PREPSOIL DELIVERABLE

Title	Technical feasibility in using CLMS satellite-based EO to estimate soil health indicators
Work package no:	WP5
Deliverable Related no:	D5.2
Deliverable no:	18
Deliverable description:	The deliverable contains a review of scientific knowledge (bibliography, expert opinions, current EU projects), an inventory of the technological resources mobilised (vectors, sensors, current and planned products, services), and the identification of obstacles to greater use of Earth observations for soil monitoring and measurement needs to reduce/minimise these difficulties.
Due date:	30.06.2024
Submission date:	28.06.2024
Version:	DRAFT NOT YET APPROVED BY THE EUROPEAN COMMISSION
Dissemination level:	PU - Public
Authors:	RENAULT, Pierre (INRAE); XIE, Guanyao (INRAE); WEISS, Marie (INRAE)
Version:	V3

Project acronym: **Project name:**	**PREPSOIL** **Preparing for the 'Soil Deal for Europe' Mission**
Project number:	**101070045**
Call topic:	**HORIZON-MISS-2021-SOIL-01-01**
Type of action:	**HORIZON-CSA**

Funded by
the European Union

Contributors

Name	Organisation & Country
RENAULT, Pierre	INRAE, France
XIE, Guanyao	INRAE, France
WEISS, Marie	INRAE, France
ŁOPATKA, Artur	IUNG, Poland
ORTMAN, Tove	NIBIO, Norway
SMEJKAL, Jaroslav	LESP, Czech Republic
Van EGMOND, Fenny	WR, The Netherlands
SIEBIELEC, Grzegorz	IUNG, Poland
CHARVAT, Karel	LESP, Czech Republic
SWIATEK, Karolina	IUNG, Poland
WAWER, Rafał	IUNG, Poland

Revision history

Version	Date	Reviewer	Modifications
V1	04.06.2024	E. Frankus (PREPSOIL ethic advisor) J. Barron (PREPSOIL WP6 Leader) K. Charvat for LESP (partner in Task 5.2) A. Łopatka for IUNG (partner in Task 5.2) F. Van Egmond for WR (partner in Task 5.2)	
V2	24.06.2024	N. Halberg (PREPSOIL coordinator); L.F. Lindner (PREPSOIL project manager)	
V3	27.06.2024		

Table of content

Acknowledgements

We would like to thank various people who were not involved in Task 5.2 of the PREPSOIL project, - including people not involved in the PREPSOIL projet -, for helping us to carry out this work.

We would like to thank the people who agreed to take part in interviews because of their recognised expertise in certain areas of remote sensing: David Sheeren and Marc Lang (landscape heterogeneity and biodiversity), Eric Ceschia (soil carbon), Olivier Cerdan (soil erosion), Anne Richer-de-Forges (digital soil mapping).

We would like to thank all the people who helped us access certain data or information: Bertrand Laroche for the Soil data from the French *Groupement d'Intérêt Scientifique Sol* (GIS Sol), Albert Olioso for the COMEPHORE data, Timo Breure from JRC for information on the remote sensing data used for the current EUSO Dashboard, and Matteo Mattiuzzi from the EEA who try to help us find (partial) answers to complex ethical questions related to remote sensing data.

We would also like to thank those outside the PREPSOIL consortium who agreed to help run the workshops organised as part of this project: Christine King, Joëlle Sauter, Dominique Arrouays, Anne Richer-de-Forges, Sébastien Lehmann, Clara Savary, Beatrice Helgheim, Erik Joner and Teresa Gómez de la Bárcena.

Finally, we would like to thank the people who agreed to review this document without having participated in Task 5.2 in the PREPSOIL project: Elisabeth Frankus (ethical advisor of PREPSOIL), Jennie Barron (leader of WP6 of PREPSOIL), Line Friis Lindner (project manager for PREPSOIL) and Niels Halberg (coordinator of the PREPSOIL project).

Table of abbreviations

AI:	Artificial Intelligence
API:	Application Programming Interface
ASTER:	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CAP:	Common Agricultural Policy
CES:	*Centre d'Expertise Scientifique*
CF:	Carbon Farming

CLC:	CORINE Land Cover
CLMS:	Copernicus Land Monitoring Service
CS:	Citizen Science
CSO:	Civil Society Organization
DEM:	Digital Elevation Model
DES:	*Domaine d'Expertise Scientifique*
DL:	Deep-Learning
DSBI:	Dry Bare-Soil Index
DSM:	Digital Surface Model
EC:	European Commission
EEA:	European Environment Agency
EGNOS:	European Geostationary Navigation Overlay Service
EJP SOIL:	European Joint Programme Soil
EnKF:	Ensemble Kalman Filter
EnMAP:	Environmental Mapping and Analysis Program
EO:	Earth Observation
ESA:	European Space Agency
EU:	European Union
EUSO:	European Union Soil Observatory
FCI:	Forest Cover Index
Fcover:	Fractional Vegetation Cover
FPCUP:	Framework Partnership Agreement on Copernicus User Uptake
GAEC:	Good Agricultural and Environmental Conditions
GHG:	Green House Gas
GIS-Sol:	*Groupement d'Intérêt Scientifique "Sol"*
GNSS:	global navigation satellite system
HBM:	Hierarchical Bayesian Method
HE:	Horizon Europe
ICOS:	Integrated Carbon Observation System
IGCS:	*Inventaire, Gestion et Conservation des Sols*
IGN :	Institut National de l'Information Géographique et Forestière
IR:	*Infrastructure de Recherche*
ISRO:	Indian Space Research Organisation
ISS:	International Space Station
JRC:	Joint Research Centre
KF:	Kalman Filter)
knn:	K nearest neighbour
LAI:	Leaf Area Index
LiDAR:	Light (or Laser) Detection and Ranging
LULC:	Land Use / Land Cover
MESALES:	Modèle d'Evaluation Spatiale de l'ALéa Erosion des Sols

ML: Machine Learning
MLR: Multiple Linear Regression
MNS: Modèles numériques de surface
MNT: Modèles numériques de terrain
MODIS: Moderate-Resolution Imaging Spectroradiometer
MRV: Measuring, Reporting and Verification
MS: Member State
MSAVI: Modified Soil Adjusted Vegetation Index
NASA: National Aeronautics and Space Administration
NDVI: Normalized Difference Vegetation Index
NGO: Non-Governmental Organization
PCR: Principal Component Regression (PCR)
PESERA: Pan-European Soil Erosion Risk Assessment
PF: Particle Filter
PLSR: Partial Least Squares Regression
Radar: Radio Detection And Ranging
RDVI: Renormalized Difference Vegetation Index
RF: Random Forest
RMQS: *Réseau de Mesure de la Qualité des Sols*
RMT: *Réseau Mixte Technologique*
RS! Remote Sensing
RUSLE: Revised Universal Soil Loss Equation
SAR: synthetic-aperture radars
SAVI: Soil-Adjusted Vegetation Index
SBAS: satellite-based augmentation system
SDG: Sustainable Development Goal
SMU: Soil Mapping Unit
STU: Soil Type Unit
SOC: Soil Organic Carbon
SRTM: Shuttle Radar Topography Mission
SVM: Support Vector Machine
TCC: Tree canopy cover
UAV: Unmanned Aerial Vehicle
USLE: Universal Soil Loss Equation
VNIR: Visible and Near-InfraRed
3DVAR: Three-Dimensional Variational Data Assimilation
4DVAR: Four-Dimensional Variational Data Assimilation

I. Executive summary

Soils contribute to the achievement of several Sustainable Development Goals through their contribution to various ecosystem services. They are subject to a variety of threats and can be degraded very quickly, even though they are formed over very long periods of time. Any sustainable soil management policy must include soil monitoring, to which Earth observations can contribute. In this report, we deal successively with the state of scientific knowledge, the technological resources that can be mobilised, and the identification of the obstacles to greater use of Earth observations for soil monitoring and the measures to reduce/minimise these obstacles.

Earth observation provides access to a wide range of information thanks to different vectors (satellite, airborne sensors, Unmanned Aerial Vehicles), different sensors (radar, passive microwave, multispectral, hyperspectral, LiDAR, gamma-ray spectrometry) and a wide range of data processing, including machine learning and deep learning. At the scientific level, the main stumbling blocks (not prohibitive) are related to the limits of information (surface characterization, clouds, compatibility of scales, standardisation/harmonization of measurements, etc.) and data treatments; various scientific works try to cope with these challenges, partly thanks to EU research projects.

Obstacles to greater use of Earth observation data vary with the national context, including the numbers of experts in remote sensing and/or soil and the skills of other end users. These last users have generally difficulties to access and use Earth observation data, as well as to acquire skills in remote sensing. A number of solutions need to be explored to solve these problems: raising awareness, supporting and training end-users of EO products and data, encouraging interaction between scientists on the one hand and public authorities and other end-users on the other (meetings, workshops, collaborative web space...); creating new links between education and research.

Much hope is pinned on hyperspectral imagery, gamma-ray spectrometry and LiDAR observations to provide new information on soil depth, chemical composition and canopy structure., respectively. Among the current promising areas of research, we may mention the link between landscape heterogeneity and biodiversity (currently “above the soil”), and the combination of different Earth observation data to cope with cloud problems.

II. Introduction

Soils contribute to the achievement of several Sustainable Development Goals (SDGs), in particular SDG 2 (zero hunger), SDG 6 (Clean water and sanitation), SDG 7 (Affordable and clean energy), SDG 13 (Climate action) and SDG 15 (Life on land). Their contributions derive from the soil's contribution to various ecosystem services: (i) the supply of biomass for food, energy or other uses (fibres, pharmaceutical compounds) and of metals *via* agromining, etc., (ii) climate change mitigation *via* organic carbon storage and CH_4 oxidation, (iii) mitigation of extreme hydrological phenomena (run-off, flooding, etc.) *via* water infiltration and retention, and regulation of water composition, (iv) regulating biodiversity which is involved in the nutrient cycle, pest control, etc. (more than 25% of Earth biodiversity is found in soils[1], the latest estimates even reaching 59% of the Earth's biodiversity[2]), (v) supporting public infrastructures (roads, power lines, etc.) and buildings, and (vi) landscape features (amenity, heritage and cultural value, archaeological value, etc.). Unfortunately, soil degradation can be very rapid, while its formation is very slow[3]. On a global scale, it is estimated that around 20% to 40% of soils are degraded[4], and that 90% of soils could be degraded by 2050 in the absence of adequate measures[5]; In the European Union, it is estimated that around two-thirds of soils are degraded[6].

Good soil management combines protecting the soil, defining sustainable practices[7] and restoring degraded soils when possible. It requires soil monitoring tailored to these objectives[8,9,10,11]. Should we be monitoring soil health (linked to their contribution to ecosystem services; human-oriented), certain soil functions (soil actions on itself, on a wider ecosystem and/or on humans), elementary soil

---

1 Bach E.M., Ramirez K.S., Fraser T.D., Wall D.H. (2020). Soil biodiversity integrates solutions for a sustainable future. Sustainability, 12, 2662. (https://doi.org/10.3390/su12072662)

2 Anthony, M. A., Bender, S. F., & van der Heijden, M. G. (2023). Enumerating soil biodiversity. *Proceedings of the National Academy of Sciences*, *120*(33), e2304663120. (https://doi.org/10.1073/pnas.230466312)

3 Valentin C. (2018). Les sols au cœur de la zone critique 5: dégradation et réhabilitation (Vol. 5). ISTE Group.

4 United Nations – Convention to combat desertification (2022). Global land outlook – second edition. Summary for Decision Makers. 24 p. (https://www.unccd.int/sites/default/files/2022-04/GLO2_SDM_low-res_0.pdf)

5 https://www.fao.org/about/meetings/soil-erosion-symposium/key-messages/fr/

6 Veerman C., Correia T.P., Bastioli C., Biro B., Bouma J., Cienciala E., Emmett B., Frison E.A., Grand A., Filchew L.H., Kriaučiūnienė Z., Pogrzeba M., Soussana J.F., Vela Olmo C., Wittkowski R. (2020). Caring for soil is caring for life: ensure 75% of soils are healthy by 2030 for healthy food, people, nature and climate: interim report of the mission board for soil health and food, 52 pp. (https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/caring-soil-caring-life_en).

7 *Soil Health Principles and Practices*. (2020, August 19). Farmers.Gov. (https://www.farmers.gov/conservation/soil-health)

8 Karlen, D. L., Veum, K. S., Sudduth, K. A., Obrycki, J. F., & Nunes, M. R. (2019). Soil health assessment: Past accomplishments, current activities, and future opportunities. *Soil and Tillage Research*, *195*, 104365. (https://doi.org/10.1016/j.still.2019.104365)

9 Rinot, O., Levy, G. J., Steinberger, Y., Svoray, T., & Eshel, G. (2019). Soil health assessment: A critical review of current methodologies and a proposed new approach. *Science of The Total Environment*, *648*, 1484–1491. (https://doi.org/10.1016/j.scitotenv.2018.08.259)

10 Jian, J., Du, X., & Stewart, R. D. (2020). A database for global soil health assessment. *Scientific Data*, *7*(1), 16. (https://doi.org/10.1038/s41597-020-0356-3)

11 *Soil Health Assessment | Natural Resources Conservation Service*. (n.d.). Retrieved April 26, 2024, from (https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health/soil-health-assessment)

processes (physical, chemical or biological), soil properties (e.g., % clay, pH, bulk density, etc.) or soil degradation indicators?[12,13,14,15] The current indicators of the European Union Soil Observatory (EUSO) dashboard are indicators of soil degradation; the list of indicators proposed in the draft EU Directive *'Soil monitoring and resilience'* published on 5 July 2023 are also mainly indicators of soil degradation or condition, and the 8 indicators initially proposed by the *"Soil health and food"* Mission Board[6] and included in the Implementation plan of the new *"A soil deal for Europe"* Mission Board[16] are more soil condition or degradation indicators than indicators of ecosystem services. Although soil health is a recent and popular concept, its definition does not yet seem to have general consensus. Critics of this concept include the fact that ecosystem services are not provided solely by the soil, that it is focused on human unlike soil functions, and that soil health should be relative to a type of soil, its designated land use, or even to a soil-climate-use context, as suggested by the SIREN project[17] (EJP Soil program). In this Deliverable, we have address soil monitoring without restricting to the concept of soil health, considering in particular that Earth Observations (EO) can help characterise soil degradation (artificialisation, erosion, etc.) as well as upstream factors that can have a positive or negative impact on soils (vegetation cover, landscape heterogeneities, etc.). We have not only considered EO by satellites, but also by unmanned aerial vehicle (UAV) and airborne sensors, the latter opening the way to other types of soil and land cover characterisation.

EO based on the use of satellite, UAV or airborne sensors offer great potential for estimating certain soil indicators and monitoring them over time. This potential results from the large ground coverage and the variety of available sensors that provide information which may complement or replace *in situ* ground observations or laboratory characterizations of soil samples. They include a variety of optical sensors that detect the solar radiation reflected by the Earth surface. Multi-spectral imaging with specific relatively large spectral bands beyond the red, green, blue and near-infrared channels captures information on the arrangement of the surface (land cover, architecture,

---

[12] Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105–125. (https://doi.org/10.1016/j.soilbio.2018.01.030)

[13] Doran, J. W., & Parkin, T. B. (1994). Defining and Assessing Soil Quality. In *Defining Soil Quality for a Sustainable Environment* (pp. 1–21). John Wiley & Sons, Ltd. (https://doi.org/10.2136/sssaspecpub35.c1)

[14] Laishram, J., Saxena, K., Maikhuri, R., & Rao, K. (2012). Soil quality and soil health: A review. *International Journal of Ecology and Environmental Sciences*, 38(1), 19-37.

[15] *Soil monitoring in Europe – Indicators and thresholds for soil health assessments—European Environment Agency*. (n.d.). [Publication]. Retrieved April 26, 2024, from (https://www.eea.europa.eu/publications/soil-monitoring-in-europe)

[16] European Commission (2021). A soil deal for Europe - 100 living labs and lighthouses to lead the transition towards healthy soils by 2030 – Implementation plan. 77 p. (https://research-and-innovation.ec.europa.eu/document/download/1517488e-767a-4f47-94a0-bd22197d18fa_en?filename=soil_mission_implementation_plan_final.pdf)

[17] Faber J.H., Cousin I., Meurer K.H.E., Hendriks C.M.J., Bispo A., Viketoft M., ten Damme L., Montagne D., Hanegraaf M.C., Gillikin A., Kuikman P., Obiang-Ndong G., Bengtsson J., Taylor A. (2022). Stocktaking for Agricultural Soil Quality and Ecosystem Services Indicators and their Reference Values. EJP SOIL Internal Project SIREN Deliverable 2. Report, 153 p. (https://ejpsoil.eu/fileadmin/projects/ejpsoil/1st_call_projects/SIREN/SIREN_D2_final_report.pdf)

roughness) and its composition (biochemical content) with a few days revisit frequency. Hyper-spectral imaging[18] enables the acquisition of a multitude of very narrow spectral bands to detect specific material signatures and better quantify their biochemical and mineral composition, but currently offers less possibilities in terms of spatial coverage and revisit frequency. While optical systems are not exploitable during cloud occurrence, active radars (e.g., synthetic-aperture radars (SAR)) which transmit microwave signals to the target, or passive microwave sensors are insensitive to clouds, with a signal related to surface moisture or roughness. In addition, Light (or Laser) Detection and Ranging (LiDAR)[19] based on the analysis of a reflected monochromatic, polarized, high-amplitude, coherent laser of near-visible light (from the visible, infrared or ultraviolet spectrum) is used to measure distances, (usually using a pulsed laser or a frequency-modulated laser source (FMCW: Frequency Modulated Continuous Wave)) and characterize object structural properties through the interaction of radiation with the target. Although all these sensors provide valuable information on soils, they allow to characterize only the first few millimetres or centimetres of soil depth and are sensitive to the possible presence of vegetation at the soil surface. Using such sensors, soil characterization is therefore either possible for bare soils between two successive crops (in the absence of intermediate crops), or by using coupled soil and vegetation functioning models with ancillary information. Satellite EO produces images of the Earth's surface with a spatial resolution depending on the sensors (e.g., 10 m spatial resolution for Sentinel-1 and Sentinel-2), and have a high and regular revisit frequency (e.g., 5 days for Sentinel-2, and about 6 days for Sentinel-1 at the Equator). Hence, it is possible to exploit long temporal archives since the 1980s to monitor certain slow changes in the topsoil over time[20]. While satellite sensors are currently the main instruments for EO, airborne sensors have been used to simulate the acquisitions of future satellites and for LiDAR, gamma-ray spectrometry and hyperspectral applications. LiDAR and gamma-ray spectrometry are not possible from larger altitudes and hyperspectral VNIR technology was not advanced enough to allow the launch of hyperspectral VNIR satellite missions. Airborne sensors have been partly replaced by UAV sensors over the last ten years for scientific studies and operational applications. Aircraft and UAV can be easily equipped with a variety of sensors (optical, SAR, LiDAR, gamma-ray). Airborne or UAV sensors may enable a higher spatial resolution compared to satellite sensors, allowing for quick detection of changes in small area. UAV sensors offer several advantages such as their ease of acquisition, operation, and manipulation by humans; they are capable of generating and providing remote sensing data of very fine spatial and temporal resolution, but UAV sensors are not suitable for covering large areas[21]. In addition to the EO technologies already mentioned, there is airborne gamma spectrometry, for which clouds and plant cover are transparent and which can penetrate the ground

[18] Hagen N., Kudenov M W. (2013). Review of snapshot spectral imaging technologies. Optical Engineering, 52(9), 090901-090901. (https://doi.org/10.1117/1.oe.52.9.090901)

[19] Diaz J.C.F., Carter W.E., Shrestha R.L., Glennie C.L. (2017). LiDAR remote sensing. Handbook of Satellite Applications, 929. In: Pelton, J., Madry, S., Camacho-Lara, S. (eds) Handbook of Satellite Applications. Springer, Cham. (https://doi.org/10.1007/978-3-319-23386-4_44)

[20] Interview of Anne Richer-de-Forges (see **subsection V.2.c.**).

[21] Zhang Z., Zhu L. (2023). A review on unmanned aerial vehicle remote sensing: Platforms, sensors, data processing methods, and applications. *Drones*, *7*(6), 398.(https://doi.org/10.3390/drones7060398)

to a depth of around 30-60 cm[22,23]. Gamma-ray sensors can be mounted on airborne, UAV and driving platforms.
Potential limitations to the use of EO data based on satellites, UAVs or airborne sensors include data access, dataset size and computation times required to obtain useful information. Some European services (e.g., Copernicus Land Monitoring Service (CLMS), European Geostationary Navigation Overlay Service (Galileo/EGNOS)) or national ones (e.g. Theïa in France) provide access to products that can be used directly (e.g., soil sealing from CORINE Land Cover (CLC)), but the use of NASA data (MODIS, SRTM, ASTER) and ISRO (Indian Space Research Organisation) data IRS-P6 LISS-II and LISS-III) to calculate several of the EUSO dashboard soil degradation indicators suggests a lack of observational data and/or products from European services (see sections IV.4 and V.4).
Some indicators may result from EO alone, but most combine EO data with other observations and/or measurements, mathematical calculations (e.g., models), and deep-/machine-learning.

Various categories of stakeholders may have an interest in the use of EO in soil monitoring. PREPSOIL Deliverable D2.1[24] distinguished politicians and government, research, soil advisors and other advisors, farmers / land users, business, CSO and NGO, each of which can be sub-divided into sub-categories. Expectations in terms of soil monitoring may vary depending on the sub-category of stakeholder. We focused on politician and government needs to support public policy goals[25]: to protect soils, to restore degraded ones, and to encourage sustainable soil management practices (e.g. zero net land take, (soil) carbon farming, good agricultural and environmental conditions (GAEC)[26] for conditional Common Agricultural Policy (CAP) subsidies, environmental services proposed at regional levels, etc.). Soil monitoring (degradation, health, functions, etc.) can contribute simultaneously to these three objectives.

Therefore, the objectives of Task 5.2 were to assess the possibility of using satellite-based EO at different scales in soil monitoring. Initially, we proposed to focus on some of the indicators proposed by the *"Soil health and food"* Mission Board, i.e., vegetation cover, landscape heterogeneity, area of

---

[22] Schwarzer, T. F., & Adams, J. A. (1973). Rock and soil discrimination by low altitude airborne gamma-ray spectrometry in Payne County, Oklahoma. *Economic Geology*, *68*(8), 1297-1312. (https://doi.org/10.2113/gsecongeo.68.8.1297)

[23] Martelet, G., Nehlig, P., Arrouays, D., Messner, F., Tourlière, B., Laroche, B., ... & Ratié, C. (2014). Airborne gamma-ray spectrometry: potential for regolith-soil mapping and characterization. *GlobalSoilMap: Basis of the global spatial soil information system*, 401-408. (https://www.researchgate.net/profile/Guillaume-Martelet/publication/259466795_Airborne_gamma-ray_spectrometry_Potential_for_regolith-soil_mapping_and_characterization/links/0046352bdec0bec7ea000000/Airborne-gamma-ray-spectrometry-Potential-for-regolith-soil-mapping-and-characterization.pdf)

[24] Bayer L., Bandru K., Chowdhury S., Gómez P., Sanchez I., Nougues L., Jordan S., Maring L., Barron J., Keesstra S., Helming K., (2023). Synthesizing soil needs and drivers of change across Europe and land use types. PREPSOIL deliverable D2.1. 501 p.

[25] Various soil indicators can be useful to the private sector: they are linked to the value of property assets, parametric insurance, environmental or quality labels, compliance with production specifications, etc.

[26] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Good_agricultural_and_environmental_conditions_(GAEC)

forest and other wooded lands, and possibly soil organic carbon concentration and/or content[27]. We later extended these objectives to several soil indicators of the EUSO dashboard and several indicators listed in the proposed EU directive on soil monitoring and resilience[28]. The work has combined:

- A review of the literature including a stocktake of existing and emerging mathematical formulations for indicators, discussions with leading scientists on topics enriched by EO (soil organic carbon, soil erosion, landscape heterogeneity, digital soil mapping), and an attempt to summarise the work in progress at European level (survey of 11 projects identified and supported by *Horizon Europe*, *EJP SOIL*, *ESA* or the *FPCUP*) (subsections **IV.1.-3.** and **V.1.-3.**);
- A stocktake of the quantitative and qualitative products of the CLMS and other services, their current use in the EUSO dashboard, and the analysis – as an example used in workshops – of the impact of the origin and resolution of EO data on the soil water erosion indicator calculated according to the JRC method in the area around Dijon (Burgundy, France) (subsections **IV.4.-6.** And **V.4.-6.**);
- The identification of bottlenecks (scientific, technological, technical, skills …) to greater use of satellite EO data and products (supplied by CLMS, Galileo/EGNOS and other services) for soil monitoring, as well as potential solutions to reduce these gaps, for some of the most common soil threats identified in the 20 selected EU regions WP2 (subsections **IV.7.** And **V.7.**).

After the presentation of the context justifying this study in section **III**, we have chosen to use the classic subdivision of scientific articles, with first a presentation of all the Materials and methods (section **IV**) followed by a presentation of the Results and discussion (section **V**). Readers can move easily from one to the other thanks to the same numbering used in these 2 sections (for example, the interview with a leading scientist on soil erosion is presented in sub-sections **IV.2.c.** and **V.2.c.**). Finally, the general conclusion of this work (section **VI**) has been enriched by a reflection on certain ethical issues, some of which are exacerbated by the potentially intrusive nature of remote sensing; at this stage, we share more questions than guarantees or solutions for ensuring the ethical dimension of soil monitoring when it makes use of remote sensing.

III. Background: soil threats and soil needs

The Deliverable D2.1 of PREPSOIL issued from its WP2 (*Identification, mapping and evaluation of EU regional soil needs*) proposed to define soil needs as *"the requirements from existing and emerging socio-economic and geo-biophysical perspectives that determine soil health and related services to human society"*. This leads the partners involved in WP2 to propose ways of modifying the current soil degradation trajectories, caused by the socio-economic context and soil management, which are specific for agricultural land, forest land, mixed production systems, and urban and agglomeration systems. Their work was based on surveys in 20 regions, selected in The Netherlands, Italy, Spain,

[27] PREPSOIL Grant Agreement – Part A (May 2022)
[28] Directorate-General for Environment. 2023. Proposal for a Directive on Soil Monitoring and Resilience. 5 July 2023. (https://environment.ec.europa.eu/publications/proposal-directive-soil-monitoring-and-resilience_en)

Germany, France, Denmark, Hungary, Norway, Slovenia, Poland, Estonia, Sweden, Turkey, Ireland, and the Czech Republic. Their work did not address the need for soil monitoring, but listed the threats identified in 18 of the 20 surveyed regions for which such threats were identified (**Table 1**). We will use the latter information in the rest of this section.

