were calculated.

We also conducted a specific analysis focused on the EnMAP SWIR bands > 1800 nm (SWIR2), to estimate the impact of the radiometric quality of these bands on the monitoring of senescent vegetation with EnMAP images. To do so, we used a well-known spectral index proposed in the literature, the Cellulose Absorption Index (CAI), a three-band SWIR index originally developed by Nagler et al. (2000) that characterizes NPV by measuring the ligno-cellulose absorption feature centered near

2100 nm relative to shoulder reflectance maxima at 2040 nm and 2210 nm (Equation 1).

$$CAI = 100 * 0.5 * (R_{B1,2040} + R_{B2,2210}) - R_{B3,2100} \quad (1)$$

We calculated CAI using the EnMAP bands closer to the original formulation (i.e. 2042, 2208 and 2096 nm bands) and tested alternative options for the B1 which is the band closest to the water absorption window and, therefore, the most affected by atmospheric correction uncertainty, to quantify the impact of the radiometric quality of the EnMAP bands on the index value. Alternative B1 bands explored were located at 1996 and 2033 nm (Table 2).

INDEX	B1 (nm)	B2 (nm)	B3 (nm)
CAI_2040	2040	2210	2100
CAI_1996	1996	2208	2096
CAI_2033	2033	2208	2096
CAI_2042	2042	2208	2096

Table 2. CAI index formula using B1=2040 nm and alternative band combinations tested in this study

3. Results and discussion

Comparison between ASD and EnMAP BOA reflectance on July 3 and July 22, 2025 is shown in Figure 2. EnMAP reflectance factors acquired on July 3, 2025, were similar to ASD field data in the visible and near-infrared (VNIR) region (400–1100 nm), but were underestimated in the SWIR for all different pixel sampling strategies, especially in the 2000–2500 nm region (Figure 2a) where the residual values exceed the mission requirements based on uncertainties represented by different

reflectance levels outside strong atmospheric absorption on flat and close-to Lambertian surfaces (Brell et al., 2026). On July 22, the match between ASD and EnMAP data improved across the entire spectral range (Figure 2b), with an overall MAE = 0.031, but still diverged between 1995–2050 nm. Larger discrepancies on July 3 might relate to the off-nadir viewing angle (-14°), as they disappeared on July 22 under nadiral view (-0.4°) and

almost identical conditions (i.e., illumination, atmospheric and vegetation conditions). This would suggest that off-nadir image acquisitions, even within the commonly accepted range of $< 25^\circ$ over typical invariant targets, are not appropriate for Cal/Val activities on vegetation targets where structural and shadow effects are maximized under viewing conditions other than nadir.

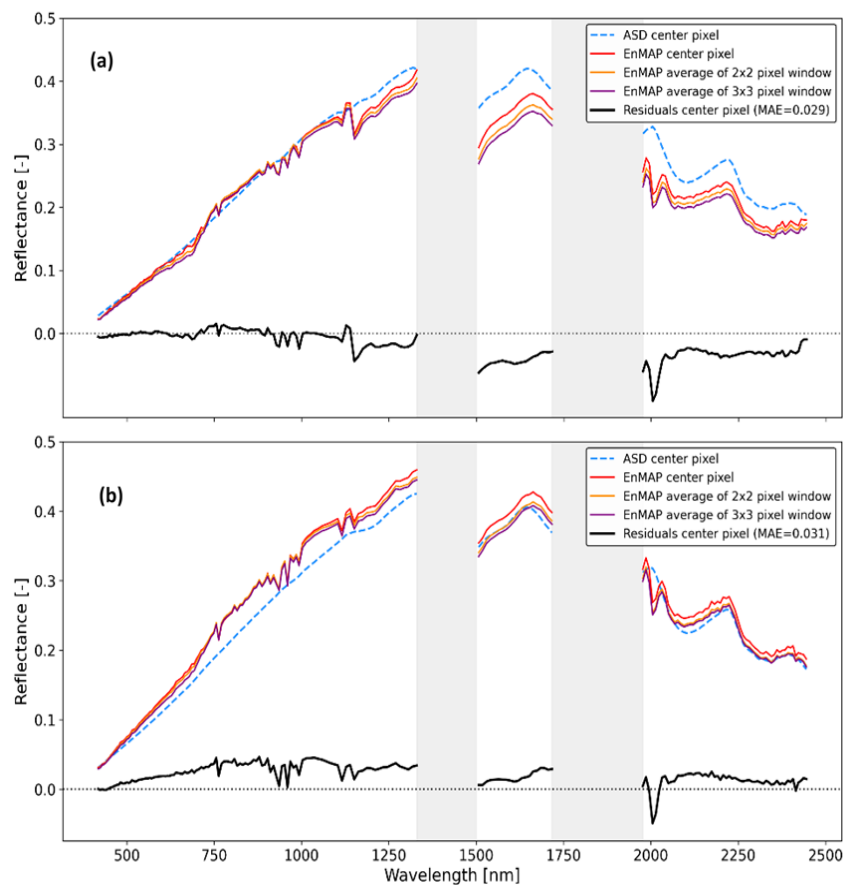


Figure 2. Comparison between ASD (blue dotted line) and EnMAP (orange, red and purple lines) BOA reflectance on (a) 07/03/2025 and (b) 07/22/2025. The black line represents the residuals for the center pixel sampling strategy, and the shaded bands the atmospheric water absorption regions removed from the analysis.

