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Exploring the actual spatial resolution of 1 km satellite soil moisture products

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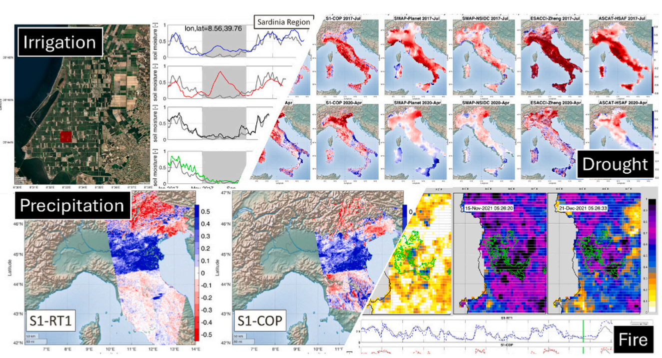
HIGHLIGHTS

- Many high-resolution satellite soil moisture products recently available
- The actual spatial resolution of the products should be assessed.
- Testing and assessment of soil moisture products in Italy
- Indirect validation for drought, fire, precipitation and irrigation applications
- Soil moisture products found to be suitable for new high-resolution applications.

GRAPHICAL ABSTRACT



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ABSTRACT

High-resolution soil moisture data is crucial in the development of hydrological applications as it provides detailed insights into the spatiotemporal variability of soil moisture. The emergence of advanced remote sensing technologies, alongside the widespread adoption of machine learning, has facilitated the creation of continental and global soil moisture products both at fine spatial (1 km) and temporal (daily) scales. Some of these products rely on several data sources as input (satellite, in situ, modelling), and therefore an evaluation of their actual spatial and temporal resolution is required. Nevertheless, the absence of appropriate ground monitoring networks poses a significant challenge for this assessment.

In this study, five high-resolution (1 km) soil moisture products (S1-RT1, S1-COP, SMAP-Planet, SMAP-NSIDC, and ESACCI-Zheng) were analysed and evaluated throughout the Italian territory, together with a coarse resolution (12.5 km) dataset for comparison (ASCAT-HSAF). The main objective is to investigate their actual spatial and temporal resolution, and accuracy. Firstly, a cross-comparison of the products in space and time is carried

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out, including the use of triple collocation analysis. Secondly, an application-based assessment is implemented, considering irrigation, fire, drought, and precipitation case studies.

The results clearly indicate the limitations and the potential of each product. Sentinel-1 based products (S1-COP and S1-RT1) are found able to reproduce high-resolution spatial patterns by detecting localised events for irrigation, fire, and precipitation. Their lower temporal resolution leads to accuracies lower than that of the SMAP-Planet product, and comparable with SMAP-NSIDC and ESACCI-Zheng products. However, SMAP-Planet is found to have an actual spatial resolution coarser than 1 km. The study highlights the need for further research to improve the high-resolution soil moisture products, and particularly to determine accurately the spatial resolution represented in soil moisture products. At the same time, the analysed products are found able to address high-resolution applications for the first time, opening promising activities for their operational use in hydrology and water resources management.

1. Introduction

Accurate and high-resolution soil moisture data are essential for improving local-scale hydrological and agricultural applications such as flash flood and landslide prediction, storm detection and precipitation estimation, fire monitoring and irrigation water use estimation (e.g., Peng et al., 2021; Alfieri et al., 2022; Zappa et al., 2022; Brocca et al., 2023; Dari et al., 2023a; Kanmani et al., 2023). In addition, high-resolution soil moisture will be extremely useful for the parameterisation of hydrological models and for improving the accuracy of hydrological simulations (Brocca et al., 2024). Indeed, the enormous challenges we are facing in recent times with the increasing occurrence of extreme events, floods and droughts (Zhang et al., 2022; Tarasova et al., 2023; Qiu et al., 2023), require the development of modelling systems at high-resolution both in time and space to support decision and policy makers.

Recently, due to the increased availability of high-resolution satellite observations, and the increased capability in data storage and high-performance computing, a large number of high-resolution datasets integrating Earth Observation, in situ observations, modelling and machine learning techniques, were developed. From a literature review of the last three years (2021–2023), global-, continental-, and regional-scale meteorological 1 km datasets for precipitation (Karger et al., 2021; Filippucci et al., 2022; Filippucci and Brocca, 2023), evaporation (Zheng et al., 2022; Hulsman et al., 2023), and other meteorological variables (Karger et al., 2022; Sekulić and Kilibarda, 2023) were published. Soil moisture is of course one of the variables included in what we call "the rush to high-resolution" with, for instance, four global scale, daily and 1 km datasets that were published in the first three months of 2023 (Han et al., 2023; Lakshmi and Fang, 2023; Zhang et al., 2023; Zheng et al., 2023), and other examples recently (Fang et al., 2022), even at 30 m sampling over the contiguous United States (Vergopolan et al., 2021; Ning et al., 2023).

The recent availability of new observations is surely beneficial for scientific and operational applications (e.g., Alfieri et al., 2022; Dari et al., 2023b), but it opens multiple challenges that have to be addressed by the scientific community. Firstly, for most of these datasets there are no ground-based observations suitable for their validation at the required spatial and temporal resolution. For instance, for soil moisture and evaporation, ground observations are available from several networks worldwide (Dorigo et al., 2021; https://fluxnet.org/), but unfortunately not enough to perform a robust assessment of these newly derived products. Only for rainfall, thanks to the availability of ground meteorological radar and dense raingauge networks, a reliable assessment of the products can be carried out (e.g., Filippucci et al., 2022). Secondly, some datasets (as some of the ones investigated in this study) include multiple input observations, which may not be independent. Therefore, it can be challenging to determine how to use the data, e.g., as input for modelling, without duplicating observations. It is important to consider this when analysing the data. For instance, if a dataset should be assimilated into a hydrological model, it should not include other modelling data as input, as it is quite frequent in level 4 data that are already the result of data assimilation of satellite products into modelling (e.g., the National Aeronautics and Space Administration (NASA) Soil Moisture Active and Passive (SMAP) Level 4 product, Reichle et al., 2019). Their assimilation into another model is not scientifically sound. A third important challenge is the understanding of the actual spatial and temporal resolution of the data. Most of the time, the datasets at high-resolution are the result of the integration of multiple datasets as input, characterised by different resolutions in space and time. The integration does not necessarily bring improved (finer) resolution, as it is the case for several downscaled datasets that are sampled onto a high-resolution grid while their effective spatial resolution is still primarily driven by a coarse resolution input data set.

Regrettably, users of these "high-resolution" datasets are often not adequately informed about the crucial difference between sampling and the effective spatial resolution of the data. One possible explanation for this oversight is that only the sampling, representing the digital manifestation of the data, is precisely known. In contrast, producers of satellite datasets frequently struggle to provide precise figures regarding the effective spatial resolution, which is why they often refrain from providing this number even though it is of paramount importance for the correct use of the data. As a result, a product labelled as "1 km data" may only be sampled to this grid size, and its actual spatial resolution might be significantly coarser, a phenomenon known as "oversampling". Note that, following the Nyquist–Shannon sampling theorem, the dataset's sampling should be half its spatial resolution to fully preserve all the physical information contained in the dataset. In line with this requirement, the Advanced Scatterometer sensor in the framework of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Satellite Application Facility on Support to Operational Hydrology and Water Management project (ASCAT-HSAF) soil moisture data, serving in this study as a reference for coarse resolution datasets with an approximate spatial resolution of 25 km, are sampled onto a 12.5 km grid.

In this context, we also must stress that the evaluation of the downscaling result needs to be performed in the spatial domain. Instead, most studies evaluate the spatial scaling performance in the temporal domain with few reference sites only, without any relevance for the scaling procedure (e.g., Zhu et al., 2023). Finally, we should bear in mind that most of the users of the datasets are not trained for having a detailed understanding on how the data were developed. There is a strong need to develop guidelines on how the datasets should be assessed, used, and tested in different applications (see e.g., Merchant et al., 2017; Tang et al., 2022).