Already in 2020, the former *"Soil health and food"* Mission Board (2019-2022) recommended to monitor soil health through 8 indicators[29], which were subsequently included in the implementation plan[30] of the current *"A soil deal for Europe"* Mission Board (2022-). These are (i) the presence of pollutants, excess nutrients and salts, (ii) soil organic carbon (SOC) stock, (iii) soil structure including soil bulk density and absence of soil sealing and erosion, (iv) soil biodiversity, (v) soil nutrients and pH, (vi) vegetation cover, (vii) landscape heterogeneity, and (viii) the area of forest and other wooded lands. These soil health indicators should provide information on the achievement of 8 objectives, each having 1 to 6 targets to be achieved by 2030. At the beginning of 2023, the European Union Soil Observatory (EUSO), set up at the end of 2020 to help produce useful data for various European policies and their implementation at national level[31], introduced a dashboard that monitors soil degradation indicators rather than soil health indicators[32]. Its soil indicators deal with soil erosion (water erosion, wind erosion, harvest erosion, tillage erosion, post-fire erosion), soil pollution (copper, mercury, zinc), soil nutrients (nitrogen surplus, phosphorus deficiency, phosphorous excess), loss of SOC (distance to maximum SOC level), loss of soil biodiversity (potential threat to biological functions), soil compaction (susceptibility to soil compaction), soil salinisation (secondary salinisation risk), loss of organic soils (peatland degradation risk), and soil consumption (soil sealing)[33]. More recently, the draft directive entitled *'Soil Monitoring and Resilience'*[34] published by the European Commission (EC) on 5 July 2023 has proposed a list of indicators for soil monitoring covering salinization, soil erosion, loss of organic carbon, subsoil compaction, excess nutrient content in soil, soil contamination, reduction of soil capacity to retain water, excess nutrient content in soil, acidification, topsoil compaction, loss of soil biodiversity, and land take and soil sealing. This draft directive gives rise to intense debate, scientists being often called upon to inform public decision-making in Member States

---

[29] Veerman C., Pinto Correia T., Bastiol C.i, Biro B., Bouma J., Cienciala E., Emmett B., Frison E.A., Grand A., Hristov Filchew L., Kriaučiūnienė Z., Pogrzeba M., Soussana J.F., Vela Olmo C., Wittkowski R. 2020. Caring for soil is caring for life – Ensure 75% of soils are healthy by 2030 for food, people, nature and climate. 82 p. (https://doi.org/10.2777/821504)

[30] EC, 2021. EU Missions: A Soil Deal for Europe: 100 Living labs and lighthouses to lead the transition towards healthy soils by 2030 - Implementation Plan. Working document of the European Commission.77 p. (https://research-and-innovation.ec.europa.eu/system/files/2021-09/soil_mission_implementation_plan_final_for_publication.pdf)

[31] Maréchal A., Jones A., Panagos P., Belitrandi D., De Medici D., De Rosa D., Martin Jimenez J., Koeninger J., Labouyrie M., Liakos L., Lugato E., Matthews F., Montanarella L., Muntwyler A., Orgiazzi A., Scarpa S., Schillaci C., Wojda P., Van Liedekerke M., Simoes Vieira D. (2022). EU Soil Observatory 2021, EUR 31152 EN, Publications Office of the European Union, Luxembourg, 2022, (https://doi.org/10.2760/582573)

[32] https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/new-tool-maps-state-soil-health-across-europe-2023-03-13_en

[33] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

[34] https://environment.ec.europa.eu/publications/proposal-directive-soil-monitoring-and-resilience_en

(MS) (ministries responsible for the environment and agriculture, parliaments, etc.) and at EU level. The European Parliament adopted a position on 10 April 2024 with numerous amendments[35,36] (the file will be followed up by the new Parliament after the European elections on 6-9 June 2024). And three successive compromise texts were proposed by the Presidency of the Council of the European Union on 19 December 2023, 19 March 2024 and 3 May 2024 before adopting the amendments on 17 June 2024. The Mission Board and the proposed EU Directive both source from science to understand which indicators are used and are useful for which soil threats, where. Both for selecting a first list, as indicated in the previous paragraph, and to update the indicators in the first evaluation of the Directive, once adopted. This is continuous research.

Taking into account all the indicators listed above, three challenges need to be met: (i) defining the concrete content of certain indicators and the associated soil descriptors, ensuring their effectiveness, (ii) classifying the indicators (from among those proposed and listed above) in terms of implementation priorities, and (iii) identifying those that can benefit from EO. In particular, the 'landscape heterogeneity' indicator should be given several definitions depending on the issue addressed (erosion; biodiversity; spread of diseases, pests and plant auxiliaries); and the effectiveness of the indicators must be assessed according to a number of successive criteria such as those proposed by *Novasol-experts* in a hierarchy ranging from scientific relevance to cost-related aspects[37]: relevance, applicability, reliability, objectivity, operationality, interpretability and accessibility.

The classification of soil degradation indicators can be based on the surface proportion of unhealthy land, although other estimators could be proposed. The EUSO dashboard[38] then lead to the following order for EU soils (in brackets, the percentages of unhealthy soils):

Loss of SOC (52.7%) > Loss of soil biodiversity (36.7%) >
Tillage erosion (26.5%) > Water erosion (24.0%) > Nitrogen surplus (22.4%) >
Phosphorus deficiency (21.3%) > Soil compaction (10.4%) > Phosphorous excess (10.2%) >
Soil sealing (7.3%) = Soil salinization (7.3%) >
Wind erosion (6.3%) > Harvest erosion (3.3%) >
Copper pollution (1.6%) > Zinc pollution (1.5%) > Mercury pollution (0.8%)

However, the proportion of unhealthy soil depends on the method used to calculate the indicator (including model hypotheses for certain indicators, etc.), the threshold chosen and the "areas with data", the extent of which is imprecise and may vary with the indicator (e.g. peatland degradation risk concerned 29.7% of “areas with data” probably restricted to peatland only; it was therefore not included in the preceding list).

[35] https://www.europarl.europa.eu/news/en/press-room/20240408IPR20304/soil-health-parliament-sets-out-measures-to-achieve-healthy-soils-by-2050
[36] https://www.europarl.europa.eu/doceo/document/A-9-2024-0138_EN.html#_section3
[37] https://www.linkedin.com/pulse/un-indicateur-cest-quoi-novasol-experts/?trk=public_post&originalSubdomain=fr
[38] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

Region / activities	Soil threat
Cow Dairy Farming: Gelderland, Netherlands	Too dry (Podzol, Anthrosol), Too wet (Fluvisol), Soil compaction (everywhere)
Sheep Agrosilvopastoral Farming:Sardegna, Italy	Erosion (water), desertification.
Irrigated Arable Farming: Communitat Valenciana, Spain	soil erosion and soil pollution. A general soil degradation process is found due to the increase in machinery (heavy machinery), pesticides, soil compaction, loss of soil structure and reduction in water retention by soils.
Olive Tree Cultivation: Andalucia, Spain	Erosion (water), desertification, salinization, pollution, compaction.
Annual Cropping Central Europe: Brandenburg, Germany	SOC decline, compaction, biodiversity decline, soil erosion (water, wind, tillage); decreasing water retention capacities
Bordeaux Vineyard	Erosion, soil sealing, compaction, biodiversity decline
Annual Cropping North: East Denmark, Denmark	Soil organic carbon (SOC) loss, nutrient loss, compaction (topsoil and subsoil), water and tillage erosion, reduced water retention capacity, reduced soil fertility.
Large Scale Annual Cropping: Emilia-Romagna, Italy	Soil consumption and sealing; soil organic matter loss; moderate- high risk of drought; moderate-high risk of flood; moderate risk of soil erosion; high risk of soil pollution; low risk of soil salinity; low- moderate risk of functional soil biodiversity deterioration.
Organic Mixed Farming East: Del-Alföld, Hungary	Wind erosion and desertification due to climate change and historical change in water management
Mixed Farming North: Trondelag, Norway	High precipitation rates, poor drainage, soil compaction (saturated soil during harvest), soil erosion, soil sealing.Part time farming, intensive agriculture, limited time to spend on farm work, sometimes lacking/to small economic incentives, high pressure on agricultural land.
Post-Mining: Vzhodna Zasavje, Slovenia	1. Soil erosion, 2. Soil contamination, 3. Soil acidification, 4. Urban sprawl and urbanization & 5. Invasive organisms
Dense Urbanism: Noord Amsterdam, The Netherlands	Sealing, contamination, loss of biodiversity, loss of organic matter (peat), land subsidence, soil degradation due to disturbance, compaction, and -in parts (external)- salinization (through Noordzeekanaal)
Post-Industrial: Upper Silesia, Poland	contamination, sealing, land abandonment
Forest Peatland Northeast: Soomaa, Estonia	Peatland drainage for forestry; tracks from harvesters
Forest North: Upper Norrland, Sweden	
Forest Tourism South East: Antalya, Türkiye	
Agro-Forestry in DEHESA: Extremadura, Spain	Erosion, compaction, lack of fertility
Alpine Tourism: Lautaret-Oisans Alpine region, France	Climate change (erosion, changes in the cryosphere and water resources, increase in climatic hazards and risks in the high mountains, increase and elevation of wooded areas, artificialization of valley bottoms, greening); Mass tourism (urbanization, biodiversity degradation, erosion)
Peatlands: Eastern and Midland, Ireland	Drainage of peatlands led to peat shrinkage, compaction, subsidence, erosion and greenhouse gas emissions
Reforestation: Vysočina, The Czech Republic	Erosion, Acidification

Table 1: Soil threats identified in 20 regions (Table proposed in this work and based on the results of PREPSOIL deliverable D2.1).

An alternative way of ranking soil degradation indicators could be based on the number of regions mentioning the corresponding threat as a current regional problem. Based on the 18 EU regions for which these threats have been identified among the 20 regions chosen in PREPSOIL WP2 (**Table 1**), we obtained the following ranking:

Erosion (14) > Compaction (10) > Soil consumption (7) > Contamination (6) >
SOC decline (4) > Biodiversity decline (4) > Reduction in water retention (3)

The differences between the two previous rankings may result (i) from the reference framework associated with the EUSO, which is based on imprecise "areas with data" and choices of thresholds separating healthy soils from unhealthy soil adopted by the EUSO, or even on the associated soil descriptors, (ii) from people's perception of the problems which may be linked to soil uses (e.g. water erosion is probably easier to observe than a loss of biodiversity), and (iii) the specific features of the 20 EU regions, which were not representative of all EU regions (**Table 1**).

Thus, while remaining cautious about prioritising the threats to soils, it seems clear that one cannot *a priori* neglect loss of SOC, loss of biodiversity, erosion (mainly water erosion), soil contamination (including contaminants not mentioned above), soil sealing and probably structural degradation affecting various soil properties (bulk density, water conductivity, etc.) and processes (run-off, erosion, water infiltration retention, colonisation of the soil by roots). However, it is likely that on a regional scale or for certain land use, soil and climate conditions, some threats may be neglected compared with others.

It should be noted that vegetation cover, landscape heterogeneity and the area of forests and other wooded land, proposed as soil health indicators only by the *"Soil Health and Food*" Mission Board, can have a significant impact on other indicators, including SOC, pH, soil erosion and biodiversity:

- Their link with erosion combines their impact on SOC and soil structural stability, soil protection against water or wind erosion, and the presence of non-productive areas such as hedgerows that can slow run-off and associated water erosion at landscape level;
- their link with soil biodiversity results from the impact of the presence of plant cover on SOC, the links between plant biodiversity and soil biodiversity (particularly for soil fungi[39]), and the impact of landscape heterogeneity on habitat diversity (see subsection **V.2.a.**).

EO can provide information on these degradation indicators. Beyond that, EO can at times give information on some diffuse soil contamination indicators through their impacts on vegetation[40], and EO data can be used as environmental covariates in "statistical modelling', i.e., in Digital Soil Mapping.

In addition, we note that the CUP4SOIL project[41] has inventoried the indicators now proposed by 19 past and ongoing EU research projects and initiatives to then use in a user requirement survey for future soil Copernicus products. It should be noted that many projects have published proposed lists, but some projects, like BENCHMARKS, AI4SoilHealth are still deriving their lists. The result of the

[39] George, P. B., Creer, S., Griffiths, R. I., Emmett, B. A., Robinson, D. A., & Jones, D. L. (2019). Primer and database choice affect fungal functional but not biological diversity findings in a national soil survey. *Frontiers in Environmental Science*, *7*, 461909. (https://doi.org/10.3389/fenvs.2019.00173)

[40] Lassalle, G., Fabre, S., Credoz, A., Dubucq, D., & Elger, A. (2020). Monitoring oil contamination in vegetated areas with optical remote sensing: A comprehensive review. *Journal of hazardous materials*, *393*, 122427. (https://doi.org/10.1016/j.jhazmat.2020.122427)

[41] https://www.copernicus-user-uptake.eu/user-uptake/details/cup4soil-high-resolution-soil-property-service-development-for-national-and-european-soil-carbon-reporting-512

potential user survey, distributed in a diverse group of potential users of EO based soil products, like maps, indicate a clear prioritisation. The top 4 priority for the simple soil properties: soil organic carbon, texture, bulk density, soil acidity. And soil water holding capacity, erosion risk, soil compaction and soil sealing/land take for the derived soil properties. The report describing this work is still under elaboration, more details have been presented already at the ESA Symposium on Earth Observation for Soil Protection and Restoration, Frascati 2024[42].

IV. Materials and methods

IV.1. Mini-review of the literature

Scopus[43] search engine was used to carry out a bibliometric analysis. It makes it easy to perform fairly sophisticated searches, using the logical operators 'AND', 'OR', 'AND NOT' etc. to link logical expressions relating to titles, summaries or keywords (isolated words or expressions), years etc. The framework of our search was to count and identify articles having in their title information on the disciplinary field ("earth observation" and/or "remote sensing"), the EO sensors ("radar", "passive microwave", "multispectral", "hyperspectral", "LiDAR" and/or ("gamma*" AND "airborne"), on their vectors/platforms ("satellite", "airborne", "UAV" and/or "drone"), and/or on the objects characterized ("soil", "crop*", "vegetation", "forest" and/or "landscape"). The evolution over time of publications associated with certain advanced searches enables us to identify certain evolutionary trends: subjects in decline, those in full expansion or stagnation, or those at the beginning of their rise to prominence.

A mini-review of the literature was carried out in order to better assess the potential of EO for soil monitoring (it was not possible to produce an exhaustive review on the subject, which was beyond the scope of PREPSOIL Task 5.2 and the time that could be devoted to it).
Its objectives were (i) to provide an up-to-date state of the art in terms of science and technology, (ii) to better assess the potential of using EO in soil monitoring, and (iii) to forecast possible developments in the short and medium term. In subsection V.1. this mini-review successively addresses passive and active sensors, vectors/platforms, algorithms/processes for using EO data/images to estimate soil properties directly from the signal or as covariates for digital soil mapping, and the use of EO data in soil modelling (assimilation or inversion), always with indicators for soil monitoring as a filigree. General uncertainties and biases in soil information derived from EO data and the potential solution for the scientific communities are discussed at the end of the study.
Several review papers (in particular the most cited papers), meta-analysis and major previous works (in particular those presenting significant methodological advances) were identified either by using the Scopus and Google Scholar search engines, or during interviews with leading scientists (see subsection **V.2.**), or on the basis of some of the papers studied (older papers in the references or more

[42] https://www.copernicus-user-uptake.eu/resources/resource-details/cup4soil-two-symposium-presentations-641
[43] https://www.scopus.com/

recent papers that cite them). In addition, several websites were also consulted as part of the study

The consortium agreement stipulates that we would give priority to 3 of the indicators proposed by the *"Soil Health and Food"* Mission Board (namely (i) vegetation cover, (i) landscape heterogeneity, (iii) area of forest and other wooded lands), and possibly to a 4th (i.e. (iv) soil organic carbon). However, we have also made inroads into other areas that could also be informed by EO (soil water erosion, soil texture, soil surface roughness, etc.). As several of these topics have been addressed in interviews with leading scientists (namely, landscape heterogeneity, water erosion, soil organic carbon, digital soil mapping (used for several soil properties)), we discuss more extensively at the end of sub-section V.1. of *"Vegetation over"* and *"The area of forest and other wooded lands"*.

IV.2. Interviews with leading scientists using EO data to characterise soils

INRAE, having more time to devote to Task 5.2 as coordinator of this Task, has undertaken 4 interviews with leading French scientists recognised for their use of satellite data for soil characterisation. Topics covered included landscape heterogeneity, soil organic carbon, digital soil mapping, and soil erosion. All the interview were recorded under Zoom, except the interview with E. Ceschia. The summaries of the interviews were submitted to the scientists, at the same time asking them if they agreed to their names appearing in this deliverable.

IV.2.a. Landscape heterogeneity (with D. Sheeren and M. Lang)

The UMR Dynafor (*Unité Mixte de Recherche Dynamiques et Écologie des Paysages Agriforestiers*) aims to generate knowledge on the representations, ecological functioning, management and governance of agroforestry landscapes in order to contribute to the implementation of sustainable agroecological and sylvoecological practices. It brings together geographers, agronomists, ecologists and specialists in landscape description. David Sheeren[44] and Marc Lang[45] belong to the latter group of researchers who use remote sensing to describe landscape heterogeneity, identify the representations most closely correlated with biodiversity, and seek to understand the reasons for these correlations in close collaboration with ecologists. They are Associate Professors.

The aims of their interview were (i) to discuss landscape heterogeneity, proposed as one of the indicators of soil health by the *"Soil Health and Food"* Mission Board, (ii) to put into perspective the results that may suggest concrete applications, and (iii) to discuss the links between aerial or surface biodiversity on the one hand, and biodiversity in soils on the other. Discussions focused on the different meanings that can be given to landscape heterogeneity with regard to the issues addressed and on the relevant indicators to be associated with it, on the concrete methodologies to be deployed

[44] Publications of David Sheeren: https://scholar.google.fr/citations?user=vIWrwWoAAAAJ&hl=fr
[45] Publications of Marc Lang: https://www.researchgate.net/profile/Marc-Lang-2

to characterise landscape heterogeneity (place of EO, measurements, data processing which may include machine learning and deep learning), on the links between landscape heterogeneity and surface and/or aerial biodiversity as well as soil biodiversity, on the characterization of landscape features and other non-productive areas (hedges, ditches, trees and fallow land) and their impact on surface and aerial biodiversity, on the possibility of using EO to help ecologist in their experimental work (sampling locations, etc.), on current research and the scientific fronts addressed by our interviewees, as well as on remaining gaps between specialists of remote sensing image processing and ecologists.

The interview took place on 16 February 2024 from 9am to 10.15am. It was conducted by Pierre Renault, Marie Weiss and Guanyao Xie. The interview was recorded in Zoom to facilitate the drafting of a report. A first version was submitted to the interviewees for correction of any errors, additional information and validation, as well as for permission to display their names.

IV.2.b. Soil organic carbon (with E. Ceschia)

Dr. Eric Ceschia[46] is working at CESBIO (*Centre d'Etudes Spatiale de la BIOsphère*) in Toulouse (France) and is a Research Director at INRAE. His research interests are centered around climate change mitigation, i.e., the reduction of GHG emissions in agriculture, carbon storage in the soil, cover crops, impact of management on albedo and energy budget. In particular, he is highly involved in the development of the pre-operational processing chain "AGRICARBON-EO" that simulate biomass, yields, CO_2 fluxes and annual C-budgets of crops as well as their uncertainties by assimilating SENTINEL-2 data. EO data allow to derive crop and soil maps, as well as vegetation characteristics (e.g., Leaf Area Index) that are then assimilated into an agronomic model (SAFYE-CO_2) dedicated to upscaling in order to derive Gross Primary Production (GPP), Autotrophic and heterotrophic respiration, Net Ecosystem Exchange (NEE), Dry Above Ground Biomass (DAM) and Yield and establish carbon budget. Eric Ceschia is deeply involved in many projects related to carbon budget, in particular CLIMATE-KIC (Experimenting Soil Carbon Sequestration Deployment in Farming Systems), SCO-Quantica (Space Climate Observatory – Quantification of Additional Carbon Stored in Soils with cover crops), H2020 CLIENFARMS (co-development and upscaling of systemic locally relevant solutions to reach climate-neutral and climate-resilient sustainable farms across Europe), H2020-NIVA which aims at providing digital tools (including EO data) to compute agri-environmental indicators related to the carbon budget, biodiversity and nitrate leaching for the CAP, Horizon ORCaSa that aim at preparing the operational phase of the International Research Consortium on Soil Carbon and Horizon MARVIC that aims at developing Monitoring Reporting and Verification tools and frameworks for Soil Carbon.

The aims of his interview were to discuss on existing methods to estimate SOC content or SOC stock changes by using EO data.

[46] Publications of Eric Ceschia: https://scholar.google.com/citations?user=awQwOrgAAAAJ&hl=en&oi=sra

The interview took place on 15 September 2023 from 9.15am to 10.30am. It was conducted by Pierre Renault, Marie Weiss and Guanyao Xie. Unfortunately, the interview was not recorded and the report is based on the written notes taken by the 3 interviewers. A first version was submitted to Eric Ceschia for correction of any errors, additional information and validation, as well as for permission to display his name.

IV.2.c. Soil erosion (with O. Cerdan)

The *'Risques et Prévention'* Division of the *Bureau de Recherches Géologiques et Minières* (BRGM) is responsible for understanding and managing the risks generated by phenomena affecting the soil and subsoil, assessing the safety and overall performance of subsoil uses and developing soil and subsoil imaging methods. Olivier Cerdan[47] is Deputy Director of this Division. He has worked on setting up and validating a European soil erosion map. His main interests include land degradation processes, soil mapping and modelling at different spatial and temporal scales. He co-developped the STREAM and WaterSed soil erosion models, and also coordinates projects aiming to establish the link between slope transfers and river sediment exports. Four people work at BRGM with Olivier Cerdan on runoff, erosion, sediment transport and even the transport of pollutants, at different scales. The work combines the whole value chain from observation (including instrumentation) to modelling (dealing with uncertainties). Approximately 50% of the group's activities involve research, and 50% support public policy (for water agencies and catchment area syndicates, in particular for development work to reduce mudflows or improve water quality).

The aims of this interview were (i) to discuss the possibilities of using EO to directly detect erosion and, if possible, quantify it, (ii) to discuss the possibilities of indirectly estimating erosion using EO to characterize certain important variables, in particular vegetation cover, which can partially protect soil surface against rain erosivity, and (iii) to gain an overview of the strengths and weaknesses of the (revised) Universal Soil Loss Equations (RUSLE) used to quantify water erosion in the EUSO Dashboard, compared with other similar models (e.g. MESALES developed by INRAE) or different mechanistic-based models (WaterSed developed by BRGM). Discussions distinguished water erosion, wind erosion, tillage erosion and harvest erosion; and water erosion is the sum of diffuse erosion and concentrated erosion (rill and gully erosion).

The interview took place on 11 March 2024 from 3.15pm to 4.30pm. It was conducted by Pierre Renault, Marie Weiss and Guanyao Xie. The interview was recorded in Zoom to facilitate the drafting of a report. A first version was submitted to Olivier Cerdan for correction of any errors, additional information and validation, as well as for permission to display their names.

[47] Publications of Olivier Cerdan: https://scholar.google.com/citations?user=q854cRcAAAAJ&hl=en&oi=ao

IV.2.d. Digital soil mapping (with A. Richer-de-Forges)

The INRAE UR Info&Sols is the result of merging on 1 January 2023, the US InfoSols (in charge of implementing the programmes of the French *GIS Sol*, responsible for soil mapping and monitoring in France) and the UR Sols, responsible for soil research. Anne Richer-de-Forges[48] is a soil and data scientist at INRAE, where she coordinates the national *"Connaissance pédologique de la France"* programme. She works on digital soil mapping using statistical modelling and makes extensive use of remote sensing data. Since the beginning of 2022, Anne Richer-de-Forges has been leading the Theia *'Digital Soil Mapping'* Scientific Expertise Centre[49],[50] (CES). Since early 2024, the CES have been reorganized. Now it is part of broader CES grouping 5 previous CES and named '*Vegetation, soils & Agrosystems'* that Anne still leads. Anne is co-leader of the INRAE 'Remote Sensing' network. She works on soil mapping and soil properties mapping, as well as on soil monitoring. She is currently working on the use of qualitative and uncertain observations data together with Remote Sensing covariates to improve maps of soil properties. Thus, her input data may be qualitative *in situ* observations, but also a large range of spatial data among which airborne gamma-ray spectrometry.

The aims of the interview of Anne Richer-de-Forges were (i) to discuss on the spatial prediction of soil properties (water holding capacity of the soil; texture and in particular sand, silt and clay composition; soil organic carbon; etc.) that can also be characterised using ground-based observations, (ii) to review digital soil mapping[51],[52],[53], and (iii) to discuss the potential of airborne gamma-ray spectrometry.

The interview took place on 12 February 2024 from 1.30pm to 2.45pm. It was conducted by Pierre Renault, Marie Weiss and Guanyao Xie. The interview was recorded in Zoom to facilitate the drafting of a report. A first version was submitted to the interviewee for correction of any errors, additional information and validation, as well as for permission to display her name.

---

[48] Publications of Anne Richer-de-Forges: https://www.researchgate.net/profile/Anne-Richer-De-Forges-2/research

[49] https://www.theia-land.fr/en/ceslist/digital-soil-mapping-sec/ and https://www.theia-land.fr/ceslist/ces-cartographie-numerique-des-sols/

[50] Richer-de-Forges, A.C., Lagacherie, P., Arrouays, D., Bialkowski, A., Bourennane, H., Briottet, X., ... & Puissant, A. (2022). The Theia "Digital Soil Mapping" Scientific Expertise Centre of France. Pedometron-Newsletter of the Pedometrics Commission of the IUSS, 46, 4-8. (http://www.pedometrics.org/Pedometron/Pedometron46.pdf)

[51] Suleymanov, A., Richer-de-Forges, A. C., Saby, N. P., Arrouays, D., Martin, M. P., & Bispo A. (2024). National-scale digital soil mapping performances are related to covariates and sampling density: Lessons from France. Geoderma Regional, e00801. (https://doi.org/10.1016/j.geodrs.2024.e00801)

[52] Richer-de-Forges, A. C., Chen, Q., Baghdadi, N., Chen, S., Gomez, C., Jacquemoud, S., ... & Arrouays, D. (2023). remote sensing data for digital soil mapping in French research—a review. Remote Sensing, 15(12), 3070. (https://doi.org/10.3390/rs15123070)

[53] Richer-de-Forges A.C., Arrouays D., Poggio L., Chen S., Lacoste M., Minasny B., Libohova Z., Roudier P., Mulder V.L., Nédélec H., Martelet G., Lemercier B., Lagacherie P., Bourennane H. (2023). Hand-feel soil texture observations to evaluate the accuracy of digital soil maps for local prediction of particle size distribution. A case study in central France. Pedosphere. 33(5): 731-743. (https://doi.org/10.1016/j.pedsph.2022.07.009)

IV.3. The use of satellite-based EO in EU projects (Horizon Europe, EJP Soil, etc.)

A survey form (**Annexe 2**) was sent to leaders or correspondents of 11 EU projects dealing with soil monitoring using satellite EO, airborne-sensors or drones on 16 March 2024 to identify:

- New knowledge already well consolidated;
- Work in progress likely to advance certain achievements;
- scientific issues relating to the sensor component, as well as to the data processing component and its use for estimation of soil health properties/characteristics/indicators;
- topics which have not yet been addressed (in any significant way) and which could be considered a priority.

A reminder was sent to some leaders or correspondents on 13 April 2024; a general reminder was systematically sent to all leaders or correspondents who had not yet replied on 29 April 2024; and a last reminder was sent on 5 June 2024. In all cases, we insisted on having feedback, even without results that could not be communicated.

For each project, information was requested on (**Annexe 2**):

- The Respondent and the identity of the project;
- Summary of the project;
- Main objectives of the project;
- For Work Packages/Tasks involving the use of EO:
    - their technical aspects;
    - Interaction with stakeholders;
    - The main results already achieved.

Other international, European or national initiatives could have been added to the map of work in progress, including the Integrated Carbon Observation System (ICOS)[54], and the French study IndiQualSols with a chapter dedicated to the use of remote sensing, the results will remain confidential until 20 November 2024. And we believe that long-term monitoring programmes such as ICOS are more long-term than the shorter-term research projects that were surveyed.