In both campaigns, EnMAP showed an absorption valley at around 2005 nm that was not observed in the field and may be related to a mischaracterization of CO_2 absorption in the atmospheric correction (Figure 3). Atmospheric CO_2 absorption bands occurs between 1000 and 2500 nm region, particularly at 1570, 1602 and 2009 nm bands commonly used for CO_2 concentration retrieval from satellite sensors, especially the latest where the absorption is stronger (Varchand et al., 2022). Atmospheric CO_2 and water vapor absorption features coexist in the same spectral locations, which makes atmospheric correction quite challenging. This uncertainty might affect the detection of NPV, as most spectral indices proposed for this application, such as CAI, quantify the depth of the ligno-cellulose absorption feature in the SWIR region. Comparison of CAI values using the original formulation and the alternative bands (Figure 4) showed a reasonable agreement with the index values calculated with the ASD and the EnMAP for $B1 = 2033$ nm and $B1 = 2042$ nm, with the second configuration offering the strongest agreement with the CAI value calculated with the original bands ($\text{CAI}_{B1=2040} = 3.63$ vs $\text{CAI}_{B1=2042} = 3.44$ and 3.68 using ASD and EnMAP data respectively). This result agrees with the study of Lamb et al. (2022) that recommended the $B1$ CAI index to be located as close

as possible to 2036 nm. The greatest discrepancies from the original index value were found when using $B1 = 1996$ nm (Figure 4). In this case the largest differences were also observed between the CAI values obtained from in-situ ASD data and that calculated from the EnMAP image. This indicates that further efforts to obtain accurate atmospheric correction for this band are necessary, but also provides insights on how to more accurately match the maxima and minima associated with observed ligno-cellulose absorption features to maximize the accuracy of NPV prediction. As the results show, CAI values increase when using bands closer to the NPV shoulder reflectance maxima near 2000 nm, which widens the difference from the ligno-cellulose absorption feature centered near 2100 nm and improves discrimination from other land covers, especially when NPV is mixed with soil or green vegetation, which tends to decrease the depth of the absorption feature. Future analysis could examine precise placement of band center wavelengths for upcoming hyperspectral missions such as CHIME, using in-situ ASD surface reflectance spectral libraries and simulating atmospheric absorption effects as proposed by Hively et al. (2021).

Our study demonstrated that some spatial adaptations can be incorporated to the official Cal/Val protocol (Brell et al. 2023) with no significant impact on the results. However, attention should be paid to the potential effect of the single-transect re-optimization and white reference panel measurement established in the EnMAP Field Guide for Cal/Val activities. Although in our

study the comparison between BOA reflectance measured on the white reference panel at the start and end of the four 90-meter transects showed residuals < 0.02 over most spectral bands (Figure 5), a single measurement of the panel every 90 m can be insufficient under suboptimal atmospheric conditions.

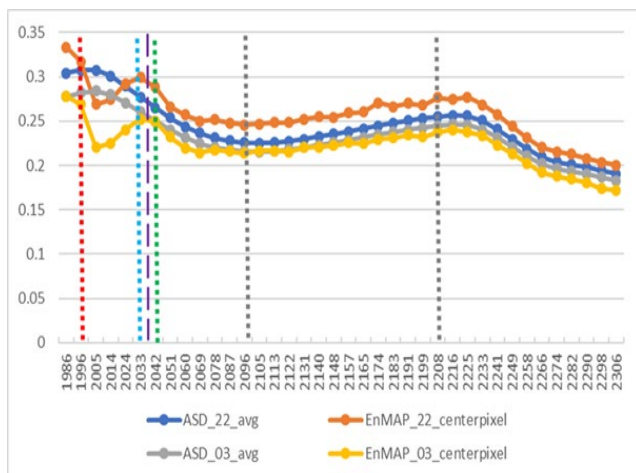


Figure 3. Comparison between ASD (blue and grey lines) and EnMAP (orange and yellow lines) BOA reflectance on 07/03/2025 and 07/22/2025. The vertical lines represent the Cellulose Absorption Index (CAI) bands as in table 2 and Figure 4.