In this study, we start to address the above challenges by assessing five different high-resolution (1 km, ~daily) soil moisture products in Italy. Specifically, we have considered: 1) the Sentinel-1 derived soil moisture obtained by using a first-order radiative transfer model (hereinafter S1-RT1, Quast et al., 2023), 2) the Sentinel-1 derived operational surface soil moisture product from the Copernicus Global Land Service (S1-COP, Bauer-Marschallinger et al., 2018), 3) the SMAP-derived 1 km experimental dataset (SMAP-Planet, Schellekens et al., 2022), 4) the gap-filled and downscaled European Space Agency - Climate Change Initiative (ESA-CCI) soil moisture combined product (ESACCI-Zheng, Zheng et al., 2023), and 5) the SMAP-Derived 1-km

Downscaled Surface Soil Moisture Product, Version 1, from the NASA National Snow and Ice Data Center (SMAP-NSIDC, Lakshmi and Fang, 2023). Among the soil moisture products currently available at high-resolution in the study area, two additional notable products are the Zhang et al. (2023) and Han et al. (2023) datasets, but we didn't include them in this analysis because the data are conceptually similar to the ESACCI-Zheng dataset and the data are more difficult to handle (data download, processing and storage). The main purpose of this study is to evaluate the actual spatial and temporal resolution of the investigated soil moisture products, and to provide insights and indications on how to use the data in high-resolution hydrological applications (severe weather alerts, floods, irrigation, fire, precipitation, and drought).

The novelties of this study are as follows: (1) to provide a first and independent assessment of five high-resolution soil moisture products recently developed, (2) to propose an application-based approach to address the challenge of evaluating the accuracy of high-resolution soil moisture products, which could be a useful alternative approach given the absence of dense ground monitoring networks for this purpose, and (3) to demonstrate the potential use of these products for new applications in hydrology and water resources management.

2. Study area

The study area is the whole Italian territory, characterised by complex topography, diverse climates from north to south, and a large variability of landscapes. Therefore, even though the total area can be considered limited (~300,000 km^2), if compared to the global scale, the heterogeneity of the territory makes it suitable for a robust assessment of satellite soil moisture products (e.g., Papa et al., 2020).

Particularly over northern regions, high-resolution precipitation data are available through the integration of a dense raingauge network and meteorological radar data (Bruno et al., 2021). Such data are quite important for the assessment of high-resolution spatial patterns of satellite soil moisture products, strongly related to rainfall.

Similarly, the knowledge of agricultural irrigated areas is also instrumental to the analyses to be carried out in the study. For instance, the concentrated type of irrigation structure in the area of the irrigation case study in Sardinia is advantageous for the assessment compared to that of other areas of Italy, such as the mosaic type of irrigation in the Po valley, as illustrated before by Elwan et al. (2022) and Dari et al. (2023a). It could be difficult to have a thorough knowledge of irrigation data and patterns. For this reason, particularly during dry summers, soil moisture and precipitation patterns could be completely decoupled in intensively irrigated areas.

Finally, in the study domain of this work (particularly over the Sardinia region), the occurrence of fire events allows us to perform an indirect high-resolution assessment of the products, which is relevant for the purpose of the paper. Indeed, due to the land cover and socioeconomic structure of Sardinia, this island is also among the most fire-prone areas of Italy (Ferrara et al., 2019).

3. Materials and methods

3.1. Satellite soil moisture products

Five different high-resolution satellite soil moisture products are considered (see Table 1). Two products are based on Sentinel-1 observations only. The S1-RT1 product is obtained by applying a first-order radiative transfer model to Sentinel-1 observations and it has been recently developed by the Vienna University of Technology, TU Wien (Quast et al., 2023). The product is characterised by a varying revisit time from 1.5 to 6 days (d, hereafter), if ascending and descending orbits are considered together, and depending on the availability of one or two Sentinel-1 satellites in orbit and on the location. The actual mean temporal sampling in the analysis period, averaged for all the pixels in the study area, is equal to 3.4 d, and the spatial sampling is 500 m. The second Sentinel-1 product, S1-COP, is produced operationally from the Copernicus Global Land Service (Bauer-Marschallinger et al., 2018, https://land.copernicus.eu/en/products/soil-moisture/daily-surface-soil-moisture-v1.0). Similarly, to S1-RT1, the temporal sampling of S1-COP (in the area and in the analysis period) is equal to 3.6 d, and the spatial sampling is 500 m.

Table 1
Main characteristics of the soil moisture products considered in this study. The actual temporal sampling is reported, i.e., the mean revisit time for each location spatially averaged.

Product	Data period	Temporal sampling	Spatial sampling	Reference
S1-RT1	Jan 2017–Sep 2022	3.4 d	500 m	Quast et al. (2023)
S1-COP	Oct 2014–now	3.6 d	500 m	Bauer-Marschallinger et al. (2018)
SMAP-Planet	Apr 2015–Dec 2021	2.1 d	1 km	Schellekens et al. (2022)
SMAP-NSIDC	Apr 2015–Sep 2022	2.5 d	1 km	Lakshmi and Fang (2023)
ESACCI-Zheng	Jan 2000–Dec 2020	1.0 d	1 km	Zheng et al. (2023)
ASCAT-HSAF	Jan 2007–now	0.5 d	12.5 km	Wagner et al. (2013)

Two products are based on SMAP observations. The SMAP-derived dataset (SMAP-Planet, Schellekens et al., 2022) has been derived experimentally for the Mediterranean region in the framework of the ESA project 4DMED Hydrology (https://www.4dmed-hydrology.org/). The temporal sampling of SMAP-Planet is equal to 2.1 d, the spatial sampling is 1 km. The SMAP-Derived 1-km Downscaled Surface Soil Moisture Product, Version 1, from the National Aeronautics and Space Administration (NASA) National Snow and Ice Data Center (SMAP-NSIDC) has been developed by Lakshmi and Fang (2023). Specifically, the Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature data are used with the SMAP Enhanced L2 Radiometer Half-Orbit 9 km Equal-Area Scalable Earth (EASE)-Grid Soil Moisture product in a downscaling algorithm to estimate soil moisture at high-resolution. The temporal sampling of SMAP-NSIDC is equal to 2.5 d, the spatial sampling is 1 km.

The gap-filled and downscaled ESA-CCI soil moisture combined product (ESACCI-Zheng) has been developed by Zheng et al. (2023). Firstly, an operational gap-filling method was developed to fill the missing data in the ESA-CCI soil moisture product using the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) reanalysis dataset (Hersbach et al., 2020). A Random Forest (RF) approach was then adopted to disaggregate the coarse resolution soil moisture to 1 km, taking advantage of the International Soil Moisture Network in situ observations (Dorigo et al., 2021), other optical remote sensing datasets (albedo and normalised difference vegetation index), and static information (digital elevation model and saturation water content). The temporal sampling of ESACCI-Zheng is 1 d (gap-filled), the spatial sampling is 1 km.

Moreover, we have included in the cross-comparison the soil moisture products obtained from the ASCAT-HSAF. The product is generated by the change detection algorithm developed by TU Wien and it is characterised by a spatial resolution of 25 km (sampling 12.5 km) and a temporal sampling of 0.5 d in the analysis period (Wagner et al., 2013).

It is worth noting that the two Sentinel-1 and SMAP derived products are dependent on each other as they both use Sentinel-1 observations, while ESACCI-Zheng includes SMAP and ASCAT products among the ones used for obtaining the ESA-CCI soil moisture combined product. Therefore, ESACCI-Zheng does not satisfy the independence requirement for the triple collocation analysis (see below). Also note that the SMAP derived products have input data at a more similar spatial resolution as the ASCAT-HSAF product.

3.2. Pre-processing and statistical intercomparison

For performing the intercomparison of the products, as a first step they have been all gridded on the same grid over Italy, having a spatial sampling of 1 km (0.01°) for a total of 408,105 data points. The data products have been reprojected by using the nearest neighbour approach. The data have also been aggregated (averaged) at 10-day and monthly time scales for the different analyses performed in the study.

The statistical validation is carried out through the comparison of: (1) maps of temporal mean and standard deviation, (2) temporal and spatial Pearson's correlation with data aggregated at monthly time scale, and (3) triple collocation analysis with data aggregated at 10-day time scale. The Pearson's temporal correlation is computed by comparing the time series of two products for each point, thus providing as output a map of temporal correlation values. Similarly, the Pearson's spatial correlation is computed by comparing the spatial maps of two products for each time step, thus providing as output a time series of spatial correlation values. For temporal (spatial) correlation values, the median of the map (of the time series) is computed for each product to provide a synthetic assessment of its performance.

