THE ESA ULYSSES PROJECT AND THE EXPLOITATION IN THE MEDITERRANEAN AREA OF SOIL SEALING PRODUCTS AND INDICATORS

Daniela Iasillo, Vito De Pasquale, Paola Di Lauro, Sadri Haouet, Amaury Truffier, Loïc Faucqueur, Luca Congedo, Michele Munafò, Olivier Arino

Abstract: Soil sealing, a phenomenon altering soil permeability, significantly impacts the environment, particularly in urban areas and local climates, affecting heat exchange and soil permeability. Monitoring soil sealing is crucial for the Mediterranean coastal regions, where it contributes to desertification alongside soil degradation, drought, and fires.
Permanent soil sealing includes features like buildings and paved roads, while reversible sealing involves features like solar panels and early-stage construction sites. The Mediterranean Soil Sealing project, led by Planetek Italia with partners ISPRA and CLS, aims to provide high-resolution maps of soil sealing and reversible sealing from 2018 to 2022, with a spatial resolution of 10m.
The project emphasizes stakeholder involvement, with users ranging from municipalities to international organizations like the UN. Efforts have been made to engage diverse stakeholders from the project's outset, and stakeholders are actively involved in shaping project outcomes. Instead of simply delivering maps, the project will provide users with an interactive dashboard containing indicators and analytics for easy access to information.

Keywords: sealing, imperviousness, coastal areas, mediterranean.

Daniela Iasillo, Planetek Italia, Italy, iasillo@planetek.it, 0000-0003-2704-5658
Vito De Pasquale, Planetek Italia, Italy, depasquale@planetek.it, 0009-0009-9946-8044
Paola Di Lauro, Planetek Italia, Italy, dilauro@planetek.it, 0009-0006-2988-5238
Sadri Haouet, CLS - Collecte Localisation Satellite, France, shaouet@groupcls.com
Amaury Truffier, CLS - Collecte Localisation Satellite, France, atruffier@groupcls.com
Loic Faucqueur, CLS - Collecte Localisation Satellite, France, lfaucqueur@groupcls.com, 0009-0000-3361-6686
Luca Congedo, ISPRA - Italian Institute for Environmental Protection and Research, Italy, luca.congedo@isprambiente.it, 0000-0001-7283-116X
Michele Munafò, ISPRA - Italian Institute for Environmental Protection and Research, Italy, michele.munafo@isprambiente.it, 0000-0002-3415-6105
Olivier Arino, European Space Agency ESRIN, Italy, Olivier.arino@esa.int

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Introduction

Soil sealing is a process resulting from human activities that alter the soil's permeability due to the use of artificial materials and compaction. The environmental consequences of soil sealing, also known as imperviousness, are numerous. It affects urban areas and local climates, impacting heat exchange, soil permeability, water infiltration, groundwater recharge, and more [3, 7, 8, 9].

At the European level, the recent proposal for a Directive of the European Parliament and the Council on Soil Monitoring and Resilience underscores the need to monitor land take, soil sealing, and the associated impacts on ecosystem services [3].

The European EAGLE classification system, developed by the EIONET EAGLE group "Action Group on Land Monitoring in Europe," categorizes soil sealing under class 1.1.1, "Sealed Artificial Surfaces and Constructions." This category includes surfaces covered with artificial structures, such as buildings, pavements, and other impervious surfaces [2].

The United Nations has also highlighted the importance of monitoring coastline imperviousness in the United Nations Environment Programme – Mediterranean Action Plan (IMAP) due to its impact on soil weathering properties and aeolian transport patterns [10].

This paper introduces a new service developed for the Mediterranean Soil Sealing project, promoted by the European Space Agency under the EO Science for Society – Mediterranean Regional Initiative. The project, named Ulysses (https://www.ulysses-project.org), aims to develop a methodology for monitoring the degree of soil sealing using Copernicus Sentinel images over Mediterranean coastal areas (within 20 km from the coast) at a spatial resolution of 10 meters (Figure 1). Currently, the service is available for the reference year 2020, and additional reference years from 2018 to 2022 will be produced by the end of the project.

Furthermore, the project aims to provide end-users with various indicators and statistics derived from the maps, offering information that can be directly integrated into their workflows.

Figure 1 – The 2020 Soil Sealing Degree Map for Mediterranean coastal regions (within 20 km from the coastline) is based on cloud-free Sentinel-2 imagery.

Materials and Methods

The project mandates the utilization of Sentinel-2 imagery, with a spatial resolution of 10 meters, to gauge soil sealing. The selection of appropriate algorithms depends on the availability of auxiliary data and the need to accurately estimate soil sealing percentages. At this scale (i.e., a pixel area of 100 m²), it is crucial to detect variations in soil sealing down to 1 m² of impervious surface.