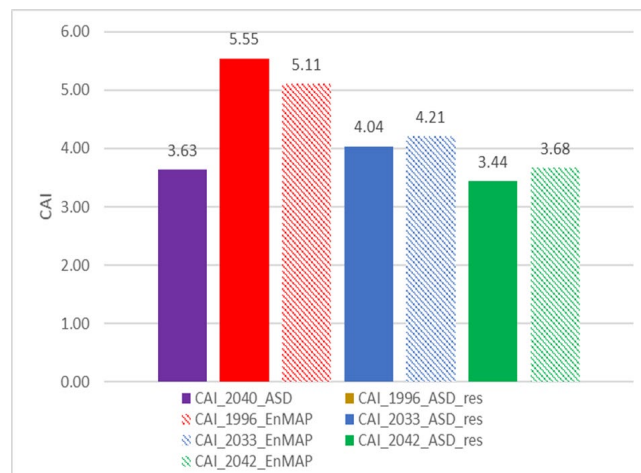


Figure 4. Comparison of CAI index values using original formulation and full resolution ASD data (purple bar) and using the alternative bands (Table 2) as measured by the EnMAP and resampled from ASD.

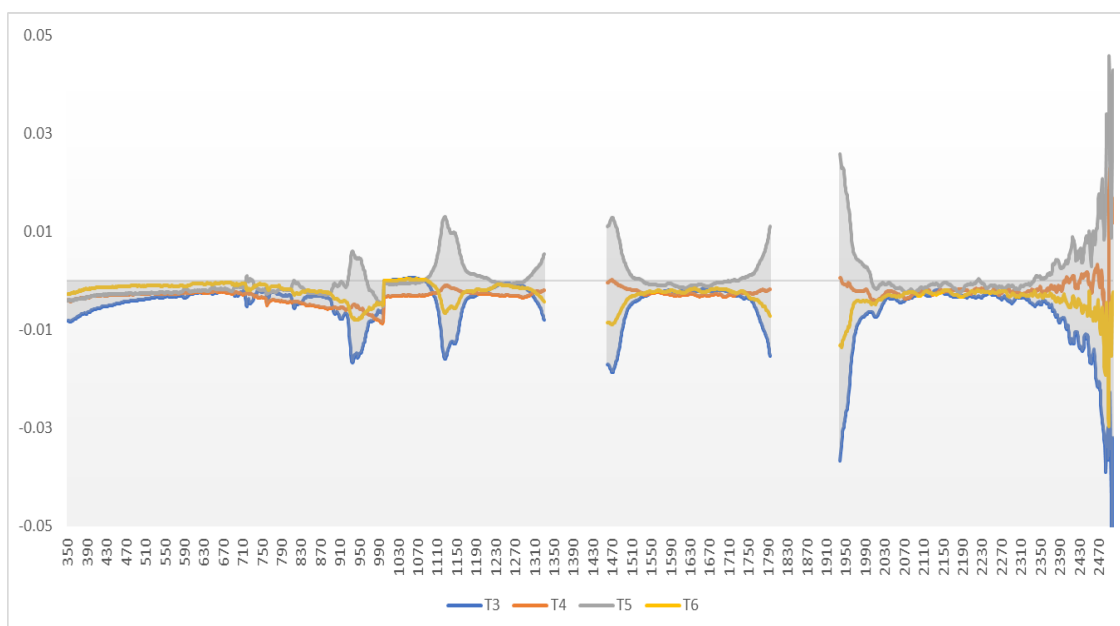


Figure 5. Wavelength-dependent BOA reflectance residuals between reference panel measurements taken with the ASD at the start and end of the 90-meter transects during the July 22, 2025 Cal/Val campaign.

4. Conclusions

This first case study highlights the potential of ICOS Ecosystem sites to complement traditional high-reflectance Cal/Val locations (usually sand-desert), thereby increasing the representativeness of terrestrial targets for hyperspectral missions increasing the representativeness of terrestrial targets. Off-nadir image acquisition conditions do not seem to be optimal

for Cal/Val activities on vegetated targets, or would require measurement protocols mimicking the sensor view angular configuration. However, future work including additional campaigns across different ICOS sites representing diverse ecosystems, phenological stages, and observing angles, is still necessary to confirm our findings. Some adaptations have been incorporated to the spatial layout defined in the official EnMAP Cal/Val protocol (Brell et al.

2023) with no significant impact on the results. This finding would depend on the spatial heterogeneity and autocorrelation of the Cal/Val area. However, attention should be paid to the potential effect of the single white reference panel measurements every 90 m transect established in the EnMAP Field Guide, especially if suboptimal atmospheric conditions are unavoidable during the campaign. Additional monitoring, as the automated PAR sensor measurements used in our study would help to determine the illumination stability and, therefore, quality of the Cal/Val field measurements.

The SWIR2 bands typically used for the estimation of non-photosynthetic vegetation demonstrated susceptibility to atmospheric effects. In this study the CAI index using band centered at 2033 nm showed the best performance. However, it is necessary to further investigate the atmospheric correction of the EnMAP SWIR bands to facilitate the discrimination of these vegetation covers under spectral mixing conditions, especially given the 30m spatial resolution of this sensor.

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