Triple Collocation (TC) technique can theoretically provide relative error and correlations of three products (a triplet) given that each of the three products is afflicted by mutually independent errors (Stoffelen, 1998). Therefore, in principle, TC can be used for assessing the quality of satellite soil moisture products without using ground observations (Scipal et al., 2008; Kędzior and Zawadzki, 2016; Brocca et al., 2019). TC is a well-established approach for assessing the error of multiple soil moisture products (Gruber et al., 2020) and indeed TC is used operationally to merge different satellite products in the ESA-CCI soil moisture product development (Dorigo et al., 2017). In this study, we have implemented the same procedure as described in Massari et al. (2017), i.e., by implementing an additive error model at daily time scale, and we refer the reader to this study for the analytical details. In synthesis, by using the extended TC method firstly proposed by McColl et al. (2014), it is possible to estimate the TC temporal correlation for each soil moisture product in the triplets with the unobserved truth.

3.3. Application-based assessment

Given the lack of dense ground-based soil moisture observation networks suitable for reliable assessment of high-resolution products, we propose an application-based approach as an appropriate method for this purpose. We have identified four possible applications for which the actual spatial and temporal resolution of the investigated soil moisture products can be assessed: 1) detection of irrigation events/periods, 2) spatial and temporal analysis before and after the occurrence of fire events, 3) comparison with high-resolution ground-based rainfall data as obtained by merging dense raingauge network and meteorological radars, and 4) drought monitoring.

The first application assumes that the occurrence of irrigation events results in significant increase in soil moisture (e.g., Brocca et al., 2018; Filippucci et al., 2020; Dari et al., 2023a), except perhaps for drip irrigation, which should be easily detected by satellite products if characterised by appropriate spatial (and temporal) resolution (Dari et al., 2022; Zappa et al., 2022). Indeed, in many contexts such as the Mediterranean, irrigation events are often localised in space and hence suitable to identify the actual spatial resolution of the soil moisture products at kilometre (and finer) scale.

Similarly, the second application consists in the analysis of spatial-temporal soil moisture patterns before and after the occurrence of fire events. After a fire it is frequent that soil water repellency can be enhanced or developed as a consequence of the heat transfer downward into the soil (DeBano, 2000), up to 10–15 cm. The soil water repellency significantly reduces the infiltration of water in deeper layers increasing the likelihood of post-fire runoff and erosion processes (Letey, 2001; Moody et al., 2013; Esposito et al., 2019). As a result, in the areas affected by fire, the uppermost soil layers can be wetter in response to the first post-fire rainfall events than layers of the surrounding unburned areas. Fire events being local events, the possibility to detect the area affected by fire with a soil moisture product is an indication of the actual spatial resolution of the product itself.

For the precipitation application, we have performed a qualitative comparison between spatial patterns of precipitation and soil moisture before and after the occurrence of the events. It is expected that the soil moisture products that better represent the spatial footprint of rainfall are the ones characterised by better accuracy and resolution.

For the drought monitoring application, we have computed monthly anomalies for each dataset by using the common period 2017–2020 as baseline. The short baseline period does not allow a robust climatology and may affect the values and even the sign of the anomaly, particularly if any relevant drought occurred during the baseline period. Still, it provides a consistent assessment between the datasets making their comparison useful and meaningful. The anomalies are computed as percentage anomalies with respect to the mean of each month of the year. The anomaly maps can be used for assessing drought conditions as already implemented by several authorities and agencies using coarse resolution data (e.g., https://edo.jrc.ec.europa.eu/).

4. Results

4.1. Statistical intercomparison

The first analysis consists of the computation of the temporal mean and standard deviation maps for each soil moisture product (Figs. 1 and 2). For some of the products, the spatial coverage is not complete due to erroneous data/retrievals and the (deliberate) masking of the data over areas where a soil moisture retrieval is not possible due to physical reasons (e.g. high topography, dense forest, etc.). Specifically, S1-COP does not have data over complex topography regions (e.g., Alps and Apennines), SMAP-Planet has erroneous data for a small area in north western Sicily (data processing error, personal communication), and SMAP-NSIDC has no data over the western coast of Italy and some erroneous data in Liguria and Calabria regions. By visual inspection of the mean maps (Fig. 1), it is already evident that the actual spatial resolution of the products is not the same. S1-RT1 and S1-COP datasets have an actual resolution of 1 km (Sentinel-1 data are averaged from the original 10 m resolution to 1 km). SMAP-Planet has a smooth spatial pattern, even smoother than the 25 km resolution product from ASCAT-HSAF. SMAP-NSIDC shows more details than SMAP-Planet, but the pixel footprints of the original SMAP 9 km product are visible in the map. The granularity of ESACCI-Zheng seems to contain more details than the 1 km resolution should have, particularly looking at the standard deviation map (Fig. 2). The temporal standard deviation maps show major differences between the products. For instance, S1-RT1 temporal variability is much higher than S1-COP, similarly SMAP-Planet with respect to SMAP-NSIDC. Overall, both the temporal mean and standard deviation maps of the products are hardly consistent with each other, even considering products based on the same satellite sensors (e.g., S1-RT1 and S1-COP or SMAP-Planet and SMAP-NSIDC).

The agreement between the different soil moisture products has been assessed by computing Pearson's temporal correlation between all pairs at monthly scale (Fig. 3). The inner table in the figure shows the median temporal correlation values for each pair (top-right triangle, red colours), and provide for each product the average of the median temporal correlation with respect to all the others (right column). Surprisingly, ASCAT-HSAF resulted to be the product in better agreement with the others, notwithstanding it is the only nominal coarse resolution product. This can be explained as Sentinel-1 and ASCAT are both active sensors,