We received complete answers for 9 projects, and succinct responses for the other 2 projects (a summary of the project and a slide-show of a presentation at the beginning of the project for 1 of them; a slide-show at the end of the project for the other) (**Table 2**).

IV.4. Inventory of existing data and products linked to European services (CLMS)

We have attempted to draw up an inventory of the resources provided by the Copernicus Land Monitoring Service (CLMS). These resources include raw satellite data, quantitative and qualitative

[54] https://www.icos-cp.eu/

Project	Fund				Period	Main topic	Importance of RS[4]	Use of RS	Website
	EJP Soil	HE[1]	FPCUP[2]	ESA[3]					
ESA WorldSoils				•	09/2020-11/2023	Downstream service for topsoil SOC product based on direct estimation and improved DSM of topsoil SOC	All the project	Direct and improved DSM Topsoil SOC prediction	https://world-soils.com/
SensRes **GA ID: 862695** (for EJP Soil)	•				02/2021-01/2024	Extrapolation of proximal sensing prediction models and downscaling of soil maps	Part of the project	EO data as covariates in DSM for SOC	https://ejpsoil.eu/soil-research/sensres
STEROPES **GA ID: 862695** (for EJP Soil)	•				02/2021-07/2024	Method improvement for EO based SOC prediction by disturbing factor correction	All the project	Direct and DSM prediction of SOC	https://ejpsoil.eu/soil-research/steropes
CUP4SOIL			•		01/2023-12/2024	CLMS products dedicated to soil health and user requirement study	All the project	Soil health indicator maps using advanced innovative EO products	https://www.copernicus-user-uptake.eu/news/news-details/cup4soil-user-survey-future-copernicus-land-monitoring-service-for-soils-574
AI4SoilHealth **GA ID: 101086179**		• (RIA)			01/2023-12/2026	Digital infrastructure, for assessing and monitoring Soil Health	A contribution (Very large project on soil monitoring)	EO data as covariates,	https://ai4soilhealth.eu/
BENCHMARKS **GA ID: 101091010**		• (RIA)			01/2023-01/2027	Develop an harmonised and cost- effective integrated soil health monitoring framework	A contribution (Very large project on soil monitoring)	Sampling, Health indicators, Predictive mapping	https://soilhealthbenchmarks.eu/

MARVIC **GA ID: 101112942**		• (RIA)	06/2023-05/2027	Monitoring, reporting and verification systems for agricultural soil carbon and greenhouse gas balances	Essential	Biomass estimation, smart soil sampling, farm management	https://www.project-marvic.eu/
MRV4SOC **GA ID: 101112754**		• (RIA)	06/2023-05/2026	Impact of crop management, climate change and socio-economic pressures	Essential	SOC, GHG balance	https://mrv4soc.eu/
ORCaSa **GA ID: 101059863**		• (CSA)	09/2022-08/2025	Launch of IRC, Impact4Soil platform, a strategic research Agenda and the development of a prototype for MRV	important	Display in platform, input to MRV and for soil maps as covariates	https://irc-orcasa.eu/
ProbeField **GA ID: 862695** (for EJP Soil)	•		11/2022-10/2024	Improve methodology for proximal Vis-NIRS to assess soil organic carbon	Proximal characterization	Use as covariate for SOC	https://ejpsoil.eu/soil-research/probefield
SANCHO's THIRST **GA ID: 862695** (for EJP Soil)	•		07/2023-07/2026	Cover crop impact on woody crop soil	Important	SOC	https://ejpsoil.eu/soil-research/second-external-call-international-call/sanchosthirst

[1]: Horizon Europe [2]: Framework Partnership Agreement on Copernicus User Uptake [3]: European Space Agency [4]: Remote Sensing

Table 2: European research projects dedicated to soil health using, at least in part, remote sensing data (we received a summary and/or a slide-show for the project in brown. Survey forms were completed for all other projects. Lines highlighted in grey correspond to completed projects).

products, as well as national or international data derived from satellites and ancillary data. However, we have focused primarily on the evaluation of soil monitoring indicators.
Copernicus is part of the EU's Space Programme. CLMS is one of six Copernicus thematic services (*'Atmosphere'*, *'Marine'*, *'Land'*, *'climate change'*, *'Security'* and *'Emergency'*) that provide to a wide range of users throughout Europe and the world not only mosaics of satellite images from dedicated satellites (e.g. the Sentinel family), but also value-added information on land cover, land use, ground motion, vegetation, the water cycle, and Earth's surface energy variables[55]. The CLMS has been implemented since 2012 by the European Environment Agency (EEA) and the European Commission's DG Joint Research Centre (JRC). Thanks to its satellite data of high spatial resolution and high revisit frequency, and thanks to its high-quality products with a high refresh rate and extensive temporal and spatial coverage (particularly since 2012), CLMS supports applications in a variety of fields, such as urban planning[56], forest resource management[57,58], and crucial ecosystem monitoring (e.g. the coastal zone[59]), as well as providing a range of potentially useful data for soil monitoring.
Searches of available raw satellite data were conducted on the following websites: Copernicus Open Access Hub[60] and Sentinel Hub[61]. In addition, the research of available ready-to-use products was conducted on CLMS[62].

Moreover, we give some information on other satellite services and missions that can provide additional information to that provided by CLMS.
In particular, the Galileo mission, an EU global navigation satellite system (GNSS) developed in 2004[63], was designed to enable various satellite-based services and applications for a broad spectrum of sectors and users (e.g., aviation, maritime location services, transport guidance). It is widely used to provide excellent global coverage and highly accurate navigation, positioning (to within 1 m) and timing information in a variety of applications using a combination of satellites. The GNSS system is helpful in soil studies due to the exact geolocation of soil descriptions and is applied in land monitoring: it is routinely used in precision agricultural operations (yield monitoring, compaction

---

[55] CLMS. (n.d.). *Copernicus Land Monitoring Service*. Retrieved May 17, 2024, (from https://land.copernicus.eu/en)
[56] Diaz-Pacheco, J., & Gutiérrez, J. (2014). Exploring the limitations of CORINE Land Cover for monitoring urban land-use dynamics in metropolitan areas. *Journal of Land Use Science*, *9*(3), 243–259. (https://doi.org/10.1080/1747423X.2012.761736)
[57] Dostálová, A., Lang, M., Ivanovs, J., Waser, L. T., & Wagner, W. (2021). European Wide Forest Classification Based on Sentinel-1 Data. *Remote Sensing*, *13*(3), Article 3. (https://doi.org/10.3390/rs13030337)
[58] Salvatori, M., De Groeve, J., van Loon, E., De Baets, B., Morellet, N., Focardi, S., Bonnot, N. C., Gehr, B., Griggio, M., Heurich, M., Kroeschel, M., Licoppe, A., Moorcroft, P., Pedrotti, L., Signer, J., Van de Weghe, N., & Cagnacci, F. (2022). Day versus night use of forest by red and roe deer as determined by Corine Land Cover and Copernicus Tree Cover Density: Assessing use of geographic layers in movement ecology. *Landscape Ecology*, *37*(5), 1453–1468. (https://doi.org/10.1007/s10980-022-01416-w)
[59] Xie, G., & Niculescu, S. (2021). Mapping and Monitoring of Land Cover/Land Use (LCLU) Changes in the Crozon Peninsula (Brittany, France) from 2007 to 2018 by Machine Learning Algorithms (Support Vector Machine, Random Forest, and Convolutional Neural Network) and by Post-classification Comparison (PCC). *Remote Sensing*, *13*(19), Article 19. (https://doi.org/10.3390/rs13193899)
[60] *Open Access Hub*. (n.d.). Retrieved May 17, 2024, from (https://scihub.copernicus.eu/)
[61] Copernicus Data Space. (n.d.). *Sentinel Hub | Copernicus Data Space Ecosystem*. Retrieved May 17, 2024, (from https://dataspace.copernicus.eu/analyse/apis/sentinel-hub)
[62] CLMS. (n.d.). *Copernicus Land Monitoring Service*. Retrieved May 17, 2024 (from https://land.copernicus.eu/en)
[63] EUSPA. (n.d.-b). *Galileo | EU Agency for the Space Programme*. Retrieved May 13, 2024 (from https://www.euspa.europa.eu/eu-space-programme/galileo)

profile sensing, tree planting, site specific fumigant application, RTK GPS-based plant mapping, precise weed management system, robotic applications)[64,65,66], and monitoring of environmental problems[67], and has been used in soil moisture estimation[68].

As a European regional satellite-based augmentation system (SBAS) of GNSS, the European Geostationary Navigation Overlay Service (EGNOS) uses a set of geostationary satellites and a network of ground stations to effectively enhance both Galileo and GPS signals, improve the accuracy of GNSS[69]. Like Galileo sytem, EGNOS has a variety of applications as well, such as soil sampling[70] and precision agriculture system[71].

In addition, the national EO data of each European country is frequently applied in European soil studies. For instance, the GEOSAT-2 Spain coverage 2022 provides available full coverage of the Spanish territory[72], and German hyperspectral satellite mission, the Environmental Mapping and Analysis Program (EnMAP) is designed to monitor and characterizes Earth's environment on a global scale[73]. In France, Theia is a continental surface data and services hub of the "Infrastructure de Recherche" (IR) *'Data Terra'*[74] which offers easy access to ready-to-use environmental data and federates scientific expertise on a national scale.

As CLMS and other EU services are recent systems, scientists often turn to a diverse range of international satellite-derived products, not limited to European sources, to supplement the CLMS data. For instance, EU scientists utilize products from the US National Aeronautics and Space

---

[64] Kikiras, P., & Drakoulis, D. (2003). The European Approach to Augmented Satellite Based Positioning Systems and their Application in Precision Faming. *Proc. Int. Symposium at Volos, Greece*, 7-9 November 2003. (https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=7331ad7f3c41214a1b2cfdfb0720d67368a39dad)

[65] Perez-Ruiz, M., Upadhyaya, S. K., Perez-Ruiz, M., & Upadhyaya, S. K. (2012). GNSS in Precision Agricultural Operations. In *New Approach of Indoor and Outdoor Localization Systems*. IntechOpen. (https://doi.org/10.5772/50448)

[66] Radočaj, D., Plaščak, I., & Jurišić, M. (2023). Global Navigation Satellite Systems as State-of-the-Art Solutions in Precision Agriculture: A Review of Studies Indexed in the Web of Science. *Agriculture*, *13*(7), Article 7. (https://doi.org/10.3390/agriculture13071417)

[67] Darrozes, J., Roussel, N., & Zribi, M. (2016). 7 - The Reflected Global Navigation Satellite System (GNSS-R): From Theory to Practice. In N. Baghdadi & M. Zribi (Eds.), *Microwave Remote Sensing of Land Surface* (pp. 303–355). Elsevier. (https://doi.org/10.1016/B978-1-78548-159-8.50007-4)

[68] Egido, A., Ruffini, G., Caparrini, M., Martin, C., Farres, E., & Banque, X. (2008). *Soil Moisture Monitorization Using GNSS Reflected Signals* (arXiv:0805.1881). arXiv. (https://doi.org/10.48550/arXiv.0805.1881)

[69] EUSPA. (n.d.-a). *EGNOS | EU Agency for the Space Programme*. Retrieved May 13, 2024, (from https://www.euspa.europa.eu/eu-space-programme/egnos)

[70] Uribeetxebarria, A., Arnó, J., Escolà, A., & Martínez-Casasnovas, J. A. (2018). Apparent electrical conductivity and multivariate analysis of soil properties to assess soil constraints in orchards affected by previous parcelling. *Geoderma*, *319*, 185–193.(https://doi.org/10.1016/j.geoderma.2018.01.008)

[71] Vázquez, J., Lacarra, E., Sánchez, M. A., Rioja, J., & Bruzual, J. (2017). *EDAS (EGNOS Data Access Service): Differential GPS corrections Performance Test with State-of-the-art Precision Agriculture System*. 1988–1998. (https://doi.org/10.33012/2017.15365)

[72] ESA. (n.d.-a). *GEOSAT-2 Spain Coverage 2022 collection open to users—Earth Online*. Retrieved May 15, 2024, (from https://earth.esa.int/eogateway/news/geosat-2-spain-coverage-2022-collection-open-to-users)

[73] *EnMAP*. (n.d.). Retrieved May 15, 2024 (from https://www.enmap.org/)

[74] https://www.data-terra.org

Administration (NASA), the Japan Aerospace Exploration Agency (JAXA) (e.g., ALOS products), and the Indian Space Research Organisation (ISRO) (e.g., ISR Missions) (see subsection **V.5.**).

In the concrete example developed as an illustration for this work (i.e., the estimation of water erosion in a French region based on the Revised Universal Soil Loss Equation (RUSLE)), we will alternatively use data accessible by CLMS or data with a higher spatial resolution and revisit frequency accessible by Théia.
Moreover, our soil studies are fortified by a range of auxiliary data, such as the French graphic parcel register, a highly reliable source that can be effectively utilized as a reference in soil analysis[75].

IV.5. The current use of satellite-based Earth Observation in the dashboard of the EUSO

The JRC representative involved in Task 5.2 was asked to fill in a table on the use of satellite data in estimating the soil degradation indicators accessible in the European Union Soil Observatory (EUSO) dashboard (https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/).
The concerned indicators deal with (i) soil erosion (water erosion, wind erosion, harvest erosion, tillage erosion, post-fire erosion), (ii) soil pollution (copper, mercury, zinc), (iii) soil nutrients (nitrogen surplus, phosphorus deficiency, phosphorus excess), (iv) loss of soil organic carbon (distance to maximum soil organic carbon (SOC) level), (v) loss of soil biodiversity (potential threat to biological functions), (vi) soil compaction (susceptibility to soil compaction), (vii) soil salinisation (secondary salinisation risk), (viii) loss of organic soils (peatland degradation risk), and (ix) soil consumption (soil sealing).
For each of these indicators, it was asked whether the dashboard uses services giving access to EO products (CLMS, Galileo/EGNOS or others). And for indicators estimated from EO data (by satellite, UAV or airborne sensors), it was asked to specify the sensor(s) used to obtain the product, the ancillary data (i.e., not derived from satellite Earth observation) used simultaneously, as well as the spatial resolution and current revisit frequency.

IV.6. An example: estimating diffuse water erosion using RUSLE model

Since the 20th century, several policies in relation to the reduction of soil degradations have been developed at the EU level (e.g., Common Agricultural Policy[76]), and the standardization of methodologies has become imperative for the identification, evaluation, prediction, and eventual prevention of soil erosion. Various models have been developed to address soil water erosion, such

[75] *RPG | Géoservices*. (n.d.). Retrieved May 15, 2024 (from https://geoservices.ign.fr/rpg)
[76] *Common agricultural policy—European Commission*. (n.d.). Retrieved May 24, 2024, from https://agriculture.ec.europa.eu/common-agricultural-policy_en

as the Revised Universal Soil Loss Equation (RUSLE)[77], the G2 erosion model[78], PESERA[79], and MESALES[80]. In addition to these models, remote sensing has been increasingly utilized.

In this sub-section, we delve into the RUSLE model, a widely recognized and extensively used tool to assess soil water erosion, notably in the dashboard of the EUSO[81]. We use it as an example to illustrate the possibilities of using EO products and other more "conventional" data (e.g. meteorological data, soil type, topographical data) to indirectly estimate soil water erosion, but also to identify some limitations to these practices. Our two objectives were:

- To reproduce the JRC's approach[82] by way of example for subsequent workshops (see sub-sections **IV.7** and **V.7**), to estimate the water erosion indicator over European MS for a small region (the surroundings of Dijon, Burgundy, France), but in 2018 for which we had fairly complete data sets;
- To assess its operational character according to some of the criteria listed in section III (relevance, applicability, reliability, objectivity, operationality, interpretability, and accessibility) with regard to the influence of the source of data and their spatial resolution, influence of the explicit non-accounting for the time dimension, etc..

The results were visualized in the form of maps.

Our study area, around the city of Dijon, is situated far inland in north-eastern France, in the department of Côte-d'Or and the region of Burgundy (**Figure 1**). It is located at the centre of a plain drained by two converging small rivers and covers a land area of 40.41 km^2.

The city's topography varies on the west and east sides. The plateau on the west side (elevation ranging from 350 to 500 meters) is dotted with mounds and valleys formed by the river running in the middle of the plateau. Western Dijon, located on the plain of Saône (elevation ranging from 170 to 240 meters), presents a relatively gentle topography despite a few hills. The land cover is characterized by urban construction, mainly in the centre, agricultural lands in the west, and various forms of vegetation (including forests, shrubs, and grasslands) in the east.

[77] Renard, K. G., Foster, G. R., Weesies, G. A., & Porter, J. P. (1991). RUSLE: Revised universal soil loss equation. Journal of Soil and Water Conservation, 46(1), 30–33. (https://www.tucson.ars.ag.gov/unit/publications/pdffiles/775.pdf)

[78] Karydas, C. G., & Panagos, P. (2018). The G2 erosion model: An algorithm for month-time step assessments. *Environmental Research*, *161*, 256–267. (https://doi.org/10.1016/j.envres.2017.11.010)

[79] Kirkby, M. J., Irvine, B. J., Jones, R. J. A., Govers, G., & Team, P. (2008). The PESERA coarse scale erosion model for Europe. I. – Model rationale and implementation. *European Journal of Soil Science*, *59*(6), 1293–1306. (https://doi.org/10.1111/j.1365-2389.2008.01072.x)

[80] Hessel, R., Daroussin, J., Verzandvoort, S., & Walvoort, D. (2014). Evaluation of two different soil databases to assess soil erosion sensitivity with MESALES for three areas in Europe and Morocco. *CATENA*, *118*, 234–247. (https://doi.org/10.1016/j.catena.2014.01.012)

[81] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

[82] Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., Alewell, .C. 2015. The new assessment of soil loss by water erosion in Europe. Environmental Science & Policy. 54: 438-447. (https://doi.org/10.1016/j.envsci.2015.08.012)

Besides the various reliefs and landscapes, the city of Dijon was chosen as our study area because numerous studies and soil ground measurements have been conducted in the area and were easily accessible thanks to our scientific colleagues. Additionally, these studies have provided valuable data and knowledge about the area, making it a suitable location for our research.

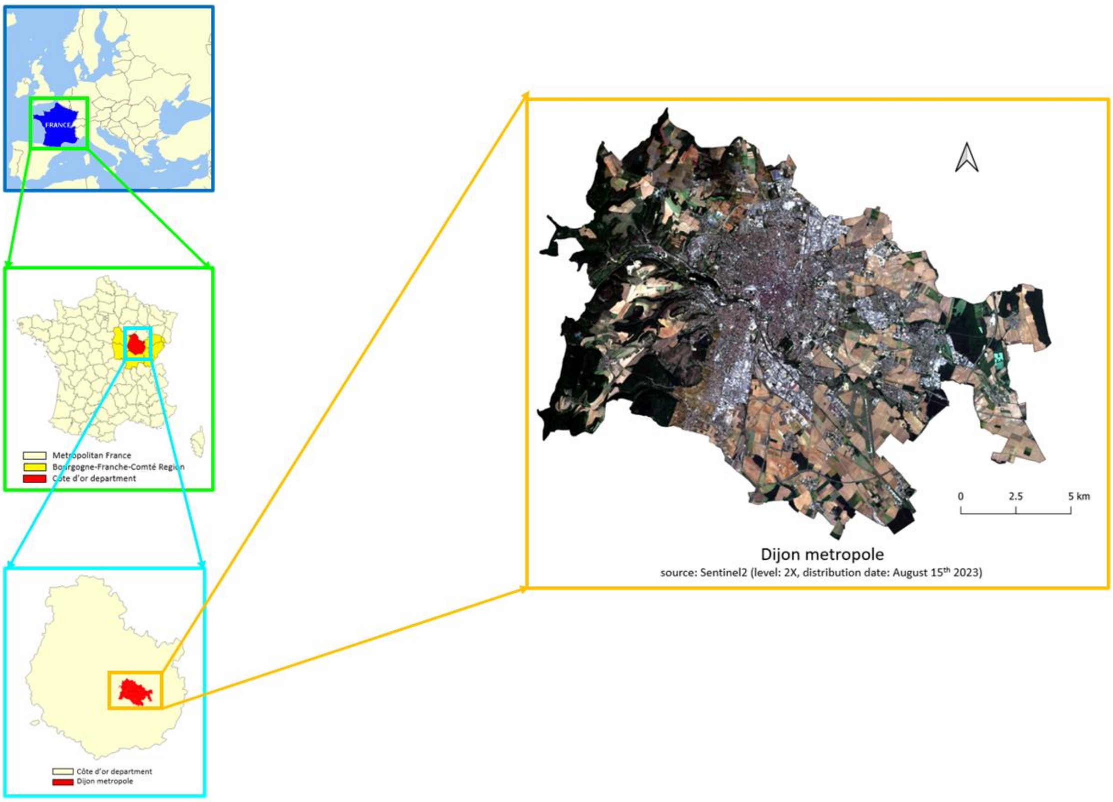


Figure 1: The geographical location of the study area, the city of Dijon

RUSLE is an upgrade of the Universal Soil Loss Equation (USLE) that combines several major ecosystem variables (e.g., climate, soil, topography, and land use). The RUSLE model expresses the average annual soil loss A (t ha^{-1} $year^{-1}$) as the product of 5 factors (i.e., implicitly assuming their independence) according to the following equation:

$$A = R \times K \times LS \times C \times P$$

where R is the long-term average of rain erosivity ($MJ.mm^{-1}.ha^{-1}.h^{-1}.year^{-1}$), K the soil erodibility ($t.h.MJ^{-1}.mm^{-1}$), LS the product of slope length and slope steepness (%), C is an indicator of the cover type and status and management practices (dimensionless), and P the conservation support practices (dimensionless). More precisely:

- R quantifies the influence of precipitation on the amount and rate of runoff factor and gives the combined effect of the duration, magnitude, and intensity of each rainfall event (i.e., amount, kinetic energy and maximum 30 min intensity)[83] [84] [85];

- K refers to the susceptibility of a soil to erode, which is related directly to soil properties such as organic matter content, soil texture, soil structure and permeability[86] [87] [88];
- LS combines slope length and slope angle measurements to describe the effect of topography on soil erosion[89];
- C quantifies the cumulative effects of land degradation caused by agricultural and management practices, and vegetation cover[90] [91] [92]; and
- P explains how conservation practices, and strategies (e.g., contour farming, strip cropping, terracing, and subsurface drainage) reduce runoff erosion potential by affecting drainage patterns, run-off concentration, run-off velocity, and hydraulic forces exerted by run-off on soil surfaces[93] [94].

---

[83] Brown, L. C., & Foster, G. R. (1987). Storm erosivity using idealized intensity distributions. *Transactions of the American Society of Agricultural Engineers*, *30*(2), 379–386. Scopus.

[84] Renard, K. G., & Freimund, J. R. (1994). Using monthly precipitation data to estimate the *R*-factor in the revised USLE. *Journal of Hydrology*, *157*(1), 287–306. (https://doi.org/10.1016/0022-1694(94)90110-4)

[85] Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadić, M. P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Beguería, S., & Alewell, C. (2015). Rainfall erosivity in Europe. *Science of The Total Environment*, *511*, 801–814. (https://doi.org/10.1016/j.scitotenv.2015.01.008)

[86] Panagos, P., Meusburger, K., Ballabio, C., Borrelli, P., & Alewell, C. (2014). Soil erodibility in Europe: A high-resolution dataset based on LUCAS. *Science of The Total Environment*, *479–480*, 189–200. (https://doi.org/10.1016/j.scitotenv.2014.02.010)

[87] Wang, B., Zheng, F., & Guan, Y. (2016). Improved USLE-*K* factor prediction: A case study on water erosion areas in China. *International Soil and Water Conservation Research*, *4*(3), 168–176. (https://doi.org/10.1016/j.iswcr.2016.08.003)

[88] Ghosal, K., & Das Bhattacharya, S. (2020). A Review of RUSLE Model. *Journal of the Indian Society of Remote Sensing*, *48*(4), 689–707. (https://doi.org/10.1007/s12524-019-01097-0)

[89] Panagos, P., Borrelli, P., & Meusburger, K. (2015). A New European Slope Length and Steepness Factor (LS-Factor) for Modeling Soil Erosion by Water. *Geosciences*, *2015*, 117–126. (https://doi.org/10.3390/geosciences5020117)

[90] Durigon, V. L., Carvalho, D. F., Antunes, M. A. H., Oliveira, P. T. S., & Fernandes, M. M. (2014). NDVI time series for monitoring RUSLE cover management factor in a tropical watershed. *International Journal of Remote Sensing*, *35*(2), 441–453. (https://doi.org/10.1080/01431161.2013.871081)

[91] Tanyaş, H., Kolat, Ç., & Süzen, M. L. (2015). A new approach to estimate cover-management factor of RUSLE and validation of RUSLE model in the watershed of Kartalkaya Dam. *Journal of Hydrology*, *528*, 584–598. (https://doi.org/10.1016/j.jhydrol.2015.06.048)

[92] Vatandaşlar, C., & Yavuz, M. (2017). Modeling cover management factor of RUSLE using very high-resolution satellite imagery in a semiarid watershed. *Environmental Earth Sciences*, *76*(2), 65. (https://doi.org/10.1007/s12665-017-6388-0)

[93] Renard, K. G., Foster, G. R., Weesies, G. A., & Porter, J. P. (1991). RUSLE: Revised universal soil loss equation. *Journal of Soil and Water Conservation*, *46*(1), 30–33.

[94] Panagos, P., Borrelli, P., Meusburger, K., van der Zanden, E. H., Poesen, J., & Alewell, C. (2015). Modelling the effect of support practices (*P*-factor) on the reduction of soil erosion by water at European scale. *Environmental Science & Policy*, *51*, 23–34. (https://doi.org/10.1016/j.envsci.2015.03.012)

Factor	Definition	Unit	Equation	Subfactors	Source
R	long-term average of rain erosivity	$MJ\,mm\,ha^{-1}\,h^{-1}\,yr^{-1}$	$R = \frac{1}{n}\sum_{j=1}^{n}\sum_{k=1}^{mj}(EI_{30})_k$	R = average annual rainfall erosivity N = the number of years covered by the data records Mj = the number of erosive events of a given year j EI_{30} = the rainfall erosivity index of a single event k	Brown & Foster, 1987
K	Soil erodibility parameter	$t\,ha\,h\,ha^{-1}\,MJ^{-1}\,mm^{-1}$	$K = \left[\left(2.1 \times 10^{-4}\,M^{1.14}(12-OM) + 3.25(s-2) + 2.5(p-3)\right)/100\right] * 0.1317$	K = Soil erodibility M =the textural factor with M = (m_{silt} + m_{vfs}) ∗ (100 − m_c) m_c = clay fraction content (<0.002 mm) m_{silt} = silt fraction content (0.002–0.05 mm) m_{vfs} = very fine sand fraction content (0.05–0.1 mm) OM = the organic matter content *s* = the soil structure class p = the permeability class	Wischmeier & Smith, 1978 Renard, 1997
LS	Slope length and slope steepness	Dimensionless	$S = 10.8 \times \sin\Theta + 0.03$, where slope gradient < 0.09 $S = 16.8 \times \sin\Theta - 0.5$, where slope gradient ≥ 0.09 $L = (\frac{\lambda}{22.13})^m$	S = slope length L = slope steepness Θ = the gradient of slope in degrees λ = the slope length (in meters) m = 0.5 for slopes steeper than 5% 0.4 for slopes between 3%–4% 0.3 for slopes between 1%–3% 0.2 for slopes less than 1%.	Renard, 1997
C	Cover and management practices	Non-dimensionless	C = C_{arable} x fraction of arable land + $C_{nonarable}$ X fraction of non-arable land • C_{arable} = C_{crop} X $C_{management}$ • $C_{nonarable}$ = Min ($C_{landuse}$) + Range ($C_{landuse}$) X (1-F_{cover})	C_{arable} = C factor estimation for arable lands $C_{nonarable}$ = C factor estimation for non-arable lands C_{crop} = C-factor based on the crop composition of an agricultural area $C_{management}$ = Quantification of the influence of management practices $C_{landuse}$ = Land-cover type F_{cover} = % of soil covered by any type of vegetation	• C_{arable}: Based on numerous literature reviews and experimental data • $C_{nonarable}$: de Asis & Omasa, 2007
P	Conservation support practices	Non-dimensionless	P = P_c X P_{sw} X P_{gm}	P_c = the contouring sub-factor for a given slope of a field P_{sw} = the stone walls sedimentation sub-factor P_{gm} = grass margins sub-factor	Blanco-Canqui & Lal, 2010 López-Vicente & Navas, 2009

Table 3: Equations used in RUSLE15 factors estimation[95].