Moreover, leveraging Sentinel-2 satellite data (comprising visible and near-infrared bands) requires analyzing land cover attributes at a subpixel level. This involves addressing the challenge of mixed pixels (which contain multiple land cover classes within a single pixel) and accounting for the spectral similarity between natural soil and artificial surfaces.

To overcome these challenges, a multifaceted methodology was devised (see Figure 2). First, Sentinel-2 Level 1C input data undergoes correction to Level 2A via the MAJA processor, while the Normalized Difference Vegetation Index (NDVI) is calculated for each image for a baseline year. Next, Level 3A cloud-free composites are generated for each month from the Level 2A data. These composites include the calculation of various indices, such as NDVI, Normalized Difference Tillage Index (NDTI), Modified Normalized Difference Water Index (MNDWI), Normalized Difference Built-up Index (NDBI), and a PANTEX band, which serves as a texture descriptor particularly useful for urban area depiction [6].

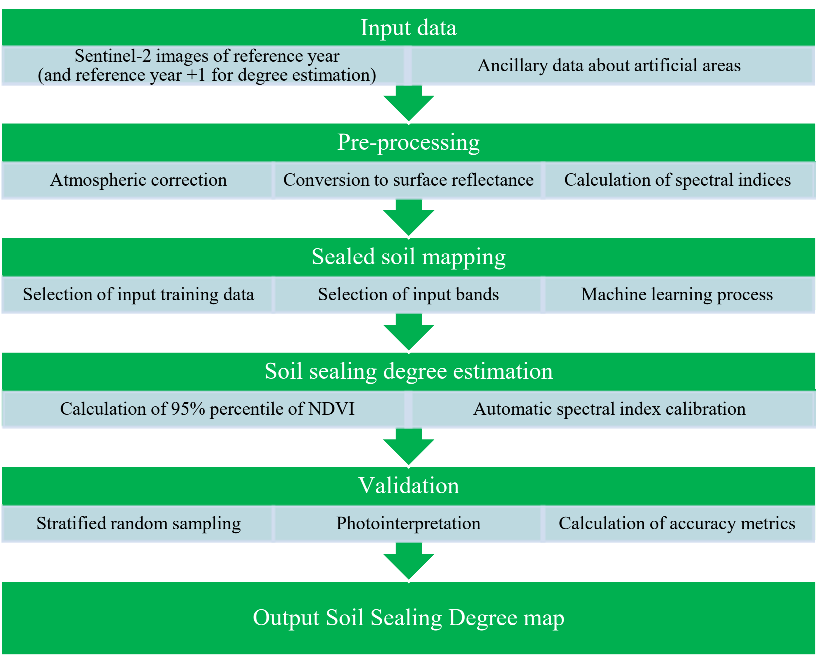

Figure 2 – Workflow of the processing chain.

Mapping of sealed terrain is carried out using machine learning techniques applied to Sentinel-2 imagery, via a tool called "Broceliande." This involves selecting bands and constructing a morphological tree model, from which multiscale characteristics (referred to as attribute profiles) are derived [1, 5]. Specific attributes (e.g., area, weight, compactness) are measured for all objects at varying scales within each hierarchical representation, and these attributes are assigned to each pixel. A binary classification process (sealed/unsealed) is then performed using a Random Forest classifier.

The estimation of soil sealing degree is carried out on the sealed soil mask generated in the previous step. A significant challenge in computing soil sealing degree is the lack of very high-resolution reference data (i.e., at least 1m resolution) that could be used as training data. To address this, an automatic approach was developed to eliminate the need for training data, particularly given the large study area (i.e., the Mediterranean basin).

Specifically, the NDVI time series calculated for each Sentinel-2 image is used to extract the 95th percentile of NDVI over the reference year and the following year. Using two years of images helps reduce NDVI fluctuations due to the seasonality of vegetation in mixed pixels and allows for the detection of changes that cause a permanent decrease in NDVI, such as new constructions. Spectral index calibration, which does not require training data, is then performed to estimate soil sealing degree at the pixel level [4]. This method automatically estimates the minimum and maximum values of the spectral index (i.e., the 95th percentile of NDVI) to calibrate a linear relationship with soil sealing degree.

The result of this entire process is a raster map with 10 m spatial resolution, where each pixel represents the soil sealing degree (ranging from 0 to 100 %) within 20 km from the coastline (Figure 3).

Validation was performed at two levels of analysis using stratified random sampling:

- Thematic validation to estimate both producer and user accuracies for the sealed areas.
- Correlation analysis with soil sealing degree to assess the reliability of the degree values.