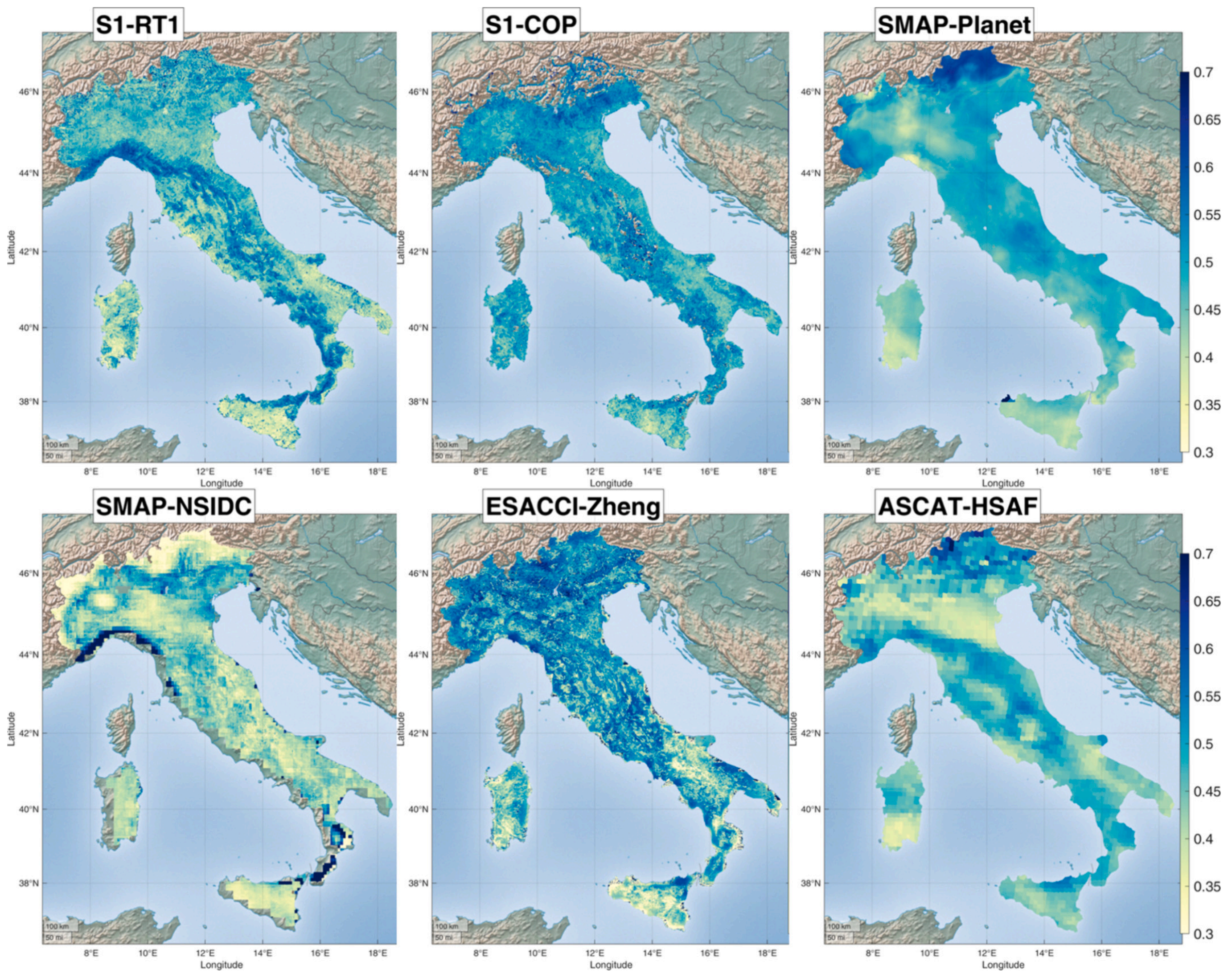


Fig. 1. Map of the temporal mean for all the soil moisture products considered in this study for the whole Italian territory. All the data are normalised between 0 and 1 to make the maps comparable in terms of units (i.e., relative soil moisture).

and hence Sentinel-1 derived products are in good agreement with ASCAT-HSAF. Particularly, we note that S1-RT1 is better correlated with ASCAT-HSAF than S1-COP. SMAP-Planet is the second product in terms of mean correlation, with a surprisingly (again) better agreement with ASCAT-HSAF than SMAP-NSIDC. S1-RT1 correlates more with the other products (mean correlation equal to 0.72) than with S1-COP (0.60). Spatially, the products show a better temporal correlation in southern Italy, particularly over the Sicily and Sardinia islands, and a lower agreement over mountainous areas (Alps and Apennines). SMAP-NSIDC shows some issues over the area around Vercelli city in north western Italy (45°19′25″N, 8°25′15″E), and S1-COP in central Italy around the Gran Sasso Mountain (42°28′08″N, 13°33′57″E).

Similarly, we have computed the spatial correlation between each pair of products. In Fig. S1 (Supplementary material) the temporal evolution of spatial correlation for each pair is shown. Again, ASCAT-HSAF has the best agreement with the other products (lower-left triangle in Fig. 3, green colours), but the mean spatial correlation value is much lower (0.32 with respect to 0.77 for the mean temporal correlation). Overall, spatial correlation values are low, and their temporal evolution is different among the different pairs of products. The only pair of products showing an acceptable spatial correlation are the ones derived from Sentinel-1 and ASCAT, with values greater than 0.40. We note that the relatively good spatial correlation of S1-COP (mean value equal to 0.32) is partly due to the masking of the mountainous areas where the spatial correlation is extremely low; by masking the pixels with no S1-COP data, the mean spatial correlation of S1-RT1 and S1-COP becomes very similar (not shown for brevity).

We have performed TC analysis to assess the best product among the two Sentinel-1 (S1-RT1 and S1-COP) and SMAP (SMAP-Planet and SMAP-NSIDC) products. The analysis is carried out by considering the products aggregated at 10-day resolution, to obtain a sufficient number of pairs (144) to be compared. Specifically, we have carried out the TC analysis by considering four different triplets: 1) ASCAT-HSAF, SMAP-Planet, S1-RT1, 2) ASCAT-HSAF, SMAP-Planet, S1-COP, 3) ASCAT-HSAF, SMAP-NSIDC, S1-RT1, and 4) ASCAT-HSAF, SMAP-NSIDC, S1-COP. The triplets only contain independent products, i.e., obtained from different sensors, which is why the ESACCI-Zheng has not been considered (see Section 3.1). In Fig. 4, the TC correlation values, rho, for assessing Sentinel-1 (left) and SMAP (right) derived products are shown. On average, S1-RT1 and SMAP-Planet are the best Sentinel-1 and SMAP derived products with median rho equal to 0.80 and 0.88, respectively, 20 % and 14 % higher than the other Sentinel-1 and SMAP derived products. It should be underlined however that all the products have extremely low performance in the northern mountainous part of Italy (e. g. Trentino Alto Adige region). By using the other two triplets, results are similar with better performance of S1-RT1 and SMAP-Planet. To avoid