[95] Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., & Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy*, *54*, 438–447. (https://doi.org/10.1016/j.envsci.2015.08.012)

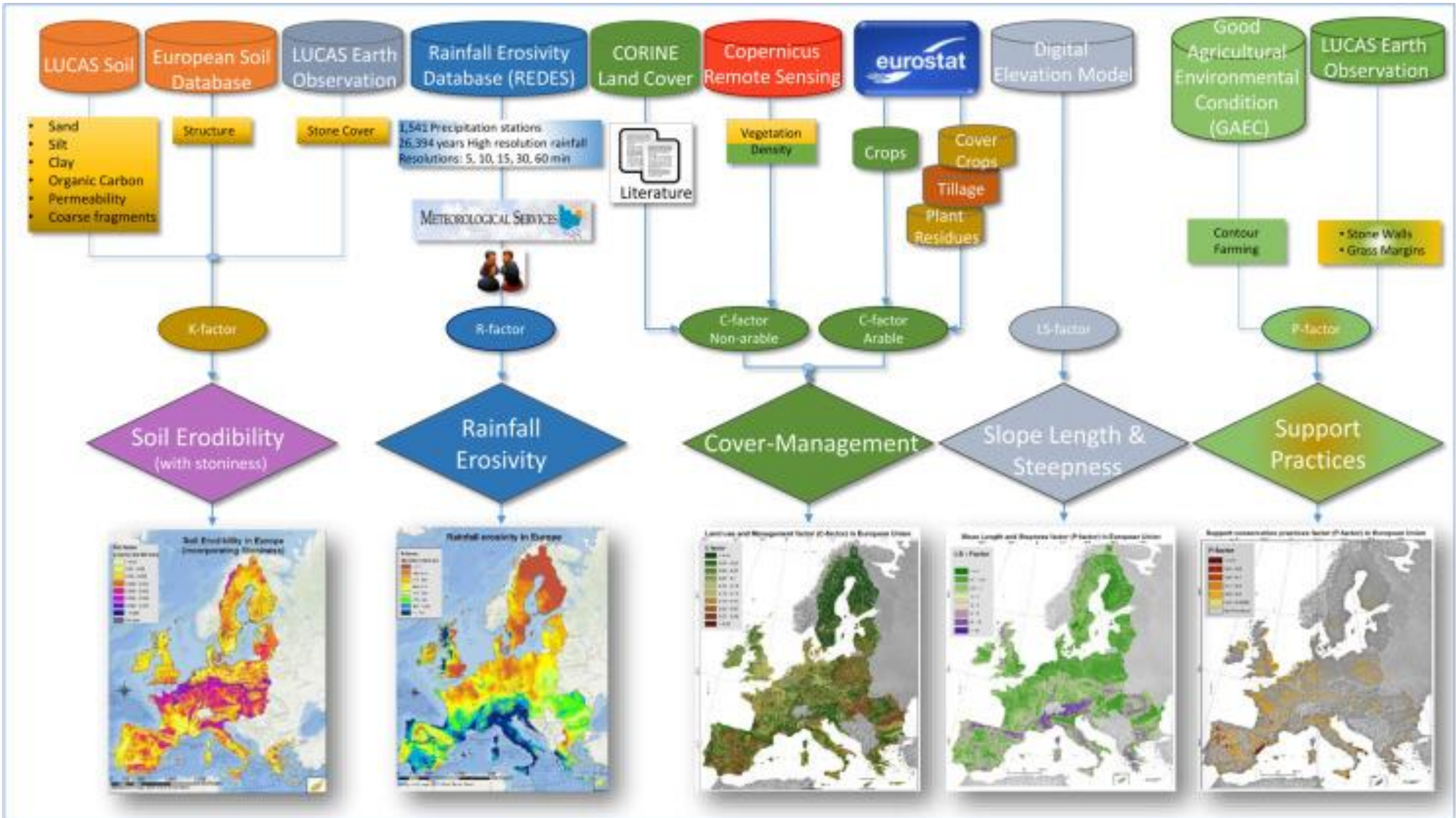


Figure 2: Input datasets uses for the estimation for soil loss factors for Europe in RUSLE2015 conducted by P.Panagos *et al.* (2015)[96].

[96] Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., & Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy*, *54*, 438–447. (https://doi.org/10.1016/j.envsci.2015.08.012)

RUSLE is an empirical model, and various methods or equations were developed by researchers worldwide to calculate the five factors in order to adapt them to different areas (e.g., tropical forest temporal construction site, taiga)[97]. At the EU level, the JRC applied the equations provided in **Table 3**. It is worth noting that one of the most practical advantages of the RUSLE model is that it can use data from free-access databases, which allows each country to easily replicate it.

Estimating soil losses due to water erosion therefore requires the ability to work with suitable spatial and temporal resolutions. The RUSLE input data requirements are specific to each factor[98]. R, K and LS factors characterise a context (climate, soil, landscape, etc.) and require the use of quantitative data at appropriate spatial resolution; and R, C and P factors require data with high temporal resolution. Generally, the leading R factor input data come from climatic databases containing information on precipitation amount and intensity (usually 30-minutely or hourly) recorded by a meteorological station[99] [100]. The input data of K-factor estimation can be a soil map derived from some soil ground samples, including diverse soil characteristics (e.g., soil properties, soil structure, soil texture) of the study area. The traditional procedure to obtain the LS factor consists in compute both slope length and slope steepness with the field measurement; however, thanks to GIS technology, topography data are mainly generated using Digital Elevation Models (DEM) that can be obtained from remote sensing data. Since the C and the P factors are user-defined factors, their input data varies a lot according to the definition and utility given by users, as well as the available information. The C factor calculation frequently uses crop datasets including agricultural management practices and land Use / Land Cover (LULC) data derived from remote sensing products as input data. Similarly to the C factor, the P factor can be estimated based on LULC maps. At the time of the last soil water erosion assessment conducted by the Joint Research Centre (JRC), the factors were estimated with the most updated and freely available datasets at the European scale (**Figure 2**). Although the JRC RUSLE 2015 input data (**Figure 2**) may be suitable for studies at the European scale, their coarse spatial resolution makes them unsuitable to get sufficiently accurate water erosion maps to evaluate erosion risks for small areas.

Therefore, we have compared in this study:

- The JRC's estimates for 2015 of the R, K, LS and C factors, as well as the resulting water erosion A, taking into account the value of the P factor used by the JRC (referred to as **RUSLE-2015** in the remainder of this report) (see **Table 4** and **Figure 2**);
- Our estimates for 2018 of the R, K, LS and C factors, as well as the resulting water erosion A, using the same methodology, but French national data with higher accuracy (including spatial, temporal and ground information), and taking into account the value of the P factor used by

---

[97] Benavidez, R., Jackson, B., Maxwell, D., & Norton, K. (2018). A review of the (Revised) Universal Soil Loss Equation ((R)USLE): With a view to increasing its global applicability and improving soil loss estimates. *Hydrology and Earth System Sciences*, *22*(11), 6059–6086. (https://doi.org/10.5194/hess-22-6059-2018)

[98] Kumar, M., Sahu, A. P., Sahoo, N., Dash, S. S., Raul, S. K., & Panigrahi, B. (2022). Global-scale application of the RUSLE model: A comprehensive review. *Hydrological Sciences Journal*, *67*(5), 806–830. (https://doi.org/10.1080/02626667.2021.2020277)

[99] Renard, K. G., & Ferreira, V. A. (1993). RUSLE Model Description and Database Sensitivity. *Journal of Environmental Quality*, *22*(3), 458–466. (https://doi.org/10.2134/jeq1993.00472425002200030009x)

[100] Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadić, M. P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Beguería, S., & Alewell, C. (2015). Rainfall erosivity in Europe. *Science of The Total Environment*, *511*, 801–814. (https://doi.org/10.1016/j.scitotenv.2015.01.008)

the JRC (referred to as **RUSLE-2018** in the remainder of this report (see **Table 4** and **Figure 3**). Due to a lack of time for a more complete calculation and their complexity that would have required additional resource, and considering that the support practices in the study area were relatively homogeneous, as indicated by JRC RUSLE-2015, the 2015 JRC P factor was applied in RUSLE-2018.
Before making this comparison, we checked our implementation by benchmarking our computations of the LS and C factors with the results obtained by JRC for year 2015 (positive conclusion). Indeed, for these two factors only, we were able to access exactly the same input data. In contrast, we were unable to recalculate the R and K factors for the same year, 2015, as we did not have access to the precipitation data used by the JRC, and the spatial resolution of the LUCAS soil database was not suited to our study area (a single sample on the outskirts of the city of Dijon).

Factor	Définition	JRC RUSLE-2015 Input data	PREPSOIL Task 5.2 Input data	
			2015	RUSLE-2018
R	Rain erosivity	Météo France	-	COMEPHORE 2018 1 km
K	Soil erodibility	LUCAS ESDAC	-	DoneSol
LS	Slope length and steepness	EU_DEM 25 m	EU_DEM 25 m	RGEALTL 1 m
C	Cover and management	CORINE Land Cover 100 m FCover Eurostat (NUTS2)	CORINE Land Cover 100 m FCover 300 m Eurostat (NUTS2)	OSO 10 m FCover 10 m Eurostat (NUTS2)
P	Support practices	LUCAS	LUCAS	LUCAS

Table 4: Sources of input data used by the JRC for 2015 (RUSLE-2015) and in this study for 2018 Our two studies (RUSLE-2018).

Note that in our study (RUSLE-2018):

- The R factor was generated directly from COMEPHORE, an hourly reanalysis of precipitation with high spatial resolution (1 km) using merged radar and rain gauge data from Météo-France for mainland France;
- The K factor was computed from the French national database DoneSol[101] managed by the French *Groupement d'Intérêt Scientifique Sol* (GIS Sol). We took the arithmetic mean of the soil measured values (e.g., soil properties, soil structure) from each Soil Type Units (STU) to generate the values of the Soil Mapping Unit (SMU) to which they belonged, while the area-weighted average of STU values would have produced slightly different results (lower that 10% relative variation). Additionally, DoneSol does not provide sufficient soil structure data to compute the subfactor s of factor K, and s was set to 2;

[101] Emmanuel Grolleau, Lionel Bargeot, Ahmed Chafchafi, Raymond Hardy, José Doux, et al.. Le système d'information national sur les sols: DONESOL et les outils associés. Étude et Gestion des Sols, 2004, 11 (3), pp.255-269. ⟨hal-02681867⟩

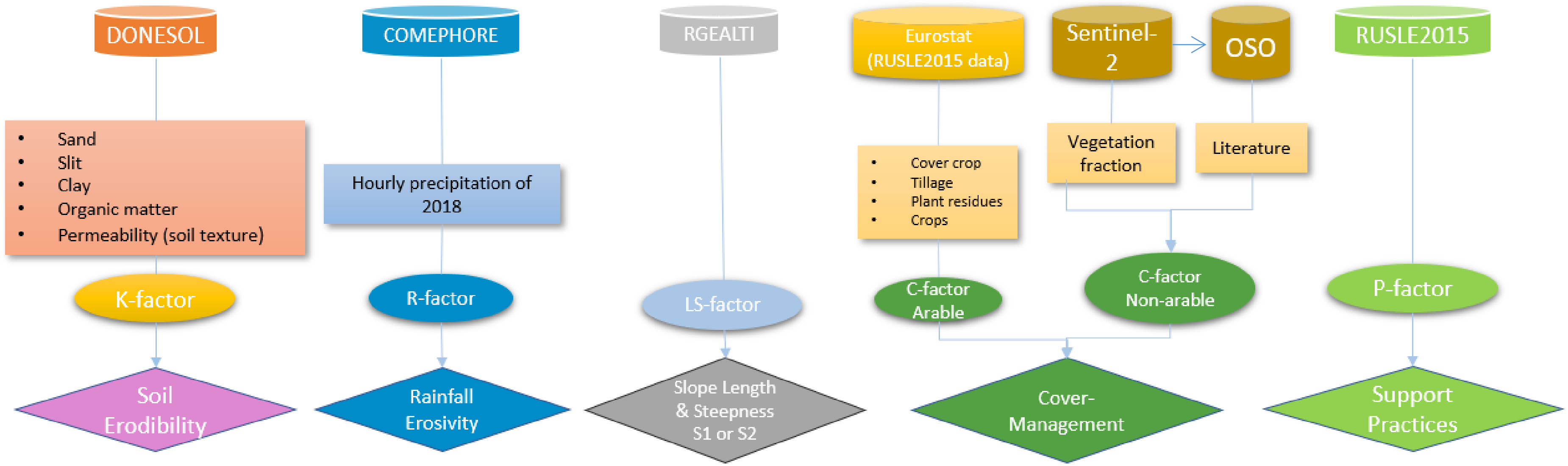


Figure 3: Input datasets for the estimation of water erosion soil loss factors in the RUSLE-2018 model (this study)

- The LS factor was computed using the RGEALTI data (1 m spatial resolution) which is the French reference elaborated from airborne LiDAR data by the French *Institut National de l'Information Géographique et Forestière* (IGN);
- The C factor was computed from the French OSO annual Land cover product delivered from THEIA at high spatial resolution (10 m) which has no equal in terms of spatial and temporal (e.g., update) frequency. The vegetation fractional cover was estimated from Sentinel-2 satellite image (10 m spatial resolution) using the SNAP algorithm developed at INRAE[102]. It is worth noting that the arable land value in the C factor from JRC RUSLE-2015 was directly adopted to generate the RUSLE-2018 since the original database no longer exists and has yet to be updated since 2015.

The final map is presented at 10 m spatial resolution.

IV.7. Obstacles to greater use of EO and measures to reduce them; workshops and virtual discussion group[103]

Four on-line workshops were organized, one for each of the countries participating in this task (with the exceptions of The Netherlands and Sweden), with the following two objectives:

- With regard to the needs of stakeholders (spatial resolution, revisit frequency, accuracy, etc.), identify the bottlenecks (scientific, technological, technical, skills, etc.) to greater use of satellite Earth Observations (EO) and CLMS and/or Galileo/EGNOS products for soil monitoring;
- Propose measures to reduce/minimise these difficulties, ranking them successively and subjectively (i) according to their supposed impact on bottlenecks, and (ii) according to how easy – or even expensive – they are to implement.

The targeted stakeholders for these workshops included scientists, public sector stakeholders including politicians, people from the private sector and people from non-governmental organisations (NGOs: associations, professional branch union, etc.), but the workshops remained open to other categories of participants. Participants were first invited to register online for each country, specifying their identity (surname/first name) and their professional status (stakeholder category, employer). As part of their registration, they were invited to download the text of an informed consent agreement detailing what would be done with their personal data, before this personal data is ultimately destroyed so that only anonymized data could be kept for analysis purposes and shared at a later date. All the workshops lasted 1h30 and included:

- An introductory presentation in a large group, based on a slide show common to all workshops, except for the language and a few specificities linked to the workshop countries (approx. 0h30, see the English support in **Annex IV**);

[102] https://www.theia-land.fr/en/ceslist/land-cover-sec/ Weiss, M., & Baret , F. (2020). ATBD for S2ToolBox Level 2 products: LAI, FAPAR, FCOVER. Version 2.1. In (p. 60): INRAE

[103] Objective 10 of the PREPSOIL Grant Agreement (Annex I, part B) was to explore the incorporation of Earth Observation (EO) and Citizen Science (CS) observatories data in soil monitoring (WP5). This objective was achieved through Task 5.2 (Earth Observation techniques for Soil Health monitoring) and Task 5.3 (Integrating citizen science). It was monitored via Key Performance Indicators (KPIs), in line with the WP5 workplan and its expected outcomes and impact. Of the 11 workshops and 2 virtual discussion groups (at EU level) to be set up for these 2 tasks, 6 workshops and 1 virtual discussion group concern Task 5.2. The workshops are to be set up by the partners participating in each task, with the exception of JRC. The general framework for the workshops was suggested by INRAE, and discussed at a meeting of the partners involved in this task (March 7, 2024; PPT file in **Annex IV**).

- Discussion in sub-groups bringing together the same types of stakeholders (approx. 0h40) with successively (i) an introduction to the SWOT analysis to be carried out and its customization for the use of satellite EO, (ii) a short period of individual brainstorming, (iii) a period of discussion on each of the 4 boxes of the SWOT analysis, including reconciliations/shifts of ideas, and (iv) a final stage during which each sub-group tries to collectively propose answers to the two objectives of these workshops;
- A final large group session (approx. 0h20), with successively the feedback from the sub-groups, an attempt at synthesis, and a conclusion indicating how the workshops will be used in the weeks and months to come.

Each workshop was summarised in a short report (around 4-6 p.) presenting successively:

- a list of participants (not registrants) at the workshop, with information on each of them provided by themselves;
- A summary of how the workshop went, indicating the difficulties/deviations encountered in relation to the proposed framework and presenting the SWOT analysis of each of the sub-groups (which was the simple reproduction of the SWOT table when tools such as MIRO or Klaxoon were used);
- A summary of the main conclusions drawn by the large group in response to the two workshop objectives.

Note that the earlier mentioned CUP4SOIL project performed a user requirements survey distributed widely along possible stakeholders in Europe, including research, public authority and business, and held a user requirements workshop inviting the same group in Autumn, Winter 2023 and Spring 2024. This included some of the questions touched upon in the abovementioned PREPSOIL workshop and will therefore be briefly discussed in the Results section. The survey and Menti during the workshop only registered type of stakeholder, ensuring anonymised results.

Three of the main conclusions of these workshops were put to anyone wishing to give their opinion *via* a virtual discussion group (forum hosted on the PREPSOIL website); in practice, the three ideas selected to initiate these complementary exchanges were chosen on the basis of their importance (assessed subjectively) and the broad spectrum of themes they made it possible to address.

The forum has been activated on the PREPSOIL website at https://forum.prepsoil.eu/d/12-remote-sensing-to-monitor-soil-health-obstacles. It was advertised through various channels: PREPSOIL channels, EJP-Soil channels, EJP Soil national hubs, country-specific mailing lists (e.g., in France, AFES, RNEST, RMT Sols et Territoires, Theia list, etc.).

As the virtual discussion forum for soil monitoring using earth observations was only activated on 15 June 2024, it is too early to take advantage of the discussions taking place there. We can only point to the recent activity it has generated.

V. Results and discussion

V.1. Mini-review of the literature

The results of the advanced search with Scopus on 8 May 2024 are shown in Annex I. We assume that the 481,142 publications resulting from the following advanced search have identified most of the EO-related publications, bearing in mind however that (i) some of the selected publications may have no connection with EO and (ii) other relevant publications may be missing as their title does not contain any of the selected terms but includes the name of a satellite, sensor or mission:

> **T*ITLE (*** *"earth observation"* ***OR*** *"remote sensing"* ***OR*** *"satellite"* ***OR*** *"airborne"* ***OR*** *"UAV"* ***OR*** *"drone"* ***OR*** *"radar"* ***OR*** *"passive microwave"* ***OR*** *"multispectral"* ***OR*** *"hyperspectral"* ***OR*** *"LiDAR"* ***OR (*** *"gamma*"* ***AND*** *"airborne"* ***))***

The titles of 13.5%, 45.1% and 36.0% of these publications contain terms referring exclusively to remote observation ("Earth observation", "remote sensing"), vectors/platforms ("satellite", "airborne", "UAV", "drone") and sensors ("radar", "passive microwave", "multispectral", "hyperspectral", "LiDAR", "gamma AND airborne"), respectively, without terms belonging to one of the other 2 categories, corresponding to a total of 94.6% of these publications. Publications whose title simultaneously contains at least one item of information about the vector and one about the sensor represent only 3.0% of all publications.

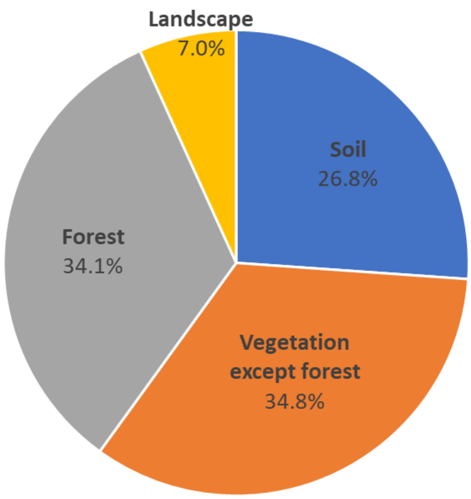


Figure 4: Relative number of publications (in %) using remote sensing to characterise soil, forest, non-forest vegetation and landscape. The number of publications in each of these four subsets was related to the total number of publications dealing with at least one of these objects. The sum of the relative contributions of each of these subsets is only 102.7%, indicating a very low rate of overlap between objects in this bibliometric analysis. (See **Annex I** for advanced search).

4.8% of the publications listed above have either ”soil”, ”crop”, ”vegetation”, ”forest” or ”landscape” in their title, with an almost balanced repartition between publications having in their title one or more terms relating to soil (”soil"), non-forest vegetation (("crop*" OR "vegetation" AND NOT ("forest" OR "landscape")), forest ("forest" AND NOT ("crop*" OR "landscape")) or landscape (i.e. “landscape”), representing 26,8%, 34,8%, 34,1% and 7%, respectively, of the latter publications (**Figure 4**) with a very low overlap between these topics (their sum is only 102,7%).

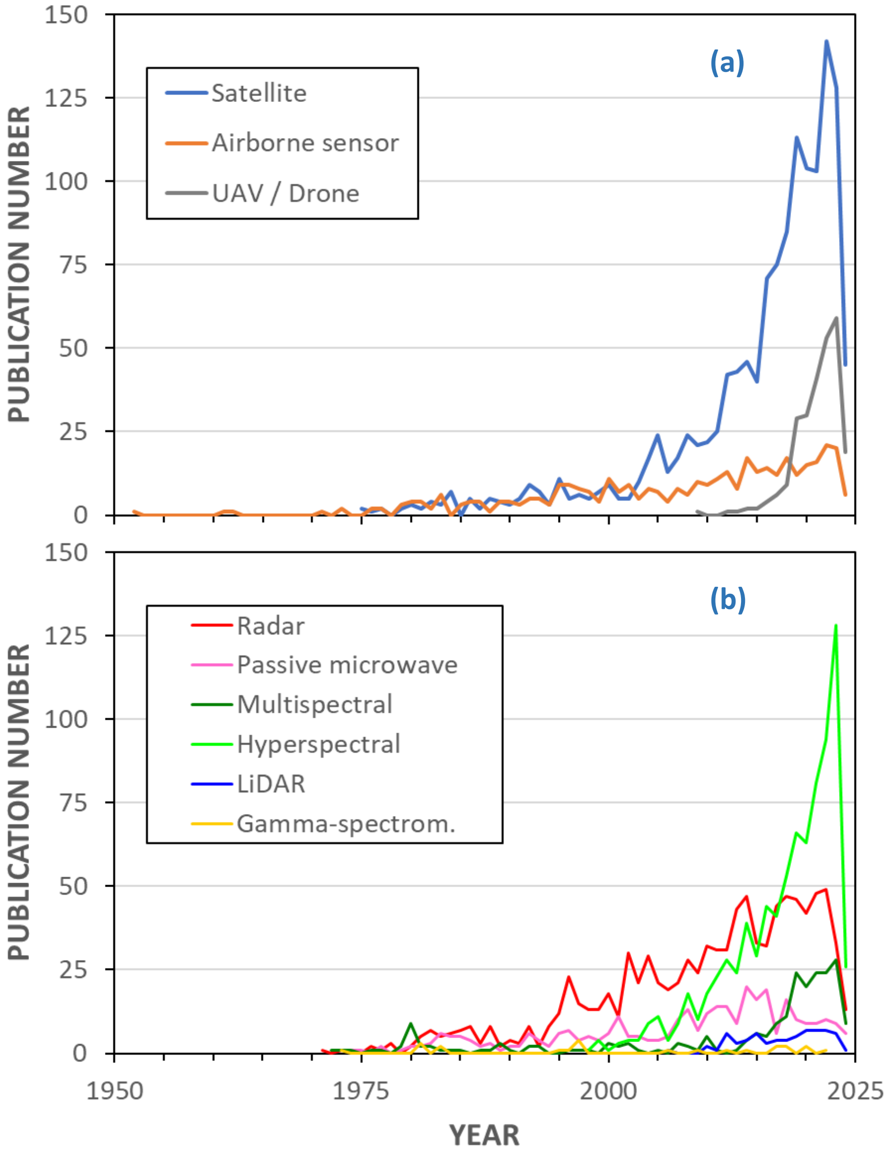


Figure 5: Trends over the years in the number of publications using remote sensing to observe soils **(a)** as a function of the vector used (satellite, airplane or drone) and **(b)** as a function of the type of sensor used (radar, etc.) (See **Annex I** for advanced search and data).

Changes over time in the number of publications with the word ‘soil’ in their title, depending on the vector, clearly show the preponderance of satellite observations and their rapid growth from the

2000s onwards after a slower start in the 1970s with the launch of the first EO satellite in 1972, Landsat 1 by NASA[104]. Then, there is the steady but modest increase in airborne observations, which began in the 1950s, and rapid development of UAV observations from the 2010s onwards (**Figure 5(a)**). Two types of sensors seem to be the main ones used as soon as "soil" issues arise: radar (whose importance has grown steadily since the 1970s) and hyperspectral imagery (whose use began in the 2000s, but whose exponential growth puts it at the top of the list of technologies currently in use certainly due to the recent developments in satellite hyperspectral observations, such as HYPERION in 2000, ENMAP, PRISMA, and CHIME in the near future[105]) (**Figure 5(b)**). Although multispectral satellites are used increasingly for digital soil mapping applications and there is an increase in VNIR sensors in the last few years, also for proximal applications, LiDAR technology certainly has more to offer in other scientific areas than just 'soil' (e.g., to describe agroforestry landscapes, hedgerow, etc.), and has a slow rise in application. The application of gamma-ray-spectrometry remains marginal for soil applications in airborne applications. Whereas the technique has a history of application for mining exploration research, the application in soils is increasing but mainly on proximal platforms such as vehicles. UAV applications are becoming available for very small at the moment. The technique is mostly suitable for soil texture estimations.

Of course, it was not possible to produce an exhaustive synthesis on the subject, which was beyond the scope of PREPSOIL task 5.2 and the time that could be devoted to it. The following analysis is based on a few review articles, major contributions to the subject, often identified during interviews with leading scientists (see sub-section V.2.), and related articles (cited by articles read or citing articles read to detect the most recent work).