The thematic validation of the sealed soil mask achieved an overall accuracy of 96 %, with a user’s accuracy of 85.9 % (indicating low commission errors) and a producer’s accuracy of 64.1 % (indicating high omission errors due to difficulties in identifying small sealed features, such as narrow roads, small and isolated buildings, and partly due to the different resolution between the product and validation reference data). Most omission errors are located in areas where the soil sealing degree is less than 30 %.

The correlation analysis of the soil sealing degree showed a significant correlation, with a coefficient of determination equal to 0.7. Additionally, the absolute difference between the product's soil sealing degree and the sample's sealing degree was less than 30 for 80 % of the samples, confirming substantial agreement, especially for higher levels of soil sealing.

Figure 3 – Example of soil sealing degree (right) compared to very high-resolution image (Google Earth, right image); different level of urban density is represented by higher values of imperviousness over compact areas, and lower values of imperviousness are present over dispersed buildings mixed with vegetation.

Results

The monitoring service is currently available, and the data can be freely accessed on the project website. Ulysses offers a comprehensive mapping tool that facilitates the use of soil sealing products by visualizing and analyzing critical soil sealing indicators through a user-friendly web application. This tool allows users to access and interpret data at both country and regional levels. These two administrative levels are represented in two different web applications (available on the project website).

The two applications contain different indicators: the country-level map offers an overview of the product series and a first global analysis (the soil sealing consumption in the countries within the AOI), while the regional-level web app provides a series of four different indicators. These indicators represent a set of geospatial data, in the form of percentage values, offering insights into the distribution of soil sealing within the area of interest. These data are derived from the output products (for the 5 years of analysis), representing the percentage of sealing in each pixel of the area of interest, with values ranging from 0 to 100.

Each indicator offers a specific analysis of sealing distribution in the studied area. The four metrics include the percentage of soil sealing within:

- the administrative boundaries (referred to the 20 km buffer from the coast);
- the 2000 m buffer zone from the coastline;
- the 1000 m buffer zone from the coastline;
- the 500 m buffer zone from the coastline.

The soil sealing indicators have been derived by considering the percentage value of each pixel. For instance, assume that within the area bounded by one of the indicators (i.e., an area up to 500 m, 1 km, 2 km, or 20 km from the coast) there are 20 pixels with a 50 % sealing percentage. The calculation is performed as follows:

$$20 \text{ [count of pixels]} \times 100 \text{ [m}^2\text{]} \times 50\%$$

This quantity, relative to the area's extent, provides the value of the indicator. Thus, if the considered polygon has an area of 10 000 m², we'll have 10 % sealing within that polygon.

In summary, the methodology for calculating the indicators involves the following steps:

- Pixel Value Consideration: Each pixel's value in the GeoTIFF represents the percentage of sealing within that specific area.
- Pixel Count: This step involves counting the pixels inside the administrative polygon.
- Conversion to Meters: The percentage value of each pixel is multiplied by the area occupied by each pixel. This value depends on the raster output resolution; in the case of Sentinel-2 datasets, this is $10 \times 10 = 100$ m².
- Aggregation and Normalization: The product of the pixel count and the relative area is normalized by the total area of the administrative polygon to obtain the sealing percentage.

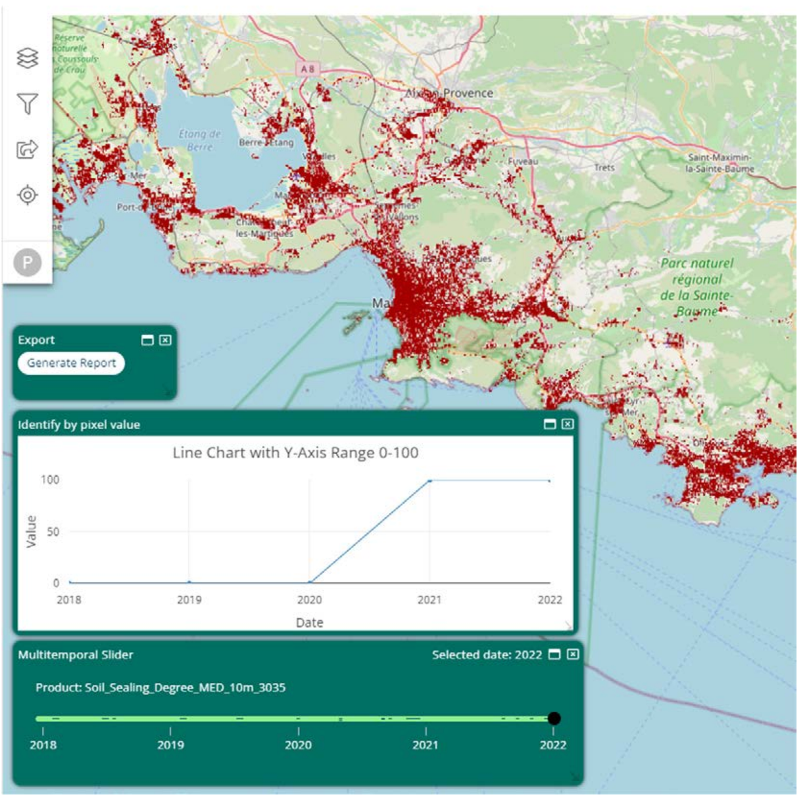

Figure 4 – Example of soil sealing trend from regional web app.