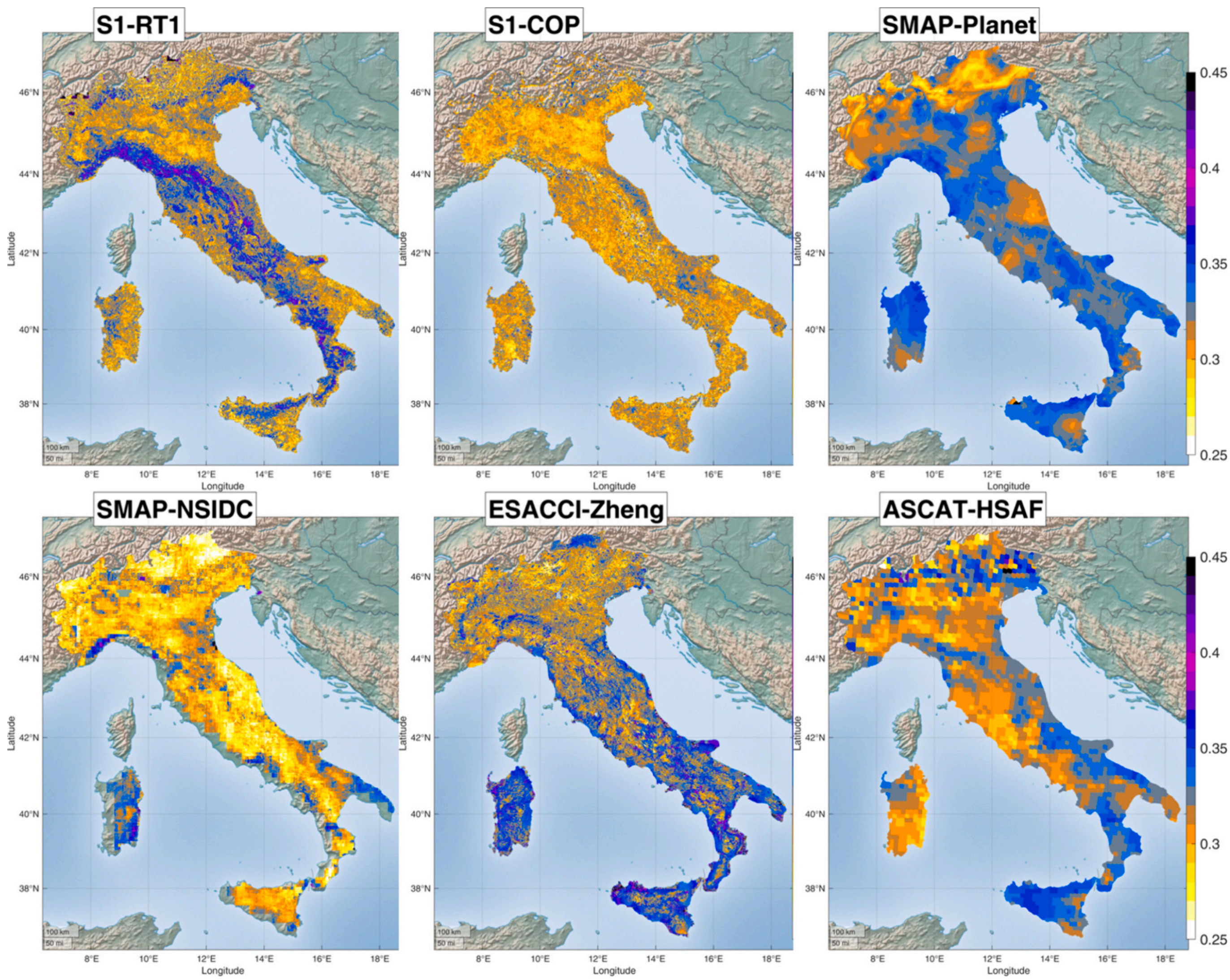


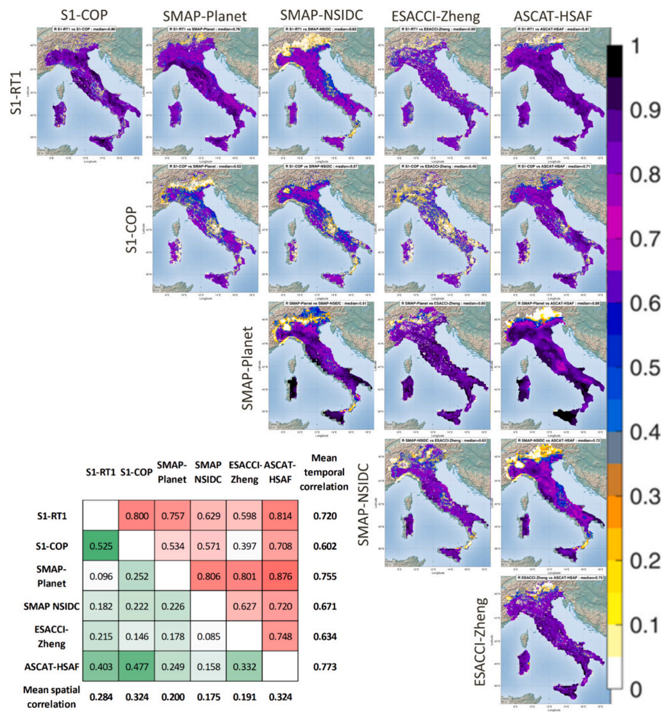
Fig. 2. Map of the temporal standard deviations for all the soil moisture products considered in this study for the whole Italian territory. All the data are normalised between 0 and 1 to make the maps comparable in terms of units (i.e., relative soil moisture). The colorbar, also used in other figures, is developed ad hoc to highlight the differences between the products for a large range of values.

potential dependencies between ASCAT-HSAF and S1-derived products, C-band active microwave sensors, we made the same analysis by substituting ASCAT-HSAF with ERA5-Land soil moisture data (Muñoz-Sabater et al., 2021). The relative performance of the products is the same with a slight reduction of 10 % (increase of 13 %) of rho values for Sentinel-1 (SMAP) derived products.

4.2. Application-based assessment

In the second part of the results, the assessment is carried out by focusing on the potential applications of high-resolution soil moisture products.

The first application is irrigation detection, as it is the most suitable to assess the spatial resolution of a soil moisture product, irrigation being applied at farm scale (even lower than 1 km resolution). We have selected several locations in Italy in which irrigation is applied, and for each of them we have plotted the time series for all the available high-resolution products against ASCAT-HSAF (that being at coarse resolution is not able to detect the irrigation signal for small agricultural areas, Brocca et al., 2018). Fig. 5 shows the example in Sardinia (close to the city of Oristano) where an extensively irrigated area is present (SMAP-NSIDC is not available for this location). From this example it is evident that only the two Sentinel-1 derived products can detect the irrigation signal, with values significantly higher than ASCAT-HSAF during the growing season (highlighted in grey). S1-COP shows values extremely high, likely due to the lacking vegetation correction for this product, whereas vegetation correction is carried out in S1-RT1 that shows better statistical performance (Figs. 3 and 4). Indeed, by considering a non-irrigated area close to the location of Fig. 5 in Sardinia, S1-COP still shows a positive bias with respect to ASCAT-HSAF not present in S1-RT1 (Fig. S2). SMAP-Planet and ESACCI-Zheng are not able to detect the irrigation signal, and hence their actual spatial resolution should be questioned. Additional examples are shown in the Supplementary material (Fig. S3), where the results are not always as evident as in Fig. 5, likely due to the relatively low absolute soil moisture values in Sardinia, leading to larger differences between irrigated and non-irrigated periods. Still, the only products potentially detecting the irrigation signal at high-resolution are those derived from Sentinel-1 (and SMAP-NSIDC but only for the Friuli Venezia Giulia region location). We should underline that this analysis is affected by uncertainties as in Italy the irrigated areas and the irrigation water amount applied are not known. For the selection of the locations we have considered extensive irrigated areas (Sardina, Friuli Venezia Giulia, Abruzzo and Campania) and irrigated areas used in previous studies (Emilia Romagna, Faenza, Dari



	S1-RT1	S1-COP	SMAP-Planet	SMAP NSIDC	ESACCI-Zheng	ASCAT-HSAF	Mean temporal correlation
S1-RT1		0.800	0.757	0.629	0.598	0.814	0.720
S1-COP	0.525		0.534	0.571	0.397	0.708	0.602
SMAP-Planet	0.096	0.252		0.806	0.801	0.876	0.755
SMAP NSIDC	0.182	0.222	0.226		0.627	0.720	0.671
ESACCI-Zheng	0.215	0.146	0.178	0.085		0.748	0.634
ASCAT-HSAF	0.403	0.477	0.249	0.158	0.332		0.773
Mean spatial correlation	0.284	0.324	0.200	0.175	0.191	0.324	

Fig. 3. Temporal correlation maps between all pairs of soil moisture products aggregated at monthly time scale for the whole Italian territory. In each plot the median value of the map is shown. On the bottom left the table shows the median values of temporal (top-right triangle) and spatial (bottom-left triangle, see also Fig. S1) correlation values. The mean spatial and temporal correlation values in the table (last row and column) are the mean values of the median values reported in the table for each product.

et al., 2023a).

An interesting application is related to the occurrence of fire events. Specifically, we have obtained the area affected by fire for an event that occurred in the Sardinia region on 23rd July 2021. Fig. 6, top panels, shows soil moisture maps in the area before and after the occurrence of the fire event by using S1-RT1 product (the event is not identified in analogous maps referring to the other datasets). As expected, due to the likely formation of water-repellent soil patches in the uppermost soil horizons (MacDonald and Huffman, 2004; Pereira et al., 2018), infiltration is reduced, and the area affected by fire is wetter than the surrounding region after the first rainfall following the wildfire. The time series shown in the lower panels of Fig. 6 (SMAP-NSIDC and ESACCI-Zheng are not available) show mean soil moisture inside and outside the area affected by fire. S1-RT1, and partly S1-COP, shows higher values after the fire event, and specifically after the first abundant rainfall occurred in the first part of November 2021 (see map of 15 November 2021 in Fig. 5), whereas SMAP-Planet and ASCAT-HSAF do not identify any changes. Therefore, only Sentinel-1 products can detect the changes in the infiltration behaviour due to the fire event, with S1-RT1 again better than S1-COP.

Generally, the fire-induced soil water repellency is very site-specific and can persist for months or years, depending on a series of factors including burn severity, vegetation type, soil texture, soil moisture, and time since burning (Doerr et al., 2000; Huffman et al., 2001).

The link between soil moisture and precipitation is strong, as demonstrated, for instance, in the development of the SM2RAIN (Soil Moisture 2 Rainfall) algorithm (Brocca et al., 2014). After a precipitation event, soil moisture increases significantly; therefore, it is possible to see the rainfall footprint in soil moisture data. Fig. 7 shows an interesting example for a summer precipitation event which occurred on 11th July 2017. For each product, the difference between soil moisture values after and before the event are plotted and compared with the spatial pattern of precipitation shown in the top panel and obtained from the interpolation of a dense rain gauge network. We have to underline that during this event Sentinel-1 images before and after the event were available, and hence it is evident that Sentinel-1 derived products can accurately capture the spatial footprint of the precipitation event (even the small and localised event in central Italy, blue spot in S1-RT1 image). However, due to sampling limitations, the spatial coverage is not complete as it is for other products, and for other precipitation events the availability of images before and after is not ensured, due to the limited revisit time of Sentinel-1. Between the two Sentinel-1 products, the footprint is clearer and less noisy for the S1-RT1 product. The spatial agreement between precipitation and soil moisture is good for the S1-RT1 product. For the two SMAP derived products, SMAP-Planet has a smooth pattern, with also positive changes in north eastern Italy that are not present in SMAP-NSIDC. The latter is in better agreement with ESACCI-Zheng and ASCAT-HSAF. However, we note a small shift toward south of the soil moisture footprint for the SMAP-derived, ESACCI-Zheng and ASCAT-HSAF with respect to observed precipitation data.