A distinction is generally made between **active and passive EO sensors**.

Passive sensors detect the energy reflected (from the solar illumination) or emitted (e.g., surface temperature) by the Earth's surface to be characterised. Each object or surface characteristics can be identified by its unique spectral signature or fingerprint at different wavelengths. Optical imaging systems are the main type of systems onboard remote sensing platforms and can be multispectral or hyperspectral sensors. Multispectral refers to sensors characterized by limited number of rather large spectral bands (few tens of nanometres) covering typically the visual region, the near-infrared and at times the short-wave infrared of the electromagnetic spectrum, the middle-infrared. Multispectral imaging can be used to assess vegetation health[106,107], biomass, greenness, vegetation typology, etc.,

[104] Jovanovic, P. (1987). Remote sensing of environmental factors affecting health. *Advances in Space Research*, *7*(3), 11–18. Scopus.(https://doi.org/10.1016/0273-1177(87)90118-9)

[105] S. -E. Qian, "Hyperspectral Satellites, Evolution, and Development History," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 14, pp. 7032-7056, 2021, (https://doi.org/10.1109/JSTARS.2021.3090256)

[106] Xiao, Q., & McPherson, E. G. (2005). Tree health mapping with multispectral remote sensing data at UC Davis, California. *Urban Ecosystems*, *8*(3), 349–361. (https://doi.org/10.1007/s11252-005-4867-7)

[107] Fraser, B. T., & Congalton, R. G. (2021). Monitoring Fine-Scale Forest Health Using Unmanned Aerial Systems (UAS) Multispectral Models. *Remote Sensing*, *13*(23), Article 23. (https://doi.org/10.3390/rs13234873)

but also ancillary variables or patterns for soil properties like soil moisture, soil texture and SOC[108,109]. It is the most-used sensor system principally in land cover (e.g., vegetation, land surface features and landscape structures) considering that there are more sensors and have been for a long time. The revisit time is faster due to a larger number of satellites in orbit and a larger swath width, which means the area included in a single image is bigger. It is therefore easier to acquire multispectral imagery and their application is quite developed for land cover, but also for other applications. Hyperspectral sensors are similar to multispectral sensors in the sense that they also cover the visible and near infrared part of the spectrum, but they acquire spectral information over much narrower areas, closely-spaced spectral bands, which are often of a few nanometres wide. The high spectral resolution of the hyperspectral system allows it to measure specific absorption peaks specific to substances that are detected such as cellulose, lignin and other building blocks of plants and soil. They can therefore be used to detect, identify and quantify surface materials and properties, and therefore deduce biological and chemical processes[110]. Thanks to these advantages, the use of hyperspectral sensors has increased considerably since 2000 to support research on soil (soil properties/parameters[111,112],

---

[108] Ahmed, Z., & Iqbal, J. (2014). Evaluation of Landsat TM5 Multispectral Data for Automated Mapping of Surface Soil Texture and Organic Matter in GIS. *European Journal of Remote Sensing*, *47*(1), 557–573. (https://doi.org/10.5721/EuJRS20144731)

[109] Hassan-Esfahani, L., Torres-Rua, A., Jensen, A., & McKee, M. (2015). Assessment of Surface Soil Moisture Using High-Resolution Multi-Spectral Imagery and Artificial Neural Networks. *Remote Sensing*, *7*(3), Article 3. (https://doi.org/10.3390/rs70302627)

[110] Malvern Panalytical. (n.d.). *Remote Sensing For Multispectral & Hyperspectral Imagery Analysis*. Retrieved April 29, 2024. (https://www.malvernpanalytical.com/en/products/measurement-type/remote-sensing)

[111] Geng, J., Lv, J., Pei, J., Liao, C., Tan, Q., Wang, T., Fang, H., & Wang, L. (2024). Prediction of soil organic carbon in black soil based on a synergistic scheme from hyperspectral data: Combining fractional-order derivatives and three-dimensional spectral indices. *Computers and Electronics in Agriculture*, *220*. Scopus. (https://doi.org/10.1016/j.compag.2024.108905)

[112] Jiang, R., Sui, Y., Zhang, X., Lin, N., Zheng, X., Li, B., Zhang, L., Li, X., & Yu, H. (2024). Estimation of soil organic carbon by combining hyperspectral and radar remote sensing to reduce coupling [112] Jiang, R., Sui, Y., Zhang, X., Lin, N., Zheng, X., Li, B., Zhang, L., Li, X., & Yu, H. (2024). Estimation of soil organic carbon by combining hyperspectral and radar remote sensing to reduce coupling effects of soil surface moisture and roughness. *Geoderma*, *444*. (https://doi.org/10.1016/j.geoderma.2024.116874)

[112] Wang, Y., Zou, B., Chai, L., Lin, Z., Feng, H., Tang, Y., Tian, R., Tu, Y., Zhang, B., & Zou, H. (2024). Monitoring of soil heavy metals based on hyperspectral remote sensing: A review. *Earth-Science Reviews*, *254*. (https://doi.org/10.1016/j.earscirev.2024.104814)

[112] Cheng, Y.-S., & Zhou, Y. (2021). Research progress and trend of quantitative monitoring of hyperspectral remote sensing for heavy metals in soil. *Zhongguo Youse Jinshu Xuebao/Chinese Journal of Nonferrous Metals*, *31*(11), 3450–3467. (https://doi.org/10.11817/j.ysxb.1004.0609.2021-42086)

[112] Wang, F., Gao, J., & Zha, Y. (2018). Hyperspectral sensing of heavy metals in soil and vegetation: Feasibility and challenges. *ISPRS Journal of Photogrammetry and Remote Sensing*, *136*, 73–84. (https://doi.org/10.1016/j.isprsjprs.2017.12.003)

[112] Liu, Z., Lu, Y., Peng, Y., Zhao, L., Wang, G., & Hu, Y. (2019). Estimation of Soil Heavy Metal Content Using Hyperspectral Data. *Remote Sensing*, *11*(12), Article 12. (https://doi.org/10.3390/rs11121464)

[112] Teke, M., Deveci, H. S., Haliloğlu, O., Gürbüz, S. Z., & Sakarya, U. (2013). A short survey of hyperspectral remote sensing applications in agriculture. *2013 6th International Conference on Recent Advances in Space Te*effects of soil surface moisture and roughness. *Geoderma*, *444*. (https://doi.org/10.1016/j.geoderma.2024.116874)

soil nutrients[113,114], heavy metals[115,116]) and agriculture[117,118] (crop yields[119], plant disease detection[120,121])). As there are not many hyperspectral satellites in orbit and their swath width is generally narrower, the revisit time is much higher and it may be challenging to acquire an image, let alone a time series of images from hyperspectral non-commercial satellites. That said, there is an increase in satellites with hyperspectral sensors and their application for crops and soils is the topic of much research at present. Commercial hyperspectral and multispectral nano-satellites offer more possibilities but are not often affordable or available to all applications. Both multi and hyperspectral sensors typically cover the visible and near infrared part of the spectrum (400-2500 nm) although many focus on the visible and near-infrared (VNIR) only due to technical reasons and the fact that many applications centre around plant (health) detection, for which the interesting features are in the visible and near-infrared part of the spectrum. Many passive satellites cover both the VNIR and one or two thermal infrared bands (e.g., LANDSAT, MODIS, ASTER, ATSR), allowing to assess mainly soil moisture, plant stress possibly and evapotranspiration. On UAVs mostly multispectral sensors are used, also because these sensors are lighter than hyperspectral sensors at present, which means smaller and lighter, and therefore cheaper drones can be used. Hyperspectral and thermal sensors for drones exist but are still more expensive to operate. The use of thermal sensors onboard UAVs is more scarce, mainly due to the difficulty of acquiring well calibrated measurements and the impact of environmental conditions (clouds, wind, moisture, etc.) on the signal. For example, plant stress can

[113] Wang, Y., Zou, B., Chai, L., Lin, Z., Feng, H., Tang, Y., Tian, R., Tu, Y., Zhang, B., & Zou, H. (2024). Monitoring of soil heavy metals based on hyperspectral remote sensing: A review. *Earth-Science Reviews*, *254*. (https://doi.org/10.1016/j.earscirev.2024.104814)

[114] Cheng, Y.-S., & Zhou, Y. (2021). Research progress and trend of quantitative monitoring of hyperspectral remote sensing for heavy metals in soil. *Zhongguo Youse Jinshu Xuebao/Chinese Journal of Nonferrous Metals*, *31*(11), 3450–3467. (https://doi.org/10.11817/j.ysxb.1004.0609.2021-42086)

[115] Wang, F., Gao, J., & Zha, Y. (2018). Hyperspectral sensing of heavy metals in soil and vegetation: Feasibility and challenges. *ISPRS Journal of Photogrammetry and Remote Sensing*, *136*, 73–84. (https://doi.org/10.1016/j.isprsjprs.2017.12.003)

[116] Liu, Z., Lu, Y., Peng, Y., Zhao, L., Wang, G., & Hu, Y. (2019). Estimation of Soil Heavy Metal Content Using Hyperspectral Data. *Remote Sensing*, *11*(12), Article 12. (https://doi.org/10.3390/rs11121464)

[117] Teke, M., Deveci, H. S., Haliloğlu, O., Gürbüz, S. Z., & Sakarya, U. (2013). A short survey of hyperspectral remote sensing applications in agriculture. *2013 6th International Conference on Recent Advances in Space Technologies (RAST)*, 171–176. (https://doi.org/10.1109/RAST.2013.6581194)

[118] Nigam, R., Tripathy, R., Dutta, S., Bhagia, N., Nagori, R., Chandrasekar, K., Kot, R., Bhattacharya, B. K., & Ustin, S. (2019). Crop type discrimination and health assessment using hyperspectral imaging. *Current Science*, *116*(7), 1108–1123.

[119] Yang, W., Nigon, T., Hao, Z., Dias Paiao, G., Fernández, F. G., Mulla, D., & Yang, C. (2021). Estimation of corn yield based on hyperspectral imagery and convolutional neural network. *Computers and Electronics in Agriculture*, *184*, 106092. (https://doi.org/10.1016/j.compag.2021.106092)

[120] Golhani, K., Balasundram, S. K., Vadamalai, G., & Pradhan, B. (2018). A review of neural networks in plant disease detection using hyperspectral data. *Information Processing in Agriculture*, *5*(3), 354–371. (https://doi.org/10.1016/j.inpa.2018.05.002)

[121] Thomas, S., Kuska, M. T., Bohnenkamp, D., Brugger, A., Alisaac, E., Wahabzada, M., Behmann, J., & Mahlein, A.-K. (2018). Benefits of hyperspectral imaging for plant disease detection and plant protection: A technical perspective. *Journal of Plant Diseases and Protection*, *125*(1), 5–20. (https://doi.org/10.1007/s41348-017-0124-6)

result in a higher leaf temperature, visible in the thermal band. But this only works if other influences on surface temperature are stable, such as solar radiance. Both multi- and hyperspectral sensor signals need atmospheric corrections and a translation between the sensor signal and the target soil or crop property is needed to turn the signal into meaningful predictions for soil indicators. This is described more below. Gamma-ray spectrometry is a passive technique that measures the gamma radiation emitted by radioactive isotopes in a given sample or object. When applied to soil, gamma spectrometry helps identify and quantify the presence of three to four radionuclides (^{40}K, ^{238}U, ^{232}Th, ^{137}Cs) present in the Earth's crust naturally or as the result of nuclear testing or disaster and therefore also in soil. The composition and amount of radionuclides depends on the provenance of the geology (where the parent material comes from) and the texture fraction of the soil since it is mostly incorporated or bound in minerals. When calibrating within the same provenance region, typically good (linear) correlations exist between radionuclides and the finer texture fractions. Since the radiation is absorbed and reflected by matter (such as soil and water), the signal measured at the soil surface usually originates from the soil between 0 to 30-60 cm depth, with the contribution to the signal decreasing exponentially with depth. The signal strength and depth contribution are affected by larger changes in water content (as a rule of thumb, 10 % more moisture typically leads to 10% less signal) and bulk density. As such, gamma-ray measurements provide valuable information about soil composition, geological formations, and if a strong correlation exists with e.g., the clay fraction also diffuse environmental contamination, and nutrients. In heavily managed or man-made systems this is of course not necessarily the case (see subsection **V.2.c.**).

Active sensors generate images by illuminating the target area by emitting their own signal, and then recording the reflection or backscatter of that signal from the Earth's surface. The first characteristic of this type of sensor is that it is independent on the natural light conditions and they can operate under almost any weather conditions[122]. The most commonly used active sensors used in soil sciences are radar and LiDAR. Radar, also called active "Radio Detection And Ranging" sensor, sends a sequence of radio wave pulses to the target and then detects the energy reflected toward the sensor. This sensor system operates in the microwave and radio wavelength regions of the electromagnetic spectrum to easily penetrate detected objects[123]. Due to their capacity for all-hour and all-weather imaging[124], radar sensors usually have a better performance in soil moisture and roughness detection[125,126]

[122] Earth Science Data Systems, N. (2020, September 18). *Vegetation Cover | Earthdata*. Earth Science Data Systems, NASA. (https://www.earthdata.nasa.gov/topics/biosphere/vegetation/vegetation-cover)
[123] ESA. (n.d.). *Active sensors*. Retrieved April 29, 2024. (https://www.esa.int/Education/7._Active_sensors)
[124] Prakash, B., & Kumar, S. (2022). Chapter 14—Emerging techniques of polarimetric interferometric synthetic aperture radar for scattering-based characterization. In P. K. Srivastava, D. K. Gupta, T. Islam, D. Han, & R. Prasad (Eds.), *Radar Remote Sensing* (pp. 259–285). Elsevier. (https://doi.org/10.1016/B978-0-12-823457-0.00014-8)
[125] Zribi, M., & Dechambre, M. (2003). A new empirical model to retrieve soil moisture and roughness from C-band radar data. *Remote Sensing of Environment*, *84*(1), 42–52. (https://doi.org/10.1016/S0034-4257(02)00069-X)
[126] Moran, M. S., Peters-Lidard, C. D., Watts, J. M., & McElroy, S. (2004). Estimating soil moisture at the watershed scale with satellite-based radar and land surface models. *Canadian Journal of Remote Sensing*, *30*(5), 805–826. (https://doi.org/10.5589/m04-043)

compared to optical systems[127]. On satellites, radar systems are called SAR, Synthetic Aperture Radar. On the ground, proximal radar sensors are called GPR, Ground Penetrating Radar. In both cases: the higher the frequency used, the higher the depth resolution but the lower the depth penetration. LiDAR uses a laser radar to emit a light pulse that travels to the ground and reflects off the target, like tree branches, then measures the backscattered light and the travel time which can be then converted to elevation[128,129]. Considering its capacity to measure vegetation height and density directly, LiDAR sensors are usually the ideal tool to derive information about vegetation structure such as canopy height[130,131], canopy cover[132,133], forest structure[134,135], individual tree species identification[136,137]. Other systems to consider are Seismic, Magnetics and Electromagnetic Induction. These are however not part of this report since they cannot be operated on a satellite and are less common on airplanes.

EO data can be collected by various platforms being:

- Satellite (also called space-borne) is the most-used platform in environmental sciences (including soil science). It enables large geographical coverage (most often global) by passive sensors, and high revisit frequency with the possibility of assessing data real-time or near-real-time data. Most of the data are made available for free, through space or governmental agencies services, who apply most of the pre-processing steps allowing to assess directly the

[127] Shanker Srivastava, H., & Patel, P. (2022). Chapter 22 - Radar remote sensing of soil moisture: Fundamentals, challenges & way-out. In P. K. Srivastava, D. K. Gupta, T. Islam, D. Han, & R. Prasad (Eds.), *Radar Remote Sensing* (pp. 405–445). Elsevier. (https://doi.org/10.1016/B978-0-12-823457-0.00022-7)
[128] Earth Science Data Systems, N. (2021, January 29). *Active Sensors | Earthdata* [Backgrounder]. Earth Science Data Systems, NASA. https://www.earthdata.nasa.gov/learn/backgrounders/active-sensors
[129] Wasser, L. A. (2024, February 5). *The Basics of LiDAR - Light Detection and Ranging—Remote Sensing | NSF NEON | Open Data to Understand our Ecosystems*. (https://www.neonscience.org/resources/learning-hub/tutorials/lidar-basics)
[130] Hudak, A. T., Lefsky, M. A., Cohen, W. B., & Berterretche, M. (2002). Integration of lidar and Landsat ETM+ data for estimating and mapping forest canopy height. *Remote Sensing of Environment*, *82*(2), 397–416. (https://doi.org/10.1016/S0034-4257(02)00056-1)
[131] Simard, M., Pinto, N., Fisher, J. B., & Baccini, A. (2011). Mapping forest canopy height globally with spaceborne lidar. *Journal of Geophysical Research: Biogeosciences*, *116*(G4). (https://doi.org/10.1029/2011JG001708)
[132] Smith, A. M. S., Falkowski, M. J., Hudak, A. T., Evans, J. S., Robinson, A. P., & Steele, C. M. (2009). A cross-comparison of field, spectral, and lidar estimates of forest canopy cover. *Canadian Journal of Remote Sensing*, *35*(5), 447–459. (https://doi.org/10.5589/m09-038)
[133] Tang, H., Armston, J., Hancock, S., Marselis, S., Goetz, S., & Dubayah, R. (2019). Characterizing global forest canopy cover distribution using spaceborne lidar. *Remote Sensing of Environment*, *231*, 111262. (https://doi.org/10.1016/j.rse.2019.111262)
[134] Dubayah, R. O., & Drake, J. B. (2000). Lidar Remote Sensing for Forestry. *Journal of Forestry*, *98*(6), 44–46. (https://doi.org/10.1093/jof/98.6.44)
[135] van Leeuwen, M., & Nieuwenhuis, M. (2010). Retrieval of forest structural parameters using LiDAR remote sensing. *European Journal of Forest Research*, *129*(4), 749–770. (https://doi.org/10.1007/s10342-010-0381-4)
[136] Michałowska, M., & Rapiński, J. (2021). A Review of Tree Species Classification Based on Airborne LiDAR Data and Applied Classifiers. *Remote Sensing*, *13*(3), Article 3. (https://doi.org/10.3390/rs13030353)
[137] Zhang, C., & Qiu, F. (2012). Mapping Individual Tree Species in an Urban Forest Using Airborne Lidar Data and Hyperspectral Imagery. *Photogrammetric Engineering & Remote Sensing*, *78*(10), 1079–1087. (https://doi.org/10.14358/PERS.78.10.1079)

surface products without atmospheric disturbances. A downside of satellites is that optical sensors cannot penetrate clouds, which are regularly blocking a satellites view of the Earth's surface, especially in more temperate regions. SAR can 'look through' clouds are is therefore regularly used for this purpose. Satellite remote sensing is principally used for large-scale assessment of soil health and degradation[138,139], vegetation and forest health[140,141],soil and agricultural productivity[142,143], precision agriculture[144 145], soil properties and parameters[146 147], soil moisture[148 149], etc. Today, the main satellite products are provided at spatial resolutions from few meters to several kilometres.

- Airborne EO refers to sensors mounted on a manned aircraft, looking down or sideways to obtain images of the Earth surface. Airborne platforms can carry active and passive sensors, and provide high spatial resolution (e.g., less than the metre or more, depending on the flight height

[138] Vågen, T.-G., Winowiecki, L. A., Tondoh, J. E., Desta, L. T., & Gumbricht, T. (2016). Mapping of soil properties and land degradation risk in Africa using MODIS reflectance. *Geoderma*, *263*, 216–225. (https://doi.org/10.1016/j.geoderma.2015.06.023)

[139] Cécillon, L., Barthès, B. G., Gomez, C., Ertlen, D., Genot, V., Hedde, M., Stevens, A., & Brun, J. J. (2009). Assessment and monitoring of soil quality using near-infrared reflectance spectroscopy (NIRS). *European Journal of Soil Science*, *60*(5), 770–784. (https://doi.org/10.1111/j.1365-2389.2009.01178.x)

[140] Eve, M. D., Whitford, W. G., & Havstadt, K. M. (1999). Applying satellite imagery to triage assessment of ecosystem health. *Environmental Monitoring and Assessment*, *54*(3), 205–227. Scopus. (https://doi.org/10.1023/A:1005876220078)

[141] Pause, M., Schweitzer, C., Rosenthal, M., Keuck, V., Bumberger, J., Dietrich, P., Heurich, M., Jung, A., & Lausch, A. (2016). In Situ/Remote Sensing Integration to Assess Forest Health—A Review. *Remote Sensing*, *8*(6), Article 6. (https://doi.org/10.3390/rs8060471)

[142] Kogan, F., Salazar, L., & Roytman, L. (2012). Forecasting crop production using satellite-based vegetation health indices in Kansas, USA. *International Journal of Remote Sensing*, *33*(9), 2798–2814. (https://doi.org/10.1080/01431161.2011.621464)

[143] Sheffield, K., & Morse-McNabb, E. (2015). Using satellite imagery to asses trends in soil and crop productivity across landscapes. *IOP Conference Series: Earth and Environmental Science*, *25*(1), 012013. (https://doi.org/10.1088/1755-1315/25/1/012013)

[144] Murugan, D., Garg, A., & Singh, D. (2017). Development of an Adaptive Approach for Precision Agriculture Monitoring with Drone and Satellite Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *10*(12), 5322–5328. (https://doi.org/10.1109/JSTARS.2017.2746185)

[145] Phang, S. K., Chiang, T. H. A., Happonen, A., & Chang, M. M. L. (2023). From Satellite to UAV-Based Remote Sensing: A Review on Precision Agriculture. *IEEE Access*, *11*, 127057–127076. (https://doi.org/10.1109/ACCESS.2023.3330886)

[146] Agbu, P. A., Fehrenbacher, D. J., & Jansen, I. J. (1990). Soil property relationships with SPOT satellite digital data in east central Illinois. *Soil Science Society of America Journal*, *54*(3), 807–812. (https://doi.org/10.2136/sssaj1990.03615995005400030031x)

[147] Silvero, N. E. Q., Demattê, J. A. M., Vieira, J. D. S., Mello, F. A. D. O., Amorim, M. T. A., Poppiel, R. R., Mendes, W. D. S., & Bonfatti, B. R. (2021). Soil property maps with satellite images at multiple scales and its impact on management and classification. *Geoderma*, *397*.(https://doi.org/10.1016/j.geoderma.2021.115089)

[148] Borodina, I. A., Kizhner, L. I., Bogoslovskiy, N. N., Rudikov, D. S., & Erin, S. I. (2015). *The research of the soil moisture satellite measurements accuracy depending on the underlying surface characteristics*. *9680*. (https://doi.org/10.1117/12.2205655)

[149] Sabadash, V., & Lopushansky, O. (2023). *Satellite monitoring of soil moisture: Applications, technologies and impact on agriculture and ecosystems*. International Conference of Young Professionals "GeoTerrace 2023." (https://doi.org/10.3997/2214-4609.2023510081)

and camera resolution) at the expense of high coverage and continuous monitoring of the Earth's surface. Airborne EO can be used for smaller scale plant health mapping, precision agriculture monitoring[150], small-scale soil properties mapping[151], etc.;

- Afterwards, UAV, also referred to drone, has emerged as the new generation of Airborne, and can be piloted remotely. In addition, UAVs operate on smaller scale due to limited uptime, but can be deployed fast and with great flexibility, allowing to time the measurement to the weather conditions and optimal surface conditions (e.g., bare soil, crop growth stage, etc.). They have the capacity to fly at low altitudes, and slow speeds in all directions to collect exact data. Moreover, UAV has higher safety factors considering that small-size drones can easily access places that are hard or dangerous for humans or vehicles to reach. UAV platform is for example, for forest and vegetation health observation to complement satellite data[152] [153], soil degradation[154] [155] and precision agriculture[156] [157] [158].

Certain vegetation and soil information can be obtained directly from EO images depending on image characteristics (spectral, spatial, radiometric and temporal resolution, etc.). Several EO data can be used as PROXY of surface properties, such as the so-called "spectral indices" (i.e., combination of surface reflectances at two or more wavelengths, intended to highlight a specific characteristic of the

[150] Mulla, D. J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, *114*(4), 358–371. (https://doi.org/10.1016/j.biosystemseng.2012.08.009)

[151] Bindlish, R., Jackson, T. J., Gasiewski, A., Stankov, B., Klein, M., Cosh, M. H., Mladenova, I., Watts, C., Vivoni, E., Lakshmi, V., Bolten, J., & Keefer, T. (2008). Aircraft based soil moisture retrievals under mixed vegetation and topographic conditions. *Remote Sensing of Environment*, *112*(2), 375–390. (https://doi.org/10.1016/j.rse.2007.01.024)

[152] Dash, J. P., Watt, M. S., Pearse, G. D., Heaphy, M., & Dungey, H. S. (2017). Assessing very high resolution UAV imagery for monitoring forest health during a simulated disease outbreak. *ISPRS Journal of Photogrammetry and Remote Sensing*, *131*, 1–14. (https://doi.org/10.1016/j.isprsjprs.2017.07.007)

[153] Ecke, S., Dempewolf, J., Frey, J., Schwaller, A., Endres, E., Klemmt, H.-J., Tiede, D., & Seifert, T. (2022). UAV-Based Forest Health Monitoring: A Systematic Review. *Remote Sensing*, *14*(13), Article 13. (https://doi.org/10.3390/rs14133205)

[154] D'Oleire-Oltmanns, S., Marzolff, I., Peter, K. D., & Ries, J. B. (2012). Unmanned Aerial Vehicle (UAV) for Monitoring Soil Erosion in Morocco. *Remote Sensing*, *4*(11), Article 11. (https://doi.org/10.3390/rs4113390)

[155] Krenz, J., Greenwood, P., & Kuhn, N. J. (2019). Soil Degradation Mapping in Drylands Using Unmanned Aerial Vehicle (UAV) Data. *Soil Systems*, *3*(2), Article 2. (https://doi.org/10.3390/soilsystems3020033)

[156] Sona, G., Passoni, D., Pinto, L., Pagliari, D., Masseroni, D., Ortuani, B., & Facchi, A. (2016). UAV multispetral survey to map soil and crop for precision farming applications. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLI-B1*, 1023–1029. (https://doi.org/10.5194/isprs-archives-XLI-B1-1023-2016)

[157] Tsouros, D. C., Bibi, S., & Sarigiannidis, P. G. (2019). A Review on UAV-Based Applications for Precision Agriculture. *Information*, *10*(11), Article 11. (https://doi.org/10.3390/info10110349)

[158] Radoglou-Grammatikis, P., Sarigiannidis, P., Lagkas, T., & Moscholios, I. (2020). A compilation of UAV applications for precision agriculture. *Computer Networks*, *172*, 107148. (https://doi.org/10.1016/j.comnet.2020.107148)

surface) are commonly used for estimations of vegetation cover[159,160,161], crop stress[162,163,164], such as the NDVI, WDVI, etc. For other surface properties, such as soil moisture and roughness[165,166,167], soil organic carbon[168,169,170], plant pathology[171 172 173], etc. indices have been proposed as well but are not applied in operational applications to our knowledge. These indices are often not calibrated and typically provide an indication of e.g. plant greenness along a relative scale (e.g., 0-1).