This procedure has been repeated four times for each of the four sealing indicators across five years of data, resulting in a total of 20 indicators, which can be visualized on a map as a time series. This time series visualization allows users to track the trend of sealing in a specific region over time.

These indicators, computed annually from 2018 to 2022, allow for temporal analysis of soil sealing trends across the different administrative levels. Figures 4 and 5 depict the web application interface.

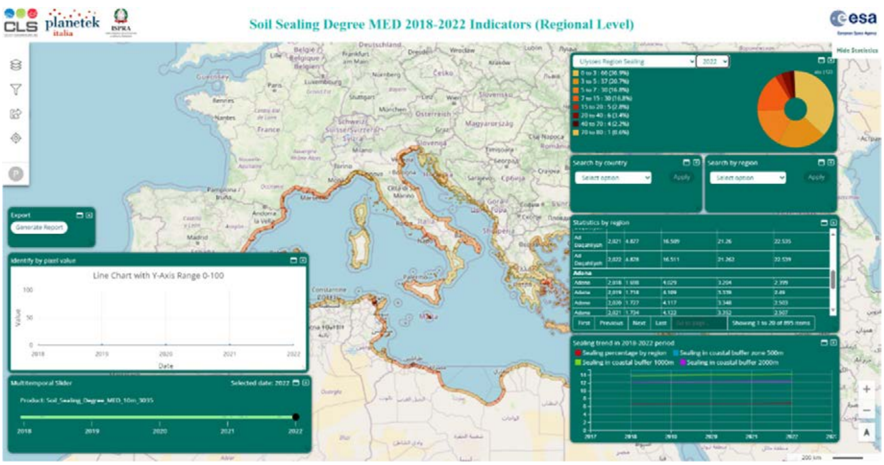

Figure 5 – Main features and analytics from regional web app.

Discussion and conclusion

The monitoring of soil sealing is of paramount importance due to its profound ramifications on human health, environmental quality, and the provision of ecosystem services. This study introduces a novel service tailored for monitoring soil sealing degrees, developed within the framework of the Mediterranean Soil Sealing project. The primary objective of this service is to furnish comprehensive insights into soil sealing dynamics across the entire Mediterranean coast. Leveraging Copernicus Sentinel-2 imagery, the methodology enables annual updates of soil sealing maps spanning from 2018 to 2022, with a spatial resolution of 10 meters. The thematic accuracy is achieved through a detailed methodology that includes pre-processing of satellite imagery (e.g., atmospheric correction and calculation of spectral indices such as NDVI), machine learning classification, and spectral index calibration without the need for high-resolution training data.

Beyond the provision of maps, the Ulysses web application enhances accessibility to soil sealing information and its temporal changes. It offers a suite of indicators correlating soil sealing with pertinent environmental parameters, such as proximity to protected areas and rivers. The platform is designed to be user-friendly, allowing easy access to critical data for a range of users, including those with limited technical expertise. The inclusion of visualizations at both the national and regional levels further enhances usability for stakeholders and urban planners, ensuring the dashboard remains accessible to users without advanced GIS or remote sensing skills.

To ensure that the project remains collaborative and responsive to stakeholder needs, regular communication and feedback mechanisms have been incorporated from the outset. Engaging municipalities, international organizations, and other stakeholders has been key to shaping the project's outcomes, with feedback being actively used to refine the interactive tools provided by the Ulysses web application. This participatory approach ensures that stakeholders are fully involved in the decision-making process and that the tools developed align with their requirements.

The maps and indicators presented in this study hold promise for fostering sustainable development within collaborative initiatives across the Mediterranean region. They align with directives set forth by the United Nations Environment Programme and contribute to broader efforts, such as the Priority Actions Programme/Regional Activity Centre under the Mediterranean Action Plan. Additionally, they offer valuable data for key indicators such as Candidate Common Indicator 25, "Land Use Change," affiliated with Ecological Objective 8 (Coastal Ecosystems and Landscapes). Metrics like the extent of impervious surfaces within a 100-meter buffer from the coastline can inform evidence-based decision-making processes, ultimately guiding sustainable management of coastal environments across the Mediterranean.

Acknowledgment

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