As a final application, we have considered drought monitoring, by computing monthly soil moisture anomalies for each product. The top panel of Fig. 8 shows the soil moisture anomaly time series averaged over the whole Italian territory for the six investigated products in the period 2015–2021 (as baseline for anomaly computation, the common period 2017–2020 is considered). Notwithstanding the products are characterised by different temporal availability, there is a good agreement between all of them except for SMAP-NSIDC, especially in the year 2021. It means that the temporal consistency of the products, aggregated over the whole Italian territory, is high. We note that at local scale, temporal differences among the products might be high. ESACCI-Zheng shows a larger temporal variability, as expected looking at its temporal standard deviation shown in Fig. 2. For two specific months, July 2017 and April 2020, the monthly anomaly maps are shown in the lower panels of Fig. 8. For July 2017, all Italy was in dry conditions with negative anomalies for all products, particularly over central-western Italy (southern Tuscany and Lazio regions) as detected by S1-RT1, S1-COP, SMAP-Planet and ASCAT-HSAF. ESACCI-Zheng shows significant anomalies while SMAP-Planet shows some spatial artefacts likely due to the soil texture maps used for its development. For April 2020, again the agreement is quite good with positive anomalies in southern Italy and negative anomalies in the north and central regions. S1-RT1, S1-COP, SMAP-Planet and ASCAT-HSAF are in good agreement, but the spatial details visible in Sentinel-1 derived products are not present in SMAP-Planet and ASCAT-HSAF, as expected for the latter due to its coarse resolution. The soil moisture anomaly maps are also in good agreement with Standardised Precipitation Index (Edwards and McKee, 1997), computed for 1-month accumulation period, maps shown in Fig. S4 and obtained from rain gauge observations available from 2008 to 2023.

5. Discussions and conclusions

The analyses carried out have clearly highlighted some important limitations and potential of the investigated products, which are also applicable for other high-resolution soil moisture datasets.

The agreement between the high-resolution products is much higher in time than in space. The temporal dynamics of soil moisture, driven by climatic factors (precipitation and evaporation), is well captured by all the products. Differently, the spatial patterns of soil moisture are driven by local conditions, e.g., soil texture and vegetation, and they are found to be more difficult to reproduce. The most significant challenge to be addressed is the characterization of soil moisture spatial variability at high-resolution, as the satellite products, and modelling (e.g., Fang et al., 2015; Polcher et al., 2016), show the larger discrepancies in this respect. The need for further research on this challenge is supported by the results presented here, such as those shown in Fig. 1 and Fig. S1.

The SMAP-Planet product fails to reproduce the high-resolution soil moisture spatial variability as given by the two Sentinel-1 derived

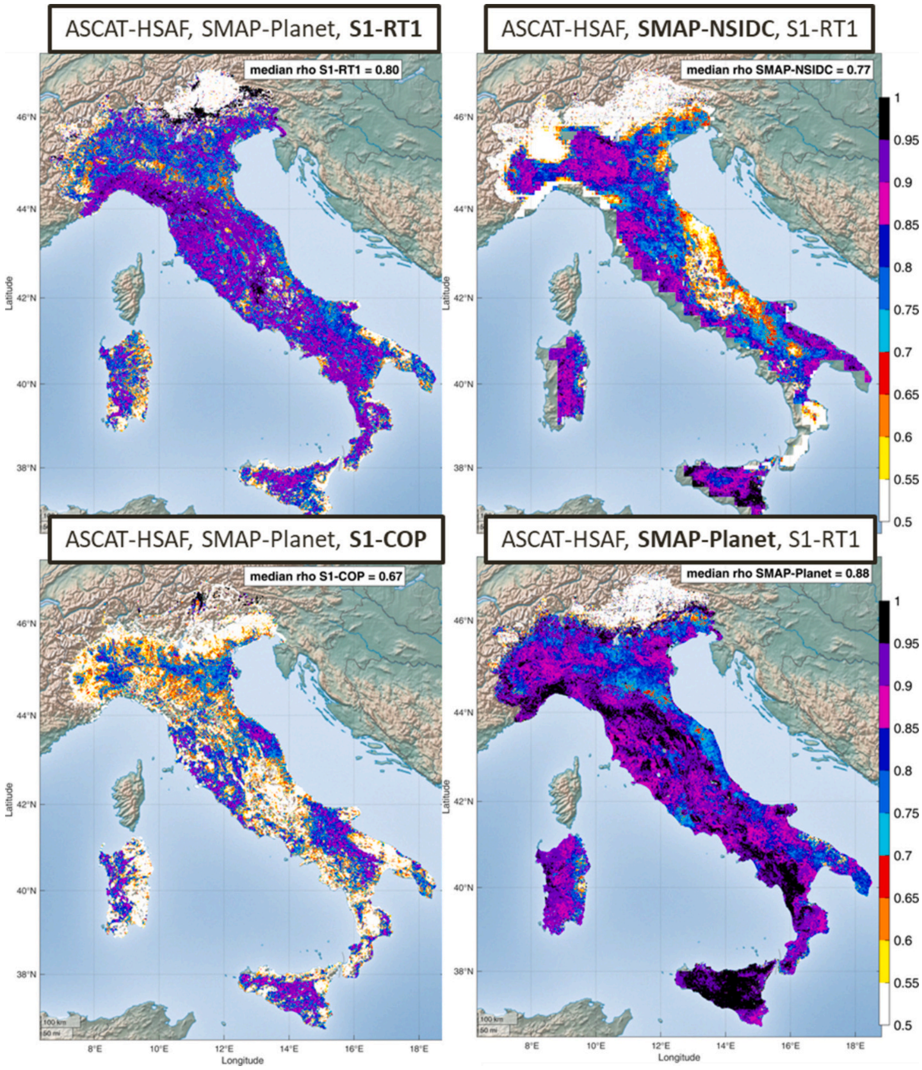


Fig. 4. Triple Collocation correlation maps for the two Sentinel-1 based (left) and SMAP-based (right) 10-day products for the whole Italian territory. On top of each panel the considered triplet is reported. Note that the colour axis is from 0.5 to 1 to better highlight the differences between the products.

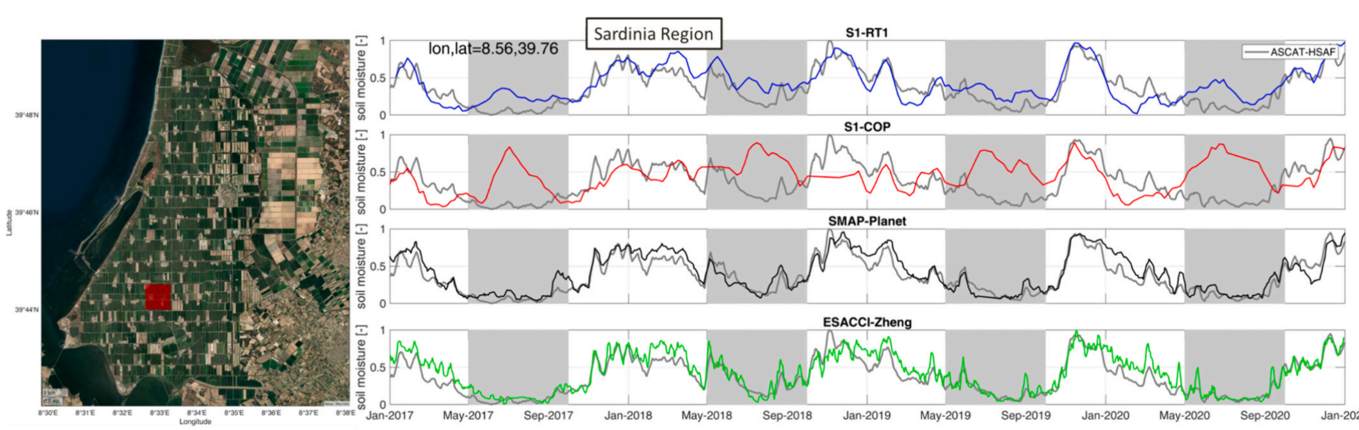


Fig. 5. Irrigation application. Time series of the available high-resolution soil moisture products for the irrigated area in Sardinia shown in the left figure, red square (Maxar, Microsoft). The products are compared with ASCAT-HSAF (in grey) that being at coarse resolution is not able to detect the irrigation signal for small agricultural areas.

products. It is evident in all the results, and particularly by considering the high-resolution applications such as irrigation detection (Fig. 5), fire detection (Fig. 6) and precipitation estimation (Fig. 7). The deconvolution approach for SMAP-Planet does not allow to identify localised events, at least in the study area investigated here. SMAP-NSIDC and ESACCI-Zheng products show more detailed spatial