Another method for the direct estimation of soil or vegetation characteristics of the Earth surface is the use of the spectral signature of these properties (the specific absorption and reflection of electromagnetic light, or energy due to the chemical composition of the object or surface that is measured) and the spectra measured by the sensor. For those soil properties that have spectral

---

159 Becker, F., & Choudhury, B. J. (1988). Relative sensitivity of normalized difference vegetation Index (NDVI) and microwave polarization difference Index (MPDI) for vegetation and desertification monitoring. *Remote Sensing of Environment*, *24*(2), 297–311. Scopus. (https://doi.org/10.1016/0034-4257(88)90031-4)

160 Shoshany, M. (2000). Satellite remote sensing of natural Mediterranean vegetation: A review within an ecological context. *Progress in Physical Geography*, *24*(2), 153–178. (https://doi.org/10.1191/030913300675148208)

161 Xie, Y., Sha, Z., & Yu, M. (2008). Remote sensing imagery in vegetation mapping: A review. *Journal of Plant Ecology*, *1*(1), 9–23. (https://doi.org/10.1093/jpe/rtm005)

162 Jackson, R. D. (1986). Remote Sensing of Biotic and Abiotic Plant Stress. *Annual Review of Phytopathology*, *24*(Volume 24, 1986), 265–287. (https://doi.org/10.1146/annurev.py.24.090186.001405)

163 Mishra, V., Cruise, J. F., Mecikalski, J. R., Hain, C. R., & Anderson, M. C. (2013). A Remote-Sensing Driven Tool for Estimating Crop Stress and Yields. *Remote Sensing*, *5*(7), Article 7. (https://doi.org/10.3390/rs5073331)

164 Virnodkar, S. S., Pachghare, V. K., Patil, V. C., & Jha, S. K. (2020). Remote sensing and machine learning for crop water stress determination in various crops: A critical review. *Precision Agriculture*, *21*(5), 1121–1155. (https://doi.org/10.1007/s11119-020-09711-9)

165 Schmugge, T. J. (1983). Remote Sensing of Soil Moisture: Recent Advances. *IEEE Transactions on Geoscience and Remote Sensing*, *GE-21*(3), 336–344. (https://doi.org/10.1109/TGRS.1983.350563)

166 Paloscia, S., Pampaloni, P., Chiarantini, L., Coppo, P., Gagliani, S., & Luzi, G. (1993). Multifrequency passive microwave remote sensing of soil moisture and roughness. *International Journal of Remote Sensing*, *14*(3), 467–483. (https://doi.org/10.1080/01431169308904351)

167 Wang, L., & Qu, J. J. (2009). Satellite remote sensing applications for surface soil moisture monitoring: A review. *Frontiers of Earth Science in China*, *3*(2), 237–247. (https://doi.org/10.1007/s11707-009-0023-7)

168 Chen, F., Kissel, D. E., West, L. T., & Adkins, W. (2000). Field-Scale Mapping of Surface Soil Organic Carbon Using Remotely Sensed Imagery. *Soil Science Society of America Journal*, *64*(2), 746–753. (https://doi.org/10.2136/sssaj2000.642746x)

169 Gomez, C., Viscarra Rossel, R. A., & McBratney, A. B. (2008). Soil organic carbon prediction by hyperspectral remote sensing and field vis-NIR spectroscopy: An Australian case study. *Geoderma*, *146*(3), 403–411. (https://doi.org/10.1016/j.geoderma.2008.06.011)

170 Angelopoulou, T., Tziolas, N., Balafoutis, A., Zalidis, G., & Bochtis, D. (2019). Remote Sensing Techniques for Soil Organic Carbon Estimation: A Review. *Remote Sensing*, *11*(6), Article 6. (https://doi.org/10.3390/rs11060676)

171 Nilsson, H.-E. (1995). Remote sensing and image analysis in plant pathology. *Canadian Journal of Plant Pathology*, *17*(2), 154–166. (https://doi.org/10.1080/07060669509500707)

172 Olthof, I., & King, D. J. (2000). Development of a forest health index using multispectral airborne digital camera imagery. *Canadian Journal of Remote Sensing*, *26*(3), 166–176. (https://doi.org/10.1080/07038992.2000.10874767)

173 Zhang, J., Huang, Y., Pu, R., Gonzalez-Moreno, P., Yuan, L., Wu, K., & Huang, W. (2019). Monitoring plant diseases and pests through remote sensing technology: A review. *Computers and Electronics in Agriculture*, *165*, 104943. (https://doi.org/10.1016/j.compag.2019.104943)

signatures that can be measured distinctly by the applied sensor, either multi- or hyperspectral, spectral libraries are used to derive a quantitative or qualitative estimate of the surface characteristics. A soil spectral library is a dataset where the soil properties of a set of samples is measured in the laboratory in the conventional way (wet chemistry) and with a spectrometer. With that library the relation between the soil properties and the spectra is established, and that relation can then be applied to new spectra of unknown soil, in the lab, the field, airborne or from satellites. It is important to have a spectral library that is contains the soil properties to be estimated, covers the range or feature space of the properties, is derived in the same geography/soil types and is of sufficient quality and spectral resolution/comparable to the sensor used to measure the new spectra. Typically, local (subsets of larger) libraries including local samples perform best. And applications in the lab perform better than in the field/outside due to the disturbing effects of moisture, the presence of (dry) vegetation or high salinity and surface roughness on the signal. Also, hyperspectral sensors perform better than multispectral due to their higher spectral information content. For this methodology, calibration samples are always needed and quality and accuracy of results are strongly dependent on the configuration and spectral library used, as well as on the soil property to be predicted. Some properties, like SOC, texture, have distinct peaks in the spectral and therefore perform better, while some others (like P) perform less well.

Most soil properties can only be estimated using advanced algorithms / mathematical tools. Above all, soil properties and soil formation can be estimated using different mathematical models since soil is a function of several factors (e.g., climate, organisms, topography parent material and time)[174], and calculable by knowing these factors. Soil forming factor (the development and properties of soils) estimation was developed by *Jenny* (1941)[175] the landscape-genetic time-integral was developed by *Haase* (1978)[176], weathering function in soil landscape was estimated by *Riebe* et al. (2003)[177], etc.

Several methods exist to indirectly **assess some soil properties at locations where neither *in situ* soil observation nor soil sampling were carried out.** Besides mathematical models, Machine Learning (ML) and Deep Learning (DL) algorithms, like quantile random forests and others, are more frequently used nowadays. These algorithms, using remote sensing and other forming factors related data together with point soil observations for example stemming from soil monitoring campaigns and national soil inventories to generate soil maps, are primarily and widely applied. This methodology, known as Digital Soil Mapping, is the main method used for soil property mapping nowadays, at the global level (e.g., SoilGrids, GSOC), at the continental level (e.g., JRC and EU project maps) and at the national level. In all cases, the strength of the (cor)relation between ancillary data incl. EO imagery

[174] Hornig, W. (2018). Mathematical models for the description of soil genesis. *Journal of Plant Nutrition and Soil Science*, *181*(6), 847–854. (https://doi.org/10.1002/jpln.201800048)

[175] Jenny, H. (1994). *Factors of Soil Formation: A System of Quantitative Pedology*. Courier Corporation.

[176] Haase, G. (1978). Struktur Und Gliederung Der Pedosphaere In Der Regionischen Dimension. *Struktur Und Gliederung Der Pedosphaere In Der Regionischen Dimension*.

[177] Riebe, C. S., Kirchner, J. W., Finkel, R. C. (2003): Long-term rates of chemical weathering and physical erosion from cosmogenic nuclides and geochemical mass balance. Geochim. Cosmochim. Ac. 67, 4411–4427.

and derived products such as DEMs, and the soil property at hand, the availability of reference point data, and the chosen resolution determines the quality and accuracy of the resulting map.
Usually, the SCORPAN-SSPFe (soil spatial prediction function with spatially autocorrelated errors) framework[178,179] Is applied, built on the soil forming factors defined by Jenny (1941)[180], namely:

1. s: for soil, other or previously measured attributes of the soil at a point;
2. c: for climate, climatic properties of the environment at a point;
3. o: for organisms, including land cover and natural vegetation;
4. r: for topography, including terrain attributes and classes;
5. p: for parent material, including lithology;
6. a: for age, the time factor;
7. n: for space, spatial or geographic position.

Environmental covariates may include EO data and other covariates (see sub-section **V.2.d.**).
Due to their capacity to learn from data how soil is distributed in space and time[181], ML methods are used in soil science since the last decade[182], for example in soil health bioindicator assessment[183,184,185] (e.g., soil fauna biomass, soil microbes, and soil organic matter), identifying the type of soil and estimating its properties[186,187], cropland estimation (e.g., yield prediction)[188], etc. ML/DL models

---

[178] McBratney, A. B., Mendonça Santos, M. L., & Minasny, B. (2003). On digital soil mapping. *Geoderma*, *117*(1), 3–52. (https://doi.org/10.1016/S0016-7061(03)00223-4)

[179] Richer-de-Forges, A. C., Chen, Q., Baghdadi, N., Chen, S., Gomez, C., Jacquemoud, S., Martelet, G., Mulder, V. L., Urbina-Salazar, D., Vaudour, E., Weiss, M., Wigneron, J.-P., & Arrouays, D. (2023). Remote Sensing Data for Digital Soil Mapping in French Research—A Review. *Remote Sensing*, *15*(12), (https://doi.org/10.3390/rs15123070)

[180] Jenny, H. (1994). *Factors of Soil Formation: A System of Quantitative Pedology*. Courier Corporation.

[181] Mcbratney, A., Gruijter, J., & Bryce, A. (2018). Pedometrics timeline. *Geoderma*, *338*. (https://doi.org/10.1016/j.geoderma.2018.11.048)

[182] Padarian, J., Minasny, B., & McBratney, A. B. (2020). Machine learning and soil sciences: A review aided by machine learning tools. *SOIL*, *6*(1), 35–52. (https://doi.org/10.5194/soil-6-35-2020)

[183] Ali, I., Greifeneder, F., Stamenkovic, J., Neumann, M., & Notarnicola, C. (2015). Review of Machine Learning Approaches for Biomass and Soil Moisture Retrievals from Remote Sensing Data. *Remote Sensing*, *7*(12), Article 12. (https://doi.org/10.3390/rs71215841)

[184] Odebiri, O., Odindi, J., & Mutanga, O. (2021). Basic and deep learning models in remote sensing of soil organic carbon estimation: A brief review. *International Journal of Applied Earth Observation and Geoinformation*, *102*, 102389. (https://doi.org/10.1016/j.jag.2021.102389)

[185] Wang, L., Cheng, Y., Meftaul, I. M., Luo, F., Kabir, M. A., Doyle, R., Lin, Z., & Naidu, R. (2024). Advancing Soil Health: Challenges and Opportunities in Integrating Digital Imaging, Spectroscopy, and Machine Learning for Bioindicator Analysis. *Analytical Chemistry*. (https://doi.org/10.1021/acs.analchem.3c05311

[186] Khanal, S., Fulton, J., Klopfenstein, A., Douridas, N., & Shearer, S. (2018). Integration of high resolution remotely sensed data and machine learning techniques for spatial prediction of soil properties and corn yield. *Computers and Electronics in Agriculture*, *153*, 213–225. (https://doi.org/10.1016/j.compag.2018.07.016)

[187] Mali, Y., Rathod, V. U., Kulkarni, M. M. S., Mokal, P., Patil, S., Dhamdhere, V., & Birari, D. R. (2023). A Comparative Analysis of Machine Learning Models for Soil Health Prediction and Crop Selection. *International Journal of Intelligent Systems and Applications in Engineering*, *11*(10s), 811-828. (https://www.ijisae.org/index.php/IJISAE/article/view/3335)

[188] Muruganantham, P., Wibowo, S., Grandhi, S., Samrat, N. H., & Islam, N. (2022). A Systematic Literature Review on Crop Yield Prediction with Deep Learning and Remote Sensing. *Remote Sensing*, *14*(9), Article 9. (https://doi.org/10.3390/rs14091990)

require to be trained with a dataset, generated either thanks to measurements (ground and remote sensing signal) or/and model simulations (generated from radiative transfer models). However, due to field constraints (manpower, time for measurement, simplicity of ground measurements), many of these datasets are limited in space, time, environmental conditions, thus limiting the accuracy of the ML/DL model applications over larger extents, other areas or other years. With the proposed EU Directive on Soil Monitoring and Resilience, this data gap is expected to decrease due to more soil monitoring locations and most importantly better harmonization and compilation of existing national and European monitoring systems. inventories and methodologies for this are under further development by EJP SOIL and will need to be continued for the implementation of the Directive.

The soil process modelling approach is also considered by science communities because soil reflectance only captures soil information about the top surface (0-5cm) while soils are 3D objects. Therefore, EO data thus provide limited information on soil properties if used standalone. However, the spatial patterns of EO based soil property maps can also be used as ancillary information to improve the prediction of soil or the soil-vegetation-atmosphere functioning models. These mechanistic-based models may be considered as a comprehensive framework, which may incorporate several covariates, including some derived from EO data (e.g., soil roughness, moisture, and vegetation residues on the topsoil) and others (climate, relief, land cover, parent material, and soil management practices, etc.). EO data may be used with mechanistic-based models for the purposes to improve soil prediction performance, with EO data assimilation: the model can incorporate EO data (e.g., linked with soil moisture, leaf area index (LAI)) using sequential data assimilation[189] [190] [191] [192] [193]. For example, the diagnostic regional modelling approach known as SAFY-CO[194] incorporates soil information derived from high spatial and temporal resolution optical EO data (such as the green area index from SPOT satellites) into a simple crop model in order to simulate daily crop development, the components of net ecosystem CO_2 fluxes, and the annual yields and net ecosystem carbon budget.

[189] Ines, A. V. M., Das, N. N., Hansen, J. W., & Njoku, E. G. (2013). Assimilation of remotely sensed soil moisture and vegetation with a crop simulation model for maize yield prediction. *Remote Sensing of Environment*, *138*, 149–164. (https://doi.org/10.1016/j.rse.2013.07.018)

[190] Prévot, L., Chauki, H., Troufleau, D., Weiss, M., Baret, F., & Brisson, N. (2003). Assimilating optical and radar data into the STICS crop model for wheat. Agronomie, 23, 297-303

[191] Varella, H., Guérif, M., Buis, S., & Beaudoin, N. (2010). Soil properties estimation by inversion of a crop model and observations on crops improves the prediction of agro-environmental variables. European Journal of Agronomy, 33, 139-147, (https://doi.org/10.1016/j.eja.2010.04.005)

[192] Mishra, V., Cruise, J.F., & Mecikalski, J.R. (2021). Assimilation of coupled microwave/thermal infrared soil moisture profiles into a crop model for robust maize yield estimates over Southeast United States. European Journal of Agronomy, 123, 126208, (https://doi.org/10.1016/j.eja.2020.126208)

[193] Lei, F., Crow, W.T., Kustas, W.P., Dong, J., Yang, Y., Knipper, K.R., Anderson, M.C., Gao, F., Notarnicola, C., Greifeneder, F., McKee, L.M., Alfieri, J.G., Hain, C., & Dokoozlian, N. (2020). Data assimilation of high-resolution thermal and radar remote sensing retrievals for soil moisture monitoring in a drip-irrigated vineyard. Remote Sensing of Environment, 239, 111622,

[194] Pique, G., Fieuzal, R., Al Bitar, A., Veloso, A., Tallec, T., Brut, A., Ferlicoq, M., Zawilski, B., Dejoux, J.-F., Gibrin, H., & Ceschia, E. (2020). Estimation of daily CO2 fluxes and of the components of the carbon budget for winter wheat by the assimilation of Sentinel 2-like remote sensing data into a crop model. *Geoderma*, *376*, 114428. (https://doi.org/10.1016/j.geoderma.2020.114428)

Despite the rapid development of remote sensing technologies, it is impossible to measure in an accurate and exhaustive way, especially when it concerns a complex medium such as soil with the objective of assessing its health[195] [196]. This is true regardless of the type of platform and associated sensor characteristics (e.g., spatial, spectral and temporal resolutions). Uncertainties may result from differences in remote sensing collection devices or in applied processing methods, inaccurate input data (e.g., having a coarse resolution, without a precise ground reference, resulting from a subjective field data collection, with an ambiguous definition of objects), natural factors (e.g., atmospheric distortion), uncertainty caused by image processing (e.g., mixed pixel problem)[197] [198]. Accuracy assessment / validation are generally assessed through ground measurements to evaluate RS soil products for a given application[199]. Indeed, uncertainties are increasingly discussed in soil studies that analyze how to quantify, model and resolve in soil information detection. These studies deal with soil moisture[200], plant species[201], crop production estimation[202], soil properties[203], land cover mapping[204], soil salinity monitoring[205], biomass estimation[206].

[195] Ricotta, C., & Anand, M. (2006). Spatial complexity of ecological communities: Bridging the gap between probabilistic and non-probabilistic uncertainty measures. *Ecological Modelling*, *197*(1), 59–66. (https://doi.org/10.1016/j.ecolmodel.2006.03.001)
[196] Rocchini, D., Foody, G. M., Nagendra, H., Ricotta, C., Anand, M., He, K. S., Amici, V., Kleinschmit, B., Förster, M., Schmidtlein, S., Feilhauer, H., Ghisla, A., Metz, M., & Neteler, M. (2013). Uncertainty in ecosystem mapping by remote sensing. *Computers & Geosciences*, *50*, 128–135.(https://doi.org/10.1016/j.cageo.2012.05.022)
[197] Rocchini, D., Foody, G. M., Nagendra, H., Ricotta, C., Anand, M., He, K. S., Amici, V., Kleinschmit, B., Förster, M., Schmidtlein, S., Feilhauer, H., Ghisla, A., Metz, M., & Neteler, M. (2013). Uncertainty in ecosystem mapping by remote sensing. *Computers & Geosciences*, *50*, 128–135. (https://doi.org/10.1016/j.cageo.2012.05.022)
[198] Stein, A., Ge, Y., & Fabris-Rotelli, I. (2018). Introduction to the Special Issue "Uncertainty in Remote Sensing Image Analysis." *Remote Sensing*, *10*(12), Article 12. (https://doi.org/10.3390/rs10121975)
[199] Tran, B. N., van der Kwast, J., Seyoum, S., Uijlenhoet, R., Jewitt, G., & Mul, M. (2023). Uncertainty assessment of satellite remote-sensing-based evapotranspiration estimates: A systematic review of methods and gaps. *Hydrology and Earth System Sciences*, *27*(24), 4505–4528. (https://doi.org/10.5194/hess-27-4505-2023)
[200] Zhang, D., & Zhou, G. (2016). Estimation of Soil Moisture from Optical and Thermal Remote Sensing: A Review. *Sensors*, *16*(8), Article 8. (https://doi.org/10.3390/s16081308)
[201] Rocchini, D., Foody, G. M., Nagendra, H., Ricotta, C., Anand, M., He, K. S., Amici, V., Kleinschmit, B., Förster, M., Schmidtlein, S., Feilhauer, H., Ghisla, A., Metz, M., & Neteler, M. (2013). Uncertainty in ecosystem mapping by remote sensing. *Computers & Geosciences*, *50*, 128–135. (https://doi.org/10.1016/j.cageo.2012.05.022)
[202] Lobell, D. B., Asner, G. P., Ortiz-Monasterio, J. I., & Benning, T. L. (2003). Remote sensing of regional crop production in the Yaqui Valley, Mexico: Estimates and uncertainties. *Agriculture, Ecosystems & Environment*, *94*(2), 205–220. (https://doi.org/10.1016/S0167-8809(02)00021-X)
[203] Poggio, L., Sousa, L. M. D., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., & Rossiter, D. (2021). SoilGrids 2.0: Producing soil information for the globe with quantified spatial uncertainty. *SOIL*, *7*(1), Article 1. (https://doi.org/10.5194/soil-7-217-2021)
[204] Congalton, R. G., Gu, J., Yadav, K., Thenkabail, P., & Ozdogan, M. (2014). Global Land Cover Mapping: A Review and Uncertainty Analysis. *Remote Sensing*, *6*(12), Article 12. (https://doi.org/10.3390/rs61212070)
[205] Metternicht, G. I., & Zinck, J. A. (2003). Remote sensing of soil salinity: Potentials and constraints. *Remote Sensing of Environment*, *85*(1), 1–20. (https://doi.org/10.1016/S0034-4257(02)00188-8)
[206] Lu, D. (2006). The potential and challenge of remote sensing-based biomass estimation. *International Journal of Remote Sensing*, *27*(7), 1297–1328. (https://doi.org/10.1080/01431160500486732)

Some of the eight soil health indicators initially proposed by the *"Soil Health and Food"* Mission Board will be discussed in the following of this Deliverable, especially (i) soil organic carbon (SOC) stock (see subsection **V.2.b.**), (ii) soil structure including soil bulk density and absence of soil sealing and erosion (see subsections **V.2.d.** and **V.6.** for soil erosion), and (iii) landscape heterogeneity (see subsection **V.2.a.**). Another soil health indicator, (iv) biodiversity in soils, will be addressed indirectly through the links between landscape heterogeneity and biodiversity. It should also be noted that the current use of EO in the EUSO dashboard shows that EO can also contribute to the monitoring of (v) the presence of (some) pollutants (see sub-section **V.5.**). Here, we present additional information about the use of EO data to assess (vi) vegetation cover, and (vii) the area of forest and other wooded lands; EO information on vegetation cover (including forest and other wooded lands) for determining soil erosion.

Vegetation cover indicators play a crucial role in ecosystem health. These indicators are susceptible to soil desertification; the higher the value, the greater the soil cover percentage. Thus, good soil protection by high-rate vegetation cover against erosion, loss of organic matter and nutrients, extremes in soil temperature, and surface water runoff; moreover, high values simultaneously favor soil hydraulic conductivity, stability of soil aggregates, and water holding capacity.
The vegetation indices have been developed to measure directly vegetated areas using the spectral reflectance of EO data. They are generally chosen based on the types of vegetation detected, the landscape, and the surface area of the vegetated area. For example, the Normalized Difference Vegetation Index (NDVI) is issued to quantify vegetation greenness, the Soil-Adjusted Vegetation Index (SAVI) to detect vegetation where vegetation cover is low, the Modified Soil Adjusted Vegetation Index (MSAVI) to minimize the effect of bare soil, the Renormalized Difference Vegetation Index (RDVI) to highlight healthy vegetation, and the Dry Bare-Soil Index (DSBI) to better difference dry vegetation and bare soil.
Other than vegetation indices, vegetation variables have also contributed to vegetation cover measurement. For example, LAI is a critical vegetation structural variable in several processes, such as photosynthesis, respiration, and precipitation interception. It is one of the most widely used measurements for describing plant canopy structure, and Fractional Vegetation Cover (Fcover), the ratio of the vertically projected area of vegetation to the total surface extent, is frequently used to quantify vegetation dynamics in system models of Earth.
Various metrics also reveal the limits of vegetation cover by EO, such as the importance of temporal resolution and the measurement's susceptibility to season and precipitation (e.g., wet/dry periods). Moreover, some small-scale plant life or a single tree might be overlooked when analysing coarse spatial resolution remote sensing data.
Sub-section **V.4**. will describe the existing vegetation cover products (CLMsS and global).

The area of forest and other wooded lands may have different definitions. According to the FAO, forest is defined as *"land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of* *more than 10%, or trees able to reach these thresholds in situ"*[207]. This definition, which makes forest a sub-category of vegetation, highlights the strong interconnection between forest and vegetation cover. Like other vegetation types, the area of forest and other wooded lands can be estimated from RS data by applying classification/segmentation methods over temporal series of spectral reflectance, vegetation indices, or other RS vegetation products like LAI or vegetation fractional cover[208] . Except for the vegetation indices mentioned previously, the Forest Cover Index (FCI) is used to estimate the potential of land for generating forest carbon credits, as well as analysing forest carbon market conditions in individual countries[209], and tree canopy cover (TCC) to estimate forest health and productivity[210].

CLMS and global data will be introduced in the next section. The limits of forest cover are that the climate zone, dominant leaf type, and plant functional type must be taken into account during the measurement. For example, broadleaf forests are strongly influenced by seasonal changes compared to coniferous forests.

V.2. Interviews with leading scientists using EO data to characterise soils

V.2.a. Landscape heterogeneity (with D. Sheeren and M. Lang)

A relevant description of landscape heterogeneity depends on the question/topic (e.g., the distribution of functional taxa). An important question is whether the temporal, spatial or spectral variations in EO reflect the thematic source of variations under study. This is not always the case; there may be a difference between human point of view and the reality of the species when land use maps are drawn up, leading to different responses, models and 'area-species' correlations. While often working with a selected representation of the landscape, an effort is done to diversify the

[207] FAO, Dept, F., Rome (Italy) Forestry, & Dept, R. (Italy) F. (n.d.). *Manual for integrated field data collection*. Food & Agriculture Org.

[208] E. D. Chaves, M.; C. A. Picoli, M.; D. Sanches, I. Rec[208] E. D. Chaves, M.; C. A. Picoli, M.; D. Sanches, I. Recent Applications of Landsat 8/OLI and Sentinel-2/MSI for Land Use and Land Cover Mapping: A Systematic Review. Remote Sens. 2020, 12, 3062. (https://doi.org/10.3390/rs12183062)

[208] UN-REDD programme. (2021, July 15). *Forest Carbon Index (FCI)*. UNREDD Programme. (https://www.un-redd.org/glossary/forest-carbon-index-fci)

[208] Derwin, J. M., Thomas, V. A., Wynne, R. H., Coulston, J. W., Liknes, G. C., Bender, S., Blinn, C. E., Brooks, E. B., Ruefenacht, B., Benton, R., Finco, M. V., & Megown, K. (2020). Estimating tree canopy cover using harmonic regression coefficients derived from multitemporal Landsat data. *International Journal of Applied Earth Observation and Geoinformation*, *86*, 101985. (https://doi.org/10.1016/j.jag.2019.101985)

ent Applications of Landsat 8/OLI and Sentinel-2/MSI for Land Use and Land Cover Mapping: A Systematic Review. Remote Sens. 2020, 12, 3062. (https://doi.org/10.3390/rs12183062)

[209] UN-REDD programme. (2021, July 15). *Forest Carbon Index (FCI)*. UNREDD Programme. (https://www.un-redd.org/glossary/forest-carbon-index-fci)

[210] Derwin, J. M., Thomas, V. A., Wynne, R. H., Coulston, J. W., Liknes, G. C., Bender, S., Blinn, C. E., Brooks, E. B., Ruefenacht, B., Benton, R., Finco, M. V., & Megown, K. (2020). Estimating tree canopy cover using harmonic regression coefficients derived from multitemporal Landsat data. *International Journal of Applied Earth Observation and Geoinformation*, *86*, 101985. (https://doi.org/10.1016/j.jag.2019.101985)

representations of the visible landscape, with discrete and continuous representations. **The challenge is to identify the factors/components of landscape heterogeneity that promote or limit biodiversity and ecosystem services and to understand how to manage and preserve biodiversity and associated ecosystem services, in order to characterize correctly this heterogeneity**.

Landscape heterogeneity can be characterised in terms of structural heterogeneity (e.g., by distinguishing between forests, grasslands, crops or species, and buildings) or functional heterogeneity (e.g., by distinguishing between granivorous and insectivorous birds). The **heterogeneity of composition** (e.g., the proportion of woodland, grassland, etc.) in the vicinity of a given site and the **heterogeneity of configuration** (for a given composition, how these habitats are arranged in space: are they all grouped together? Or are they more fragmented and scattered?) must be taken into account. Connectivity of the landscape may impact the flows of living organisms (crop pathogens, pests or auxiliaries; other living organisms) and is often introduced into models by ecologists, who calculate this type of variable once satellite data maps are available[211]. Another aspect is the **temporal heterogeneity**, i.e., the variation in composition and configuration over time.

EO images can be characterized by (1) **spatial heterogeneity**, based on spatial resolution within a range of possible spatial resolutions depending on the chosen protocol for acquiring biodiversity surveys and their extent (e.g., point scale, landscape scale such as a 1 x 1 km square, 1 ha circular plot in a forest) and which may be < 1 m, which makes it possible to see fine details, to characterise the spatial distribution of details of different sizes and to calculate texture indices that can be linked to the heterogeneity of configuration; (2) **spectral heterogeneity**, which gives access to biophysical or biochemical variables linked to vegetation, pigments, water content, leaf surface, minerals, etc. (this heterogeneity can be finely described by hyperspectral sensors); and (3) **temporal heterogeneity**, at intra-annual or inter-annual scales to go beyond the description of the state of a landscape with its spatial heterogeneity and move towards a description of its 'functioning' (in different forms) and variability over time (which may result from agricultural practices, phenology, appearance of diseases, pests, etc, accessible thanks to satellites, which can acquire images at regular intervals at the same place).

The spatial, spectral and temporal dimensions that characterise the optical types[212] must therefore be examined, in an attempt to link these optical types to information about the vegetation (structural, biochemical or physiological information), or to phenology when a time series is examined.

[211] Sirami, C., Gross, N., Baillod, A. B., Bertrand, C., Carrié, R., Hass, A., ... & Fahrig, L. (2019). Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. *Proceedings of the National Academy of Sciences*, *116*(33), 16442-16447. (https://doi.org/10.1073/pnas.1906419116)
[212] Ustin, S. L., & Gamon, J. A. (2010). Remote sensing of plant functional types. *New Phytologist*, *186*(4), 795-816. (https://doi.org/10.1111/j.1469-8137.2010.03284.x)

Digital images can be processed using one of three general methods, with or without the use of artificial intelligence[213]:

- **Discrete representations of the landscape** are derived from **classification algorithms**: each pixel is assigned a discrete value in order to obtain a map of strata from the initial image. The map may vary slightly with the classification method, and post-processing may erase heterogeneities, e.g., by considering agricultural plots to be homogeneous. There are machine learning and now deep learning techniques to do this[214]**;**
- **The continuous approach takes into account the spatial, spectral or temporal variations** that are derived from the original image, assuming that certain variations are PROXY of the heterogeneity of the landscape. However, the relationship between these abstract representations, which in some way characterise the heterogeneity of landscapes, and biodiversity has not yet been examined in the department of the interviewees[215]. Spectral diversity can either be calculated from the pixels present in a neighbourhood window, or after pixel aggregation. In this last case, the space is discretised by clustering, i.e., by grouping together pixels that have similar values (possibly after a preliminary principal component analysis), then calculating a diversity index for each cluster (e.g., a Shannon index) and checking whether the Shannon index based on spectral information is correlated with the Shannon index based on biological information. This type of method is widely used for forests, or more generally for vegetation.

The current break with the past is trying to stop classifying (not all the time) in order to get away from preconceived ideas. A hypothesis is that spectral diversity in a landscape window can be directly linked to biological diversity[216].

Numerous studies have shown that a highly heterogeneous landscape favours biological abundance and taxonomic diversity on the ground or in the air, as there are more ecological

[213] Fassnacht, F. E., Müllerová, J., Conti, L., Malavasi, M., & Schmidtlein, S. (2022). About the link between biodiversity and spectral variation. *Applied Vegetation Science*, *25*(1), e12643. (https://doi.org/10.1111/avsc.12643)

[214] Kattenborn, T., Leitloff, J., Schiefer, F., & Hinz, S. (2021). Review on Convolutional Neural Networks (CNN) in vegetation remote sensing. *ISPRS journal of photogrammetry and remote sensing*, *173*, 24-49. (https://doi.org/10.1016/j.isprsjprs.2020.12.010)

[215] Ecologists look for the scale at which the ecological process responds. They create analysis windows of 1 km by 1 km, or 500 m by 500 m, or 200 m by 200 m, and identify the spatial extent that is most suitable, i.e. that ultimately produces the best correlation in relation to heterogeneity variables. In remote sensing, we often propose a representation to ecologists, but without varying its spatial resolution (although we could do so) and/or its semantic precision (the number of classes and level of detail). Deep learning makes it possible to generate a range of levels of spatialized detail over a range of spatial extents fairly quickly. We're not doing it yet; these are things we're questioning, and we think we need to look into it. Beyond finding correlations that work well, we need to understand why one representation responds better than another: this can only be an interdisciplinary task. The aim is then to identify the causes and sources of heterogeneity;

[216] Coops, N. C., & Wulder, M. A. (2019). Breaking the Habit (at). *Trends in Ecology & Evolution*, *34*(7), 585-587. (https://doi.org/10.1016/j.tree.2019.04.013)

niches[217218,219,220,221], which has a positive impact on certain ecosystem services (e.g., biological regulation service, pollination service). There is also work that has directly linked spectral information to fungal richness, i.e., things that can't be seen directly in the image[222],[223].
DYNAFOR Department demonstrated this for grasslands[224,], forests[225], and for birds by linking variables calculated on an Normalized Difference Vegetation Index (NDVI) with bird richness in agricultural and forest environments[226,227].
Not quite on the same subject, but in the same vein, there is a review on the impact of soil pollution by hydrocarbons on the reflectance spectra of vegetation[228].

In addition to continuing work in line with previous projects, scientific fronts have been opened

---

[217] Priyadarshana, T. S., Martin, E. A., Sirami, C., Woodcock, B. A., Goodale, E., Martínez-Núñez, C., ... & Slade, E. M. (2024). Crop and landscape heterogeneity increase biodiversity in agricultural landscapes: A global review and meta-analysis. *Ecology Letters*, *27*(3), e14412. (https://doi.org/10.1111/ele.14412)
[218] Martin, E. A., Dainese, M., Clough, Y., Báldi, A., Bommarco, R., Gagic, V., ... & Steffan-Dewenter, I. (2019). The interplay of landscape composition and configuration: new pathways to manage functional biodiversity and agroecosystem services across Europe. *Ecology letters*, *22*(7), 1083-1094. (https://doi.org/10.1111/ele.13265)
[219] Stein, A., Gerstner, K., & Kreft, H. (2014). Environmental heterogeneity as a universal driver of species richness across taxa, biomes and spatial scales. *Ecology letters*, *17*(7), 866-880. (https://doi.org/10.1111/ele.12277)
[220] Estrada-Carmona, N., Sánchez, A. C., Remans, R., & Jones, S. K. (2022). Complex agricultural landscapes host more biodiversity than simple ones: A global meta-analysis. *Proceedings of the National Academy of Sciences*, *119*(38), e2203385119. (https://doi.org/10.1073/pnas.2203385119)
[221] Tonetti, V., Pena, J. C., Scarpelli, M. D., Sugai, L. S., Barros, F. M., Anunciação, P. R., ... & Ribeiro, M. C. (2023). Landscape heterogeneity: concepts, quantification, challenges and future perspectives. *Environmental Conservation*, *50*(2), 83-92. (https://doi.org/10.1017/S0376892923000097)
[222] Bae, S., Levick, S. R., Heidrich, L., Magdon, P., Leutner, B. F., Wöllauer, S., ... & Müller, J. (2019). Radar vision in the mapping of forest biodiversity from space. *Nature Communications*, *10*(1), 4757. (https://doi.org/10.1038/s41467-019-12737-x)
[223] It should be noted that other studies have clearly demonstrated the link between the diversity of fungal mycelia in the soil and plants, fungi being symbionts, saprophytes and/or plant pathogens with very specific links.
[224] Fauvel, M., Lopes, M., Dubo, T., Rivers-Moore, J., Frison, P. L., Gross, N., & Ouin, A. (2020). Prediction of plant diversity in grasslands using Sentinel-1 and-2 satellite image time series. *Remote Sensing of Environment*, *237*, 111536. (https://doi.org/10.1016/j.rse.2019.111536)
[225] Lang, M., Ferriere, M., de Boissieu, F., Briottet, X., Fabre, S., Sheeren, D., & Féret, J. B. (2023, June). Cartographie de la diversité spécifique forestière des milieux tempérés à partir d'imagerie hyperspectrale. In *Spatial Analysis and GEOmatics 2023* (pp. 107-121). (https://hal.inrae.fr/hal-04440898)
[226] Sheeren, D., Bonthoux, S., & Balent, G. (2014). Modeling bird communities using unclassified remote sensing imagery: Effects of the spatial resolution and data period. *Ecological Indicators*, *43*, 69-82. (https://doi.org/10.1016/j.ecolind.2014.02.023)
[227] Bonthoux, S., Lefèvre, S., Herrault, P. A., & Sheeren, D. (2018). Spatial and temporal dependency of NDVI satellite imagery in predicting bird diversity over France. *Remote Sensing*, *10*(7), 1136. (https://doi.org/10.3390/rs10071136)
[228] Lassalle, G., Fabre, S., Credoz, A., Dubucq, D., & Elger, A. (2020). Monitoring oil contamination in vegetated areas with optical remote sensing: A comprehensive review. *Journal of hazardous materials*, *393*, 122427. (https://doi.org/10.1016/j.jhazmat.2020.122427)

up by David Sheeren and Marc Lang[229]:

- **Characterisation of hedgerows using remote sensing[230]** (after initially attempting to map landscape features and other non-productive areas (hedges, ditches, trees and fallow land) more generally) by successively**:**
    - Development of tools for individualising objects (resulting in maps of hedgerows with a confusion rate of around 5%) and then identifying the median axis of the hedgerow by skeletonisation in order to calculate a planar graph and then a connectivity index;
    - Development of tools and indicators to characterise hedges (structure, species composition, context (on a slope, near a ditch, etc.), etc.), allowing to characterize different hedge geometries from which very simple morphological indicators can be calculated (width, length, height and variability of hedge height);
    - the ongoing use of these tools to retrieve all the information on hedgerows, calculate the variables describing their horizontal and vertical structure, and see whether there is a link with the biodiversity observed in these hedgerows.

  Current work focuses on what happens in the hedgerow (colleagues have worked in the past on the question of biodiversity in plots as a function of distance from the hedgerow; and there has been some work on the impact of edges and hedges on the diversity of wild bees in agricultural environments[231]). There are complex associated issues such as hedgerow management practices, the presence of dendro-microhabitats on old hedgerow trees, etc. Work is also in progress on how LiDAR can contribute to the characterisation of vertical heterogeneity and complexity within the hedgerow: identification of several vegetation strata within the hedgerow, plant cover and diversity by stratum, etc. And David Sheeren and Marc Lang are also interested in the windbreak effect of the hedge on adjacent agricultural plots and its impact on yields, as a function of the height, width and porosity of the hedge;
- **The use of UAVs (with the recent acquisition of an UAV):** The use of drones allows fine resolution but limited coverage, and gives the freedom to make observations at selected dates (which is particularly interesting when working on phenology, such as flowering) while still hampered by meteorological or legal rules conditions. However, UAV equipped with spectral and LiDAR sensors are now available at affordable prices[232] and are considered as a valuable

[229] Sheeren, D., Marquès, G., Villierme, L., Boissonnat, J. B., Guébin, G., Lang, M., & Monteil, C. (2023, June). HedgeTools: une boîte à outils pour caractériser automatiquement les haies en milieu agricole. In *Spatial Analysis and GEOmatics 2023* (pp. 9-22). (https://hal.science/hal-04455630)

[230] Working on hedges is nothing new. There was already work being done in the SPOT era, but it has become an important subject again and, above all, we have more data available (cheaper and more frequent data).

[231] Rivers-Moore, J., Andrieu, E., Vialatte, A., & Ouin, A. (2020). Wooded semi-natural habitats complement permanent grasslands in supporting wild bee diversity in agricultural landscapes. *Insects*, *11*(11), 812. (https://doi.org/10.3390/insects11110812)

[232] The most common combination of remote sensors is currently the LiDAR - hyperspectral combination, which provides simultaneous access to very precise information on spectral heterogeneity and a very large amount of information on the structure of the environment. It often produces remarkable results. However, hyperspectral data are still often taken from aircraft (few come from satellites), and their spatial resolution is coarse. LiDAR sensors are also often airborne, so we have no context; and they cannot yet be deployed on a large scale. This

tool to assess landscape heterogeneities.

In partial conclusion, the work carried out by UMR DYNAFOR on the characterisation of landscape heterogeneity is very promising. It opens up the possibility of observing, and even monitoring, landscape heterogeneity that is favourable to biodiversity and that is highlighted by the European Green Deal and the European Common Agricultural Policy 2023-2027, in particular through eco-schemes[233] and the enhanced conditionality of EU financial support. These heterogeneities may involve the juxtaposition of different landscape elements, but these heterogeneities may also be mixtures of plant species within agricultural plots, hedgerows, etc. While it has already been shown that landscape heterogeneity favours surface or aerial biodiversity, certain elements show us that it has an impact on soil diversity (particularly fungal diversity), and the diversity of habitats that it generates in the soil suggests that landscape heterogeneity affects soil biodiversity in a fairly general way. It is also legitimate to ask whether the spectral heterogeneity of soils can also more directly reflect biological diversity or the abundance of a specific soil feature. The remaining challenges may then be to identify the most relevant descriptors of soil biodiversity and its spatial distribution. Moreover, landscape heterogeneity has other impact including impact on soil erosion.

V.2.b.Soil organic carbon (with E. Ceschia)

There is no mean of estimating SOC or SOC variations directly from EO data without doing strong hypothesis on the SOC concentration profile in the soil, since EO only allows to observe the top layer of soil, and only when the soil is not covered by vegetation or crop residues. Indeed, direct quantification of the top-layer SOC concentration from EO data is actually possible only for cultivated land, at specific times (e.g., only between the harvest date of a crop and the sowing date of the next), which will be hampered by the recent development on new and complex agroecologic agrosystems (e.g., cover crops, no till, agroforestry).
Therefore, they are mainly four ways of using EO data for SOC evaluation:

- For mapping crops and practices that have an impact on SOC stocks (e.g., crop rotations, cover crops, soil work, application of organic amendments). Note that many practices cannot be detected/mapped by remote sensing including some that have a strong impact on SOC stock changes (e.g., quantification of organic amendments application, export of straw);
- For mapping SOC superficial content: Regional or global approaches that use EO data as covariates among various other ones to create superficial SOC concentration maps (see for examples https://soilsrevealed.org/ using approaches like the SCORPAN model, SoilGrids

is starting to change with GEDI (LiDAR attached to the International Space Station (ISS)) and PRISMA (hyperspectrral, decam, PRecursore IperSpettrale della Missione Applicativa, an Earth observation satellite belonging to the Italian Space Agency (ASI), which will be launched into orbit on 22 March 2019, and which, among other things, will make it possible to use hyperspectral imaging technology), ENMAP (hyperspectral, decam), CHIME (ESA, hyperspectral, hectom ... to be launched).

[233] https://agriculture.ec.europa.eu/common-agricultural-policy/income-support/eco-schemes_en

https://soilgrids.org/ and the GlobalSoil Map https://www.isric.org/projects/globalsoilmapnet, and see sub-section **V.1** for more information about these approaches). These approaches are traditionally based on geostatistical methods and now integrate machine or deep learning to better take into account intrinsic links between the covariates;

- For mapping biophysical variables related to vegetation development (e.g., Leaf Area Index or vegetation indices, Fraction of Absorbed Photosynthetic Active Radiation, FCOVER…) or phenology. Using high resolution (e.g., decametric (like SENTINEl-2 or SENTINEl-1) allows in particular to take into account of the intra-field spatial heterogeneity; and

- For quantifying SOC stock changes: here vegetation biophysical characteristics (Leaf Area Index, proxy of the biomass…) derived from EO are assimilated in crop models or to calibrate/force the crop model to reproduce the intensity of development and the dynamic of the vegetation observed by remote sensing. The objective is to better quantify the biomass produced and returned to the soil and to account for its spatial variability in order to simulate more accurately SOC stock changes. Here the methodology is based on the C balance approach that aims at quantifying all C inputs (photosynthesis, organic amendments) and outputs (plant & soil respiration, harvest) to the field but also the pools of carbon and their dynamics during the cropping year (net primary production, allocation of biomass, SOC pools). "Classical" crop models such as STICS, EPIC…can be used without or with EO data assimilation but their need for a lot of input data (e.g., activity data) and parameters limit their applicability at large scale and they cannot represent the intra-inter field spatial variability in crop development observed in the landscapes. Therefore, a new generation of crop models (e.g., SAFYE-CO_2) developed specifically for upscaling are developed which require few input data (only data on organic amendments and harvest of straws) but they are very dependent on EO data for the calibration of the crop parameters. Those models/processing chains (e.g. Remote C, Agricarbon-EO) are developed for local approaches (e.g. field or ensemble of fields level) for the voluntary C market (that allows companies to compensate for their CO_2 emissions by supporting CO_2 sequestration in the agriculture production chain), for the insetting (that allows agri-food companies to compensate for their CO_2 emissions by supporting CO_2 sequestration in the agriculture production chain), for the CAP or for national scales to answer the needs for national inventories., The objective is to support carbon farming activities and provide quantitative evaluations of SOC stock changes.

Other methods can be applied for these local approaches:

- *In situ* measurements and remeasures of SOC stocks which are quite tedious and constraining as they require the collection of a sufficient number of soil samples that are further analysed at the laboratory (between 25 to 75 soil samples.ha^{-1} are needed to detect a variation of 0.3 $t.ha^{-1}y^{-1}$ according to the EDF[234];
- Indirect estimate of SOC stock changes based on the soil carbon balance approach can also be achieved through actual measurements operated at flux tower sites but those setups are too

[234] https://www.edf.org/sites/default/files/content/agricultural-soil-carbon-credits-protocol-synthesis.pdf

expensive to be applicable at large scale. They are very useful though to evaluate/develop/ improve process-based models.

These models allow to compute the annual carbon budget by modelling processes like plant respiration, net primary production, above-ground production and soil respiration that can also be more or less detailed depending on the complexity of the model (e.g., coupling SAFYE with AMG). EO data products, and eventually flux tower measurements, are then used to improve the parametrization of the vegetation functioning models (e.g., like SAFYE-CO_2 [235,236] which was specifically designed to use EO data) estimates through data assimilation scheme.

As part of several EU projects (H2020 NIVA, Horizon ORCaSa, ClieNfarms or MARVIC), Eric Ceschia, the CESBIO team and their partners have developed3 different approaches[237] to computes net annual CO_2 fluxes or crop annual carbon budgets using three types of indicators with the aim of better assessing the impact of new agroecological practices on SOC stock changes in different context (CAP, Voluntary Carbon Market…):

- Tier 1: The methodology for Tier 1 estimates the net annual CO_2 fluxes between the parcels and the atmosphere: it takes into account the CO_2 emitted to atmosphere by the plants and the soil respiration (mineralisation of the soil organic matter) and the CO_2 absorbed by the plants through photosynthesis. The indicator computation is based on an empirical linear relationship between the net annual CO_2 flux and the number of days with active vegetation which is valid for most crop types in Europe. Requires only two information: crop type and plot contours;
- Tier 2: This indicator allows computing annual carbon budgets at plot level, which represents how much carbon has been lost or gained by the soil over a cropping year. The tool uses the results from the Carbon Tier 1 indicator, combined with the farmer's FMIS data (the type and an amount of organic amendments, harvest). As for Tier 1, Tier 2 is based on an empirical approach and it can be applied to most crop species. Issue related to access to the FMI data;
- Tier 3: It is produced by the most advanced and complex approach and requires intensive computing and large data storage capacities. Carbon Tier 3 is based on a the SAFYE-CO_2 crop modelling approach that has been tested and validated for straw cereals, maize, sunflower and cover crops. The method has been validated against *in-situ* data (flux tower measurements, data from the Regional Space Observatory). The model SAFYE-CO_2 simulates CO_2 fluxes (photosynthesis, plant and soil respiration), biomass and yield. As an input, it requires information on crops and plot contours, meteorological data, LAI (Leaf Area Index data derived from Sentinel 2 like satellites) to calibrate the model's phenology and photosynthesis capacity. Biomass simulated by SAFYE-CO_2 that returns to the soil is then used as an input of the AMG soil model (but other soil models can be coupled). As for Tier 2, farmer's FMIS data on organic

[235] https://www.cesbio.cnrs.fr/agricarboneo/saye-co2/
[236] Pique, G.; Fieuzal, R.; Debaeke, P.; Al Bitar, A.; Tallec, T.; Ceschia, E. Combining High-Resolution Remote Sensing Products with a Crop Model to Estimate Carbon and Water Budget Components: Application to Sunflower. Remote Sens. 2020, 12, 2967. (https://doi.org/10.3390/rs12182967)
[237] https://www.niva4cap.eu/wp-content/uploads/2022/12/NIVA-Policy-Brief-nr.-5-Agro-environmental-indicator-carbon-D1.0.pdf

NIVA also proposed two indicators related to nitrate leaching (to elaborate risk maps) and two other ones for biodiversity (presence and types of semi-natural habitat maps, like ponds, grasslands, hedges, woods...)[238].

V.2.c. Soil erosion (with O. Cerdan)

In **tillage erosion**, the soil remains in the field. On a sloping plot, soil is removed from the top of the plot and added at the bottom. This can be seen in the landscape, especially when there are hedges or roads: banks are created at the bottom, and there may be a height difference between 2 plots at the top. When we see an artificial height difference between 2 plots, it is generally linked to soil erosion. Tillage erosion can be seen in more complex reliefs, for example in limestone regions, all the convexities (heights) will be white and the concavities (hollows) will be a little darker; this is very visible when there is moisture: the moisture is found more in the concavities than in the convexities. In an intensive ploughing system, tillage erosion (of the order of 1 to 2 tonnes per hectare per year) is of the same order of magnitude as water erosion. This may have a local impact on the soil, but it will have much less impact on water quality, diffuse pollution and mudflows. If the recent trends of moving towards simplified tillage were to be confirmed, **tillage erosion would tend to be reduced**.

Soil erosion by crop harvesting can also be observed, but it has a similar impact on the field as a whole. For example, in areas where a lot of sugar beet is grown, the level of the plot may be lower than that of adjacent plots if the latter are not used for sugar beet. Thanks to remote sensing, **it may be possible to identify these anomalies in the landscape using precise digital elevation readings**. But the consequences will only be visible after several years; it is conceivable that remote sensing will make it possible to find/see these anomalies after a long period of use. The importance of soil erosion by crop harvesting rates depends on environmental conditions but in flat or gently sloping cropland, with no or limited soil erosion by water or tillage, this erosion process can become dominant and reach several tons per hectare and per year.

Wind erosion is less prominent in France, affecting, for example, very sandy soils.

Water erosion combines diffuse erosion caused by the impact of rain and concentrated erosion caused by runoff, which can be Hortonian runoff (when rainfall intensity exceeds the water infiltration capacity of the soil) or saturation runoff (when the soil is saturated). In France, water erosion is most pronounced in anthropized systems, especially in cultivated areas that include bare soils (i.e., on plots cultivated with bare soil in winter: maize, spring crops, etc.) and on crops with bare soil between rows (vineyards, orchards, etc.). **It is difficult to see water erosion by remote sensing**: diffuse water erosion is extremely difficult to see and concentrated erosion is a highly localised phenomenon in time and

[238] Eric Ceschia, Clélia Sirami, Christian Bockstaller, David Sheeren, Ludovic Arnaud, et al.. NIVA UC1b Agro-environmental indicators. Stackeholder Forum, European Environmental Bureau, Dec 2020, online (Brussels), Belgium. ffhal-04221939f. (https://hal.inrae.fr/hal-04221939)

space. Most common forms of concentrated erosion are generally no more than 30 cm deep and 1 m wide, but they are more usually 30-40 cm wide; in this last case, the farmer can then fill in the gully with 2 or 3 passes of the plough to prevent problems for farm machinery. Remote sensing with a resolution ≤ 10 m can be used to detect linear gullies; so, it's probably feasible with Sentinel 2 ... but one has to get there at the right time. With satellites like PLANETSCOPE, which pass by every day, with a spatial resolution of 3 m, this would be sufficient, especially as the farmer cannot immediately return to his field after a rain to fill in a gully..., but there may also be the problem of cloud cover, which prevents us from seeing the state of the soil just after a rain. However, EO did not enable to quantify soil erosion, unless a field calibration is carried out using empirical models based on slope, soil type, etc. (*a priori*, never done). In Mediterranean marl systems, where the soil erodes over several metres, it is possible to estimate the volume of soil eroded. This is not the case in mainland France: concentrated erosion takes the form of temporary gullies that can be ploughed. The danger of having too much confidence in remote sensing is that, if the satellite passes over the gully after the farmer has filled it in, it can be said that there has been no erosion. A great deal of work is currently being done to quantify erosion using LiDAR. It's not trivial, because it's often based on a difference in height between the ‘digital surface model’ (DSM) and a ‘digital elevation model’ (DEM). So, if we have erosion of several tens of centimetres with erodible materials, we can detect things. But for diffuse erosion, it can be complicated because erosion speeds are of the order of a mm per year, which corresponds to the recording error between the DEM images.

Monitoring sediment transport in streams can only be a means of monitoring soil erosion for small streams and watershed heads (up to 1 km^2). For larger watersheds, it's highly variable. Various other processes interfere (sediment deposition in the river, etc.). However, taking landscape connectivity into account enabled to establish a link between soil erosion and sediment export to some extent. Typically, in Brittany and more generally in regions where bocage is still present, erosion can occur while rivers export little sediment. The same phenomenon occurs in the silty Paris region, with very strong local erosion but plains where eroded sediments are deposited (about 90% of eroded material does not reach the river). Conversely, a much higher percentage of what is eroded is exported for the small rivers of Adour (France) or Piedmont (Italy).
Working with people who do tracing gives access to the origins of the eroded particles if the tracer is conservative. Different types of erosion can be distinguished, when using radionuclides deposited from the atmosphere. And erosion of organic matter can also be monitored using hyperspectral sensors.

Models can provide indirect access to erosion risks. There is no such thing as a bad model a priori; but a model and the data that can support it may or may not allow us to do what we want to do with it.
In Europe, there are very few researchers (not to say none, at least to the best of O. Cerdan’s knowledge) currently working on soil erosion that use the Revised Universal Soil Loss Equation (RUSLE), but it's not necessarily a bad model. The Universal Soil Loss Equation (USLE) was initially proposed in the 1960s by a group of extremely well-organised and well-supported Americans; their

proposal followed the 'Dust Bowl' of the 1930s[239], considered to be one of the worst man-made environmental disasters in the history of the United States, where huge wind erosion problems had arisen as a result of the major transformations in agriculture that had begun in the 1930s. Their aim was to provide an engineering and diagnostic tool (i.e., the assessment of erosion risks in a given context). USLE (and RUSLE) is an empirical model that multiplies parameters that have no physical significance and cannot be measured. (R)USLE, does not describe concentrated erosion (caused by runoff) but only rill and interrille erosion (caused by rain). It works well in the United States, because tens of thousands of plots have been studied, characterised and monitored over many years that served as a strong calibration basis. This model is very easy to use and is very well calibrated for the United States. The first publications[240],[241] were so successful that in 1976, its designer published an article saying that their model could not do everything[242]. Using an empirical model requires the means to calibrate it, which is not the case for the current application of RUSLE in Europe. Moreover, taking average erodibility as RUSLE does doesn't make sense in certain regions: by taking only average factors for example in Alsace, RUSLE could predict no erosion, even though there are quite violent storms on silty-sloping slopes where "everything" goes away; and conversely, the RUSLE model could predict erosion in the Vosges on mountainous areas, even though these are granitic arenas capable of absorbing 300 mm per hour of rainfall. Finally, the RUSLE model is not spatially distributed (the erosion of a plot of soil does not take into account what happens to it from above (runoff, etc.), and does not take into account changes over time (leading to variable correlations between weather and soil cover). At present, the RUSLE is therefore not an adapted modelling approach to be used in Europe at regional scale. The MESALES model (*Modèle d'Evaluation Spatiale de l'ALéa Erosion des Sols*), initially developed by INRAE to describe soil crusting and describing only rill-interrille erosion, was designed by season. MESALES does not necessarily work well on very sandy or very clayey soils (these soils do not respond to the same surface degradation processes); however, the maps of erosion in France produced by MESALES seem fairly relevant.