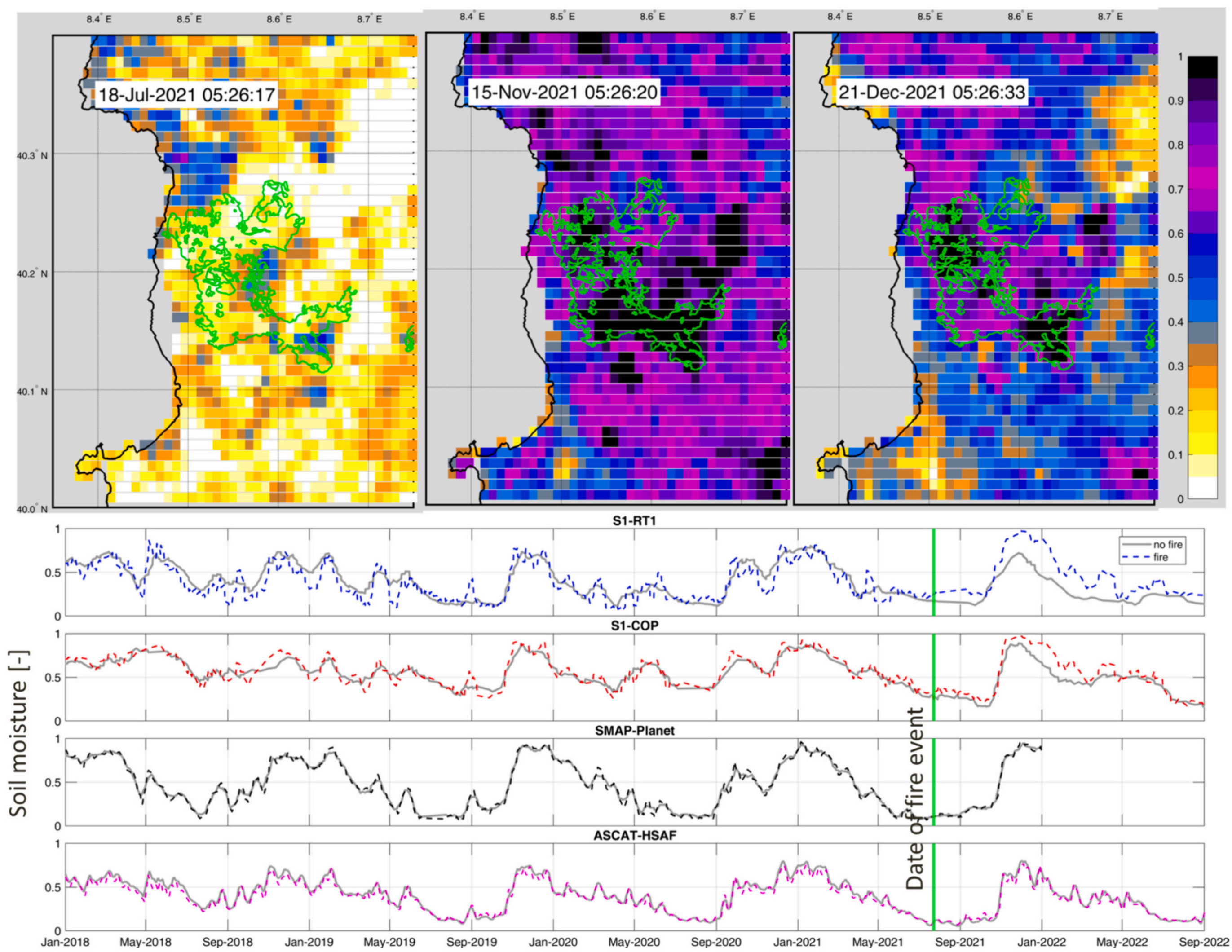


Fig. 6. Fire application. Top panels: Soil moisture maps from S1-RT1 before and after the occurrence of the fire event in Sardinia (23 July 2021). The green boundaries represent the area affected by fire. Bottom panels: Time series of the available soil moisture products inside (dashed line) and outside (continuous) the area affected by fire.

patterns, but we have found no evidences that the downscaling (SMAP-NSIDC) and machine learning (ESACCI-Zheng) approaches are able to reliably identify localised events (Figs. 5–7). These results should be attributed to the use of coarse resolution data in the development of these two products, which influences the actual spatial resolution of the final products.

In the comparison of the two Sentinel-1 based products, S1-RT1 has been found outperforming S1-COP, both in terms of temporal accuracy when compared to the other products (Figs. 3–4), and particularly for the detection of localised events (Figs. 5–7). This result is expected as the S1-COP product has limitations in disentangling the vegetation contribution from the soil moisture signal. It is already planned that in the next Sentinel-1 based operational product distributed by Copernicus (likely by the end of 2024), these limitations will be overcome also based on the results shown here (personal communication).

Between the two SMAP products, SMAP-Planet is better in terms of temporal accuracy (Figs. 3–4) because SMAP-NSIDC experiences some winter-related coverage gaps (Fang et al., 2022), but as mentioned before, SMAP-Planet seems not able to detect high-resolution spatial patterns as partly done by SMAP-NSIDC (Fig. S3). The improvement of the algorithm and the inclusion of high-resolution data as in SMAP-NSIDC and ESACCI-Zheng, might be able to mitigate this limitation.

The analyses done in the study have highlighted limitations in the products, but also their potential in addressing high-resolution applications (irrigation, fire, precipitation, and drought) for the first time. S1-RT1 and to a certain extent S1-COP have shown good skill in terms of irrigation, fire, and precipitation events detection. Its temporal sampling is limited by the availability of only two (now one) satellite sensors in orbit. The low temporal resolution of Sentinel-1 is a limitation for hydrological applications where high spatial resolution should be combined with high (daily, sub-daily) temporal resolution to properly assess the processes (e.g. irrigation, precipitation, small-scale flood prediction). However, it is expected to be improved in the near future, with the launch of the next Sentinel-1C satellite (2024), and the launch of the NASA-ISRO Synthetic Aperture Radar (NISAR) mission (January 2024). The currently only operationally available S1-COP product is found to be a reliable product for characterising drought conditions at 1 km resolution. Thus, its operational availability over the whole of Europe can be exploited for enhancing operational drought monitoring systems in the continent.

Our application cases evidence that S1-based products demonstrate notable spatiotemporal consistency suitable for high-resolution applications. The shown range of applicability may well reach the plot-scale even with different aggregation levels (van Hateren et al., 2023). In terms of larger scale applications such as drought monitoring, also the downscaled products show good skills. However, due to smooth,