The big advantage of physically-based models, which can be wrong for other reasons, is their greater extrapolation power. And the data needed for the RUSLE model would enable other estimates to be made with the latter models.

In Europe, an EU-funded project bringing together the erosion specialists has made it possible to build a process-based model, the PESERA (Pan-European Soil Erosion Risk Assessment) model[243], that is simple to implement with readily available data. It was the official EU model used and deployed by the JRC. It includes a crop rotation model, a plant growth model, etc. The temporal dimension is

[239] https://digitalprairieok.net/dust-bowl/

[240] Wischmeier, W. H., & Smith, D. D. (1960). A universal soil-loss equation to guide conservation farm planning. Transactions 7th int. Congr. Soil Sci., 1, 418-425.

[241] Wischmeier W.H. 1960. Cropping-management factor evaluations for a universal soil-loss equation. Soil Science Society of America Journal, 24(4), 322-326. (https://doi.org/10.2136/sssaj1960.03615995002400040032x)

[242] Wischmeier W.H. (1976). Use and misuse of the universal soil loss equation. Journal of Soil and Water Conservation. 31(1), 5-9

[243] https://esdac.jrc.ec.europa.eu/themes/pesera-model

explicitly taken into account: leaf area index (LAI) - and therefore soil protection - varies with date; soil surface conditions evolve and different soil types are taken into account. PESERA remains a local model (i.e., without spatialization) but takes into account lateral processes (runoff, soil transport, etc.). It seems important to approach erosion on a watershed scale, to explicitly describe the processes involved.

BRGM develops erosion models for research purposes and erosion models for 'applied' use. One of the latter is the WaterSed model, which we use a lot. This is a spatially distributed model (on a watershed scale), with a non-dynamic version (i.e., on a rainfall event scale) requiring the model to be run as many times as there are rainfall events (around 100 times per year).

Two articles were published in 2005 on the parameterization of erosion models using remote sensing data[244,245].

V.2.d.Digital soil mapping (with A. Richer-de-Forges)

There are two main ways of using remote sensing data to characterize soil:

- Either use these data as PROXI to a soil measurement in the field or a lab, as soil input in models;
- Or use these data as environmental covariates supposed to explain – or to be correlated – with a given soil property, and use them to predict this property at any point in space[246].

Soil properties may be soil moisture, surface roughness, SOC content, colour, albedo, texture, etc. Environmental covariates may include vegetation, land use, lithology, parent material, relief, climate, etc. In EU, satellite data come mainly from Sentinel-2 and Sentinel-1, but other EO data can be very useful (e.g., airborne gamma-ray spectrometry for texture mapping). Remote sensing data can be combined with other data to predict soil properties.

Input soil data may include:

- Quantitative data from soil databases (in France, for example, the DoneSol database is enriched by various programmes, including the French soil monitoring programmes *Réseau de Mesure de la Qualité des Sols* (RMQS), which has been in existence for 23 years, as well as other soil mapping programmes dating back to the 1960s);
- Qualitative data from *in situ* soil observations, e.g., topsoil structure, soil structure stability and soil texture class which is related to relative importance of clay, silt and sand, and is assessed empirically by touch.

Vegetation maybe a problem for remote Sensing covariates when sensors are carried by satellites. Working only on bare soil works well for estimating organic carbon in the soil surface layer (work

---

[244] King C., Lecomte V., Le Bissonnais Y., Baghdadi N., Souchère V., Cerdan O. (2005). Remote-sensing data as an alternative input for the 'STREAM'runoff model. Catena, 62(2-3), 125-135. (https://doi.org/10.1016/j.catena.2005.05.008)

[245] King C., Baghdadi N., Lecomte V., Cerdan O. (2005). The application of remote-sensing data to monitoring and modelling of soil erosion. Catena, 62(2-3), 79-93. (https://doi.org/10.1016/j.catena.2005.05.007)

[246] Richer-de-Forges, A. C., Chen, Q., Baghdadi, N., Chen, S., Gomez, C., Jacquemoud, S., ... & Arrouays, D. (2023). remote sensing data for digital soil mapping in French research—a review. Remote Sensing, 15(12), 3070. (https://doi.org/10.3390/rs15123070)

carried out with Emmanuelle Vaudour[247]).

The SCORPAN[248] model is currently the worldwide basis for Digital Soil Mapping. SCORPAN acronym stands for **S**oil, **C**limat, **O**rganisms (e.g., vegetation, land use), **R**elief (use.g., elevation from DEMs and its derivatives), **P**arent materials (e.g., lithology and geology), **A**ge (duration of processes involved in soil formation) and **N** (XY location). It offers a generic analysis framework that can be adapted to a wide variety of datasets. As well as providing estimates of mean or median soil property values, it estimates a matched error, quantifying the uncertainty of the model output.
Most often, each soil property has a specific model, which takes into account the covariates linked to the factors controlling the pedogenesis of that soil property, though some related properties can be modelled together. Machine learning models allow to rank the covariates importance, enabling the most relevant to be selected. Model quality indicators indicate whether or not the model is statistically acceptable; and the contribution of each covariate to the prediction of the soil property can be estimate. At the end, we obtain a property distribution map and an uncertainty distribution map for each pixel, so that we know where the values are most reliable and where we can use them with confidence or if the least reliable areas should be more sampled.
The output resolution is generally based on the specifications of a worldwide programme, *GlobalSoilMap*[249], with pixels of 90 m x 90 m (in fact, these are voxels, as soil properties are considered at different depths, from 0 to 2 m). The reason for this is that this resolution is based on that of SRTM (Shuttle Radar Topography Mission), the source of covariates that are freely accessible worldwide.

Spatial and spectral resolution increases over the years, as does the frequency of revisits. Revisits can be used to mosaic bare soil to obtain as much information as possible: in this case, multi-date input data are used simultaneously, retaining only pixels without vegetation and other perturbing factors (e.g., clouds, shadows) at each date. In the future, revisits might enable monitoring of changes in soil properties with time.
EO data on vegetation can also be used in model inversions to obtain information on the properties of soils at depth, that are accessed indirectly through vegetation, such as the maximum water holding capacity of the soil: for example, if a revisit of remote sensing is carried out in summer, we can estimate the quantity of water contained in the soil as a function of the yellowing or the thermal response of the vegetation, but we obtain it indirectly. Remote sensing data can also be used for assimilation; this involves readjusting/reinforcing models.

[247] Vaudour, E., Gholizadeh, A., Castaldi, F., Saberioon, M., Borůvka, L., Urbina-Salazar, D., ... & Van Wesemael, B. (2022). Satellite imagery to map topsoil organic carbon content over cultivated areas: An overview. Remote Sensing, 14(12), 2917. (https://doi.org/10.3390/rs14122917)
[248] McBratney, Alex B., ML Mendonça Santos, and Budiman Minasny. "On digital soil mapping." Geoderma 117.1-2 (2003): 3-52. (https://doi.org/10.1016/S0016-7061(03)00223-4)
[249] Arrouays D., McKenzie N., Hempel J., Richer-de-Forges A.C., McBtratney A.B. (Eds.). (2014). GlobalSoilMap: Basis of the global spatial soil information system. London. CRC Press Taylor & Francis Group. 494 p. https://doi.org/10.1201/b16500

Airborne gamma-ray spectrometry has 2 specific features: it is very little affected by the vegetation cover, and the signal measured at the soil surface usually originates from the soil between 0 to 30-60 cm depth. It is widely used by the French BRGM. Thanks to BRGM, we're using gamma-ray spectrometry to improve the distribution maps of clay, silt and sand (in %), and it's working fairly well[250]. For forest soils in France, a possible added value to the use of gamma-ray spectrometry data for digital soil mapping is the use of the very large number of *in situ* observations of soil texture classes estimated only in the field (i.e., uncertain qualitative data). These data enabled us to discover unexpected spatial structures, and produced highly accurate maps[251].

A number of satellites and sensors have recently been launched, or are about to be, opening up major prospects:

- The PRISMA satellite (*PRecursore IperSpettrale della Missione Applicativa*) is an EO satellite of the Italian Space Agency (ASI) that was put into orbit in 2019. The aim of this experimental satellite is to provide Italy with its own EO capability in the optical field and to acquire expertise in the various techniques for acquiring images from space, in particular the hyperspectral imaging technique;
- Sentinel-10 or CHIME (*Copernicus Hyperspectral Imaging Mission for the Environment*) is a European Space Agency Earth observation satellite that will use hyperspectral imaging to provide useful data for agriculture, food security, soil condition, biodiversity, natural disasters, coastal and inland waters and forests. The satellite is due to be placed in sun-synchronous orbit around 2029. It will have a resolution of 30 m and will be revisited every 25 days.

As partial conclusions to this interview:

- Digital Soil Mapping methods can considerably improve soil mapping and could, under certain conditions, be one of the tools for soil monitoring. They make it possible to estimate certain soil properties indirectly and fairly reliably outside the sites where these properties have been characterized, thanks to the use of various environmental covariates, as long as these covariates are related to- are PROXI of the targeted soil property. *A priori*, the generic SCORPAN method is the one recognized by the entire soil science community. The possibility of explicitly taking into account qualitative and uncertain variables (e.g., belonging to a texture class based on a field assessment) may open the door to the use of data from citizen sciences (e.g., smartphone photography of soil surface). However, if the aim is not only to refine soil mapping, but also to use such method for soil monitoring, it is imperative that some of the relevant environmental

[250] Loiseau, T., Richer-de-Forges, A.C., Martelet, G., Bialkowski, A., Nehlig, P., & Arrouays, D. (2020). Could airborne gamma-spectrometric data replace lithological maps as co-variates for digital soil mapping of topsoil particle-size distribution? A case study in Western France. Geoderma regional, 22, e00295. (https://doi.org/10.1016/j.geodrs.2020.e00295)

[251] Eymard, A., Richer-de-Forges, A.C., Martelet, G., Tissoux, H., Bialkowski, A., Dalmasso, M., ... & Arrouays, D. (2024). Exploring the untapped potential of hand-feel soil texture data for enhancing digital soil mapping: Revealing hidden spatial patterns from field observations. Geoderma, 441, 116769. (https://doi.org/10.1016/j.geoderma.2023.116769)

covariates allow us to take into account the controlling factors and hazards explaining certain soil degradations;
- The use of airborne gamma-spectrometry differs from most other methods in that it is very little affected by the presence of vegetation cover, and explores soil depths of around 30-60 cm. Combined with the associated wavelengths, it is perfectly suited to characterizing several soil properties.

V.3. The use of satellite-based EO in EU projects (Horizon Europe and EJP Soil)

Eleven European projects initiated in 2020 or later, dealing with soil health monitoring and using remote sensing data at least partially, were identified: respectively 1, 1, 4, and 5 projects were/are supported by the FCUP, the ESA, the EJP Soil or the Horizon Europe programme. 3 of these projects are now completed (**Tables 2** and **5**). **Annexe III** presents all the responses to the survey. These responses are obviously much richer than the small summary we provide here, and we strongly suggest that interested readers take the time to read them in full.

Of these 11 projects, only 3 deal with soil health with a relatively broad vision: AI4SoilHealth, BENCHMARKS and CUP4SOIL. These projects differ in their objectives and aims: BENCHMARKS pursues very broad objectives around soil monitoring and uses remote sensing as a means of observation among others; AI4SoilHEalth is more focused on data processing and the use of artificial intelligence with the development of a soil health assessment toolbox and a web application based cyber infrastructure to serve users; and CUP4SOIL aims to promote the use of CLMS data to monitor soil health, *via* the contribution to a CLMS downstream service and the provision of new products on soils (**Table 5**).

The other 8 projects were/are dedicated to soil organic carbon storage, and some also to greenhouse gas emissions. Most have a strong methodological dimension.
The ESA's WorldSoils and the SensRes projects, which has been completed, and the STEROPES and ProbeField projects currently underway can be seen as methodological projects aimed at estimating SOC stocks and their variations in the soil. STEROPES focused on spectral models from the reflectance image spectra of optical satellites to estimate surface SOC and improve these models by taking into account disturbing/influencing factors (soil moisture, texture, vegetation, salinity) as well as other ancillary data (environmental covariates). ProbeField focuses on the methodological improvement of the use of proximal or UAV Vis-NIRS sensors by correcting for moisture and stimulate the use of these sensors by providing cost/accuracy information. And SensRes project focused on downscaling soil properties.

Project	Topic	Main objectives[1]	Strengths, points for attention, risks	Main results
ESA WorldSoils *(slide-show presented in July 2022)*	Topsoil SOC maps using Sentinel	**(1)** Develop a pre-operational monitoring system to estimate topsoil SOC, exploiting EO data, leveraging large soil data archives and modelling techniques and taking into account cloud environment; **(2)** developing soil indices relevant for monitoring the global top soils	**Strengths:** Combining direct spectral estimation and digital soil mapping, using yearly composites of Sentinel data, well documented, operational service: https://gui.world-soils.com/ **Point of attention:** No other soil properties, continuation of time series needs new funding. Maps would benefit from more harmonised point data	SOC content maps incl. uncertainty 100 m EU, 50 m regional per year, integrating 3 years of Sentinel 2 imagery 11 peer reviewed publications https://world-soils.com/resources/publications/ User requirements document
SensRes	Downscaling soil properties (SOC, soil texture)	Downscale soil maps using sensing products, extrapolation of the models to other fields	**Strengths:** potential decrease in the need for reference data at field scale **Point of attention:** Requires soil maps as start	A model for downscaling soil properties (https://github.com/anbm-dk/soilscaler)
STEROPES	**Stock of SOC:** methodology: Satellite data	**(1)** spectral models from the reflectance image spectra of optical satellites, **(2)** account for disturbing/influencing factors (soil moisture, texture, vegetation, salinity), **(3)** ancillary data to improve predictions and incorporate results in spatial models	**Point of attention:** clouds, soil roughness, need to harmonize SOC determination methods **Risks:** bare soil rarely appearing	https://doi.org/10.3390/rs14122917 https://doi.org/10.1016/j.isprsjprs.2023.03.016 https://doi.org/10.3390/rs15092410 https://doi.org/10.3390/rs15092410 https://doi.org/10.3390/w16010040 https://doi.org/10.3390/rs15174264
CUP4SOIL *(Summary and slide-show presented on 7 February 2024)*	Prepare future soil products within the CLMS	**(1)** Enhance the user uptake of existing CLMS data, thanks to the development of a CLMS downstream service to support the reporting on soil health/quality, and **(2)** generate European-wide data products and indicators characterising soil health/quality.	**Strengths:** several soil property maps derived using digital soil mapping methodology with advanced EO derived covariates. Includes uncertainty maps User requirement survey **Point of attention:** still to be identified, ongoing work	*Too early* reporting and products expected end of 2024/early 2025
AI4SoilHealth	Co-design, create and maintain a European digital infrastructure,	**(1)** Develop a framework for indicator selection and testing; **(2)** Develop a soil health assessment toolbox combining spectroscopy, genomics, *in-situ* measurements, etc.; **(3)** Develop a web appl. based cyber infrastructure to serve	**Strengths:** Landsat time-series 2000-2022 bimonthly indices allowing to determine long-term trends and identify their key drivers, as well as allowing to follow crop rotations and quantify effects of seasonal events.	Gully erosion mapped using Landsat indices (https://www.kaggle.com/competitions/esa-eo4soilprotection-2024-predicting-erosion-cat/)

	using state-of-the-art Artificial Intelligence (AI) methods for assessing and continuously monitoring Soil Health	users with current data at farm scale with a secure API; **(4)** Develop and deploy the EO-based soil monitoring (CLMS data as covariates for soil property mapping;); **(5)** Test, harmonize and update the proposed indicators and define acceptable limits or thresholds.	**Point of attention: (i)** Limited quality and spatial resolution of Landsat data. Sentinel-2 images are about 5–10 times more detailed and come with less artifacts, but are more expensive to process (higher data volume) and are only available since 2016; **(ii)** inter-annual variability in biophysical indices often needs to be filtered when it results from climatic oscillations that do not affect changes in soil properties; (iii) collecting and using a large amount of soil data requires significant effort which is essential for fully understanding the maximum potential of using EO images for soil monitoring	Eurostat data compared with results obtained from Landsat / Sentinel-2 biophysical indices (https://doi.org/10.21203/rs.3.rs-4251113/v1)
BENCHMARKS		**(1)** Co-develop a coherent Integrated Soil Health Monitoring Framework, **(2)** test the Soil Mission indicators as well as alternative / additional indicators (applicability of EO sensors for retrieving soil health indicators, and (ii) using satellite data for predictive mapping using AI), **(3)** develop a sampling framework (EO data for soil sampling designs)	**Strengths:** Optimizing soil sampling; Assessing within field variability of soil health indicators and context-specific variability; Mapping of proxy indicators **Point of attention:** Accuracy (studied i) depends on the scale of assessment, land use and the spatial and spectral resolution of the sensors; Validation of the soil variables modelled requires sufficiently recent chemical, physical and biological soil data, with possible problems of harmonization.	*Too early*
MARVIC	Carbon farming	**(1)** Develop and test a framework for the design of harmonized, context-specific MRV[2] systems for assessing carbon stock changes in soils, woody biomass and soil GHG emissions (analyse how to use EO data in the Monitoring and verification components of MRV); **(2)** Investigate how different building blocks of (farm) data, sampling	**Strengths:** Various information issued from satellite: superficial soil water / C contents and albedo when the soil is bare; biomass, phenology, soil coverage; time series of biophysical products (e.g. LAI) assimilated in soil / crop models to estimate biomass input to the soil and soil water dynamics; mapping agricultural practices (tillage, cover crops…);	Development of the AgriCarbon-EO processing chain assimilating EO data in a model to Monitor SOC stock changes (common to OrCaSa (CSA) and MARVIC (RIA)); A methodological framework on how to use EO data to monitor SOC stock changes.

		strategies (Use EO data), benchmark sites, models and remote and proximal sensing technologies could efficiently be connected into operational processing chains (some of them will involve EO data assimilation in a coupled crop-soil models);	**Points of attention / Risks: (i)** gaps in observations during cloudy periods (we are working on the combined use of optical and radar satellite data to produce continuous time series of biophysical indicators (e.g., LAI)); **(ii)** the spatial resolution of satellite data (we are analysing the potential of assimilating higher-resolution data into crop/soil models from private constellations such as Planet).	
MRV4SOC	**Monitoring SOC and GHG balance**	**(1)** assess how C farming practices, socio-economic pressures and climate change impact SOC accumulation, **(2)** develop a MRV[2] to ensure transparency, robustness, and cost-effectiveness and facilitate results-based payments and seek out revenue opportunities to unlock these payments with RS[3] data inputs for modelling approaches, **(3)** increase stakeholders' faith in Voluntary Carbon Markets.	**Strengths:** Spatial, spectral and temporal resolutions; Global cover; Non-invasive; Quality assurance; Dataset generally free. **Point of attention:** Very coarse spatial resolutions; Cloud and atmosphere attenuations; Deterioration of satellite sensors; Data processing (Cost, Harmonization of spectral libraries ...); Data sharing with regard to privacy, and data ownership rights. **Risks:** Impact of data quality, calibration and validation on public decision;	*Too early*
OrCaSa	Carbon farming	**(1)** prepare the launch of the International Research consortium on soil carbon; **(2)** Define a strategic research and innovation agenda; **(3)** develop a knowledge platform **(4)** Propose a unified methodological framework for MRV and a first prototype of operational SOC monitoring (analyse how to use EO data in the Monitoring and verification components of MRV; develop a	*The same general strengths, points of attention and risks as for MARVIC project.*	Development of the AgriCarbon-EO processing chain assimilating EO data in a model to Monitor SOC stock changes (common to OrCaSa (CSA) and MARVIC (RIA)); Assessment of how EO data could be used in the MRV process for M and V (https://www.isric.org/sites/default/files/ORCASA_D4-1_FinalDeliverable_InReviewByEU_0.pdf)

		prototype of operational processing chain for Monitoring SOC stock changes at cropland involving EO data assimilation in a coupled crop-soil model (AgriCarbon-EO processing chain).		(3) Development of a methodological framework on how to use EO data to monitor SOC stock changes
ProbeField	**Stock of SOC:** methodology: proximal and UAV Vis-NIRS	**(1)** Spectral soil sampling and measurement in the field, **(2)** application of lab-based soil spectral libraries to field-obtained soil spectra, **(3)** best practice advice for converting 1 or 2D measurements into 3D information	**Strengths:** taking into account covariates **Point of attention:** impact of soil texture, nutrients	https://www.sciencedirect.com/science/article/pii/S0016706123003130 https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/sum.12952 https://www.tandfonline.com/doi/full/10.1080/05704928.2022.2128365
SANCHO's THIRST	**Cover crop for sustainable soil management** in woody crops (SOC...)	**(1)** Deepen the knowledge on Carbon sequestration, (**2**) Identification/ quantification of ecosystem services andthe development of a composite indicator, (**3**) Improving SOC predictions from satellite imagery and/or UAV with multispectral, hyperspectral and RGB imagery by considering disturbing factors (texture, roughness, iron oxide compounds)	**Risks:** Multi-effects of certain variables can hinder SOC prediction	*Too early*

[1]: We have focused on scientific, methodological, technological and technical objectives. We have not included other equally important objectives (Data acquisition; Make sure to follow the FAIR principles; Networking; Cooperation with other projects; Development of an end-user community; Communication, dissemination and exploitation; Soil literacy; Capacity building; Policy and stakeholder engagement; Support activities (to the JRC, the EUSO, etc.)

[2]: Measuring, Reporting and Verification [3]: Remote sensing

Table 5: Main topics, objectives, strengths, points for attention, risks and main results of European research projects dedicated to soil health and using, at least in part, remote sensing data.

MRV4SOC and MARVIC are both concerned with carbon farming, and provide two different approaches to design harmonized, context-specific MRV systems for assessing carbon stock changes in soils, woody biomass and soil GHG emissions. ORCaSa is a CSA (Coordinating and Supporting Action) and has set up the International Research consortium (IRC). It is also closely linked to the MARVIC project on the MRV systems design.
Finally, SANCHO's THIRST is more interested in SOC storage associated with cover crops for sustainable soil management in woody crops.

The recognized strengths of remote sensing are its spatial, spectral and temporal resolutions, its ability to provide a global coverage, its non-invasive nature, and the fact that data sets are generally free of charge and quite easily accessible. It can be used to assess within-field variability of soil health indicators and context-specific variability, to map PROXYs and to optimise soil sampling. Satellites provide access to a wide range of information: surface water and organic carbon content, as well as albedo for bare soil; biomass, phenology, soil cover; time series of biophysical products (e.g., LAI) assimilated in soil/crop models to estimate the contribution of biomass to the soil and soil water dynamics; mapping of agricultural practices (tillage, cover crops, etc.). However, these advantages depend on the sensors (including their age), etc. For example, Landsat's 2000-2022 bimonthly time series can be used to determine long-term trends and identify their main drivers, as well as tracking crop rotations and quantifying the effects of seasonal events, but the spatial resolution and revisit frequency of Sentinel-2 images are better, but they are more expensive to process (due to the greater volume of data) and have only been available since 2016.

Unfortunately, the use of remote sensing data also presents various weaknesses/risks: (i) gaps in observations during cloudy periods for optical sensors, (ii) the need to take into account disturbing factors (soil texture, roughness, nutrients, iron oxide compounds, etc.) and the need to harmonize the products derived from different sensors, especially throughout time, , (iii) the shallow penetration depth in soil of a millimetre for optical satellites and limited penetration by SAR of up to 15 – 20 cm, (iv) the sometimes coarse spatial resolution of satellite data, (v) the inter-annual variability of biophysical variables, which often needs to be filtered out when it results from climatic oscillations that do not affect changes in soil properties, and (vi) the need for sufficient recent chemical, physical and biological soil data to parameterize models using remote sensing data. Some of these weaknesses lead to additional research: e.g. MARVIC project a work on the combined use of optical and radar satellite data to produce continuous time series of biophysical indicators (e.g. LAI)), and on the assessment of the potential of assimilating higher-resolution data into crop/soil models from private constellations such as Planet. And various projects explicitly take into account disturbing factors.

V.4. Inventory of existing data and products linked to European services (CLMS)

CLMS offers a diverse range of reliable, ready-to-use products for soil studies (**Table 6**). These products can be broadly categorized into land cover data and vegetation data. Land cover products, such as CORINE Land Cover, are the cornerstone of CLMS, providing crucial information on European land cover/land use for over three decades[252].

---

[252] *CORINE Land Cover*. (n.d.). Retrieved May 20, 2024, from https://land.copernicus.eu/en/products/corine-land-cover

Service	Product name	Satellite	Temporal coverage	Spatial resolu-tion	Spatial coverage
CLMS	**Global land cover**	PROBA-V	2015-2019 (Updated yearly)	100 m	Global
CLMS	**CORINE Land cover**	Lansat-5 MSS/TM (1990) Landsat-7 ETM (2000) SPOT-4/5 (2006) IRS P6 LISS III (2006, 2012) RapidEye (2012) **Sentinel 1/2 (2018)**	1990, 2000, 2006,2012, 2018 (Updated 6-yearly)	100 m	Europe
CLMS	**Leaf Area Index (LAI)**	SOPT/VEGETATION (1km) **PROBA-V** (300m, 1km) **Sentinel-3 OLCI (300m)** (present)	**LAI 1km**: 1999 – June 2000 **LAI 300m**: Jan 2014 - present (Updated 10 daily)	1 km 300 m	Global
CLMS	**Normalized Difference Vegetation Index (NDVI)**	SPOT VEGETATION **PROBA-V** **Sentinel-3 OLCI** (Present)	**NDVI 1km**: 1998-2020 **NDVI 300m**: 2014 – present (Updated 10 daily)	1 km 300 m	Global
CLMS	**Fraction of green Vegetation Cover (FCover)**	SPOT VEGETATION PROBA-V Sentinel-3 OLCI (present)	**FCover 1km**: 1999-2020 **FCover 300m**: Jan 2014-presence (Updated 10 daily)	1 km 300 m	Global
CLMS	**Forest Type**	Sentinel-2 (2018)	2012, 2015, 2018 (Updated 3-yearly)	10 m 100 m (2018)	Europe
CLMS	**Burnt Area**	Sentinel-3 OLCI and SLSTR	2023 – present (Updated daily)	300 m	Global
CLMS	**Soil Water Index (SWI)**	Sentinel-1 C-SAR and Metop ASCAT	Jan 2015 – present (Updated daily)	1 km	Europe
CLMS	**Surface Soil Moisture (SSM)**	Sentinel-3 C-SAR	Oct 2014 – present (Updated daily)	1 km	Europe
CLMS	**Plant Phenology Index**	Sentinel-2	Oct 2016-present (Updated daily)	10 m	Europe

CLMS	**Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)**	SPOT VEGETATION PROBA-V **Sentinel-2** (present)	1999–June 2020 (Updated 10 daily) Oct 2