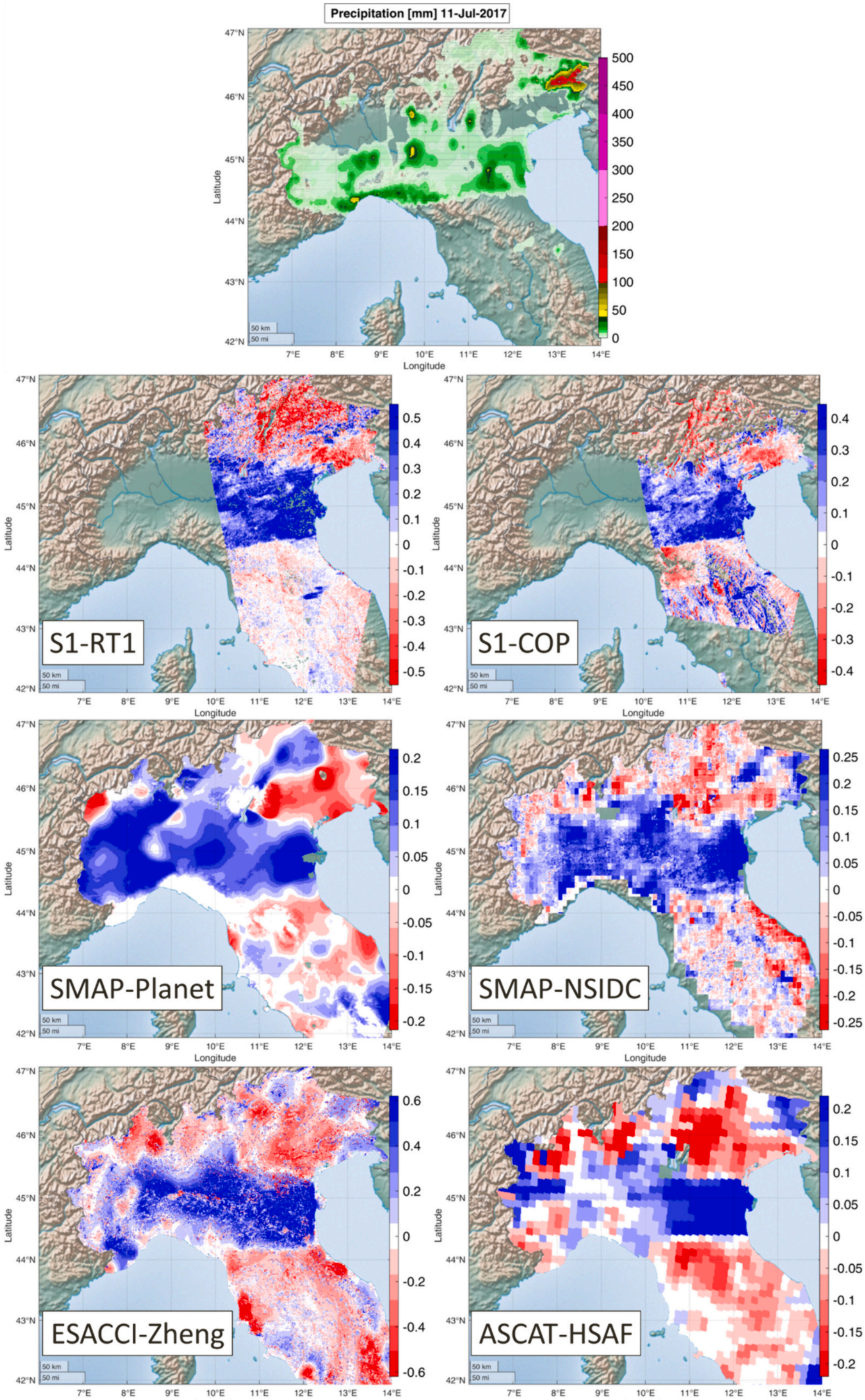


Fig. 7. Precipitation application. The top panel shows the amount of precipitation occurred on 11th July 2017 over northern Italy as obtained from rain gauge interpolation. Bottom panes show the difference in relative soil moisture after and before the occurrence of the event for the various products.

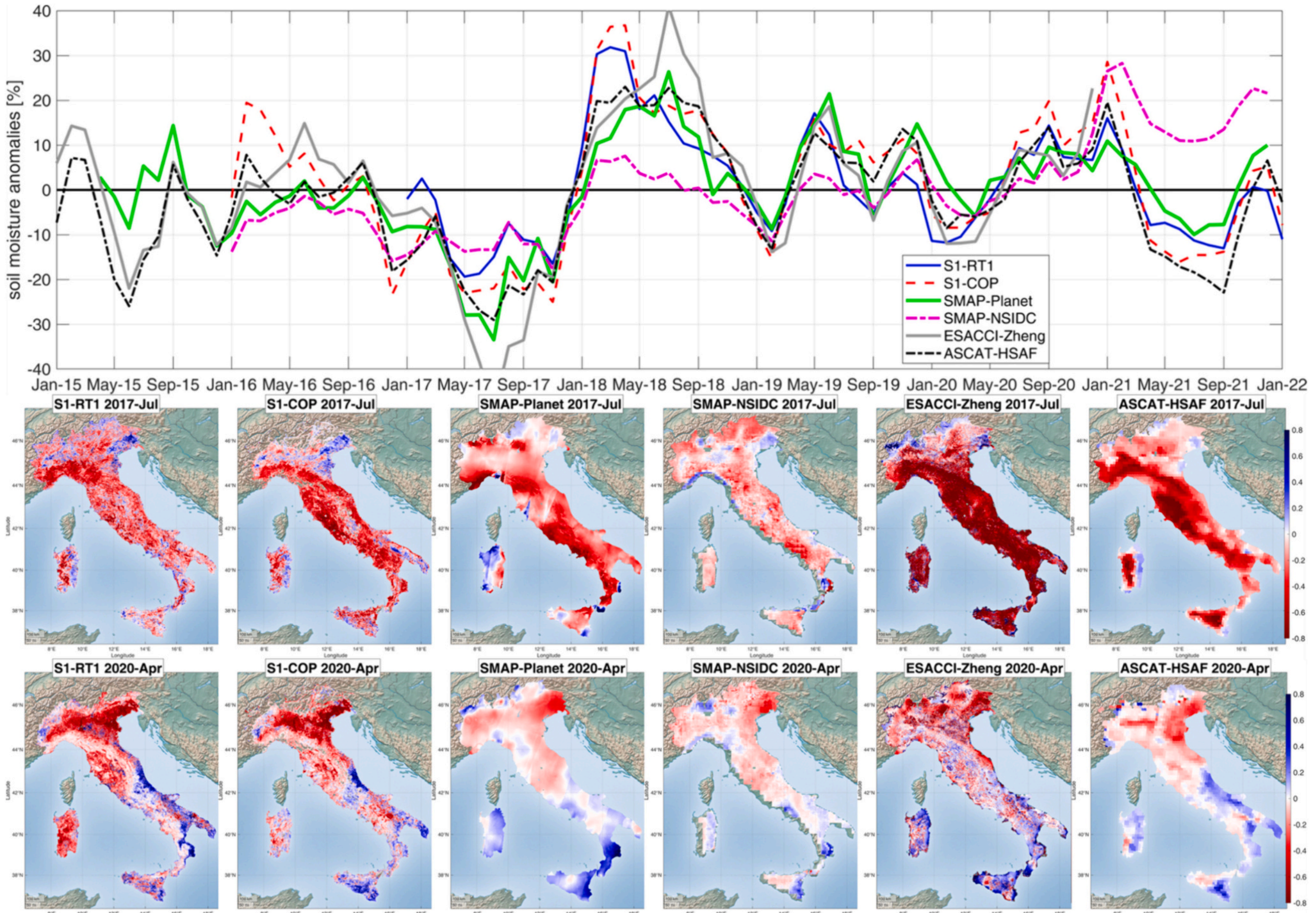


Fig. 8. Drought application. Monthly soil moisture anomalies [%] (top panel) averaged over the whole Italian territory for the six soil moisture products. Monthly anomalies for July 2017 (middle panels) and April 2020 (bottom panels).

pixelized, noisy or discontinuous features, these ones may be challenged by the degree of detail required for irrigation and forestry application. Therefore, although the label of high-resolution may be more application- than product- dependent, caution is needed when assuming downscaled products may sufficiently depict the small-scale patterns of interest, which are often of complex or poorly understood nature (Blöschl et al., 2019).

Finally, we are aware that the application-based assessment cannot be considered flawless due to the limited number of events considered. Indeed, the analysis done here has been carried out for only some locations in Italy and a more comprehensive evaluation is required. However, the application-based assessment is the only way to evaluate high-resolution products due to the absence of dense ground-based soil moisture observation networks. Even when available, we underline that establishing and maintaining such networks is expensive in terms of human effort and economical costs. Therefore, the evaluation of the high-resolution products by considering the application for which they should be used is a promising approach to be explored further. Moreover, there is the clear advantage to directly assess the usability of the products for hydrological and water resources management applications.

CRediT authorship contribution statement

Luca Brocca: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jaime Gaona:** Writing – review & editing, Data curation. **Davide Bavera:** Writing – review & editing, Conceptualization. **Guido Fioravanti:** Writing – review & editing, Data curation. **Silvia Puca:** Writing – review & editing. **Luca Ciabatta:** Writing – review & editing, Data curation. **Paolo Filippucci:** Writing – review & editing, Data curation. **Hamidreza Mosaffa:** Writing – review & editing. **Giuseppe Esposito:** Writing – review & editing, Methodology. **Nicoletta Roberto:** Writing – review & editing. **Jacopo Dari:** Writing – review & editing, Data curation, Conceptualization. **Mariette Vreugdenhil:** Writing – review & editing, Data curation. **Wolfgang Wagner:** Writing – review & editing.

Declaration of competing interest

Luca Brocca reports financial support was provided by National Research Council of Italy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.174087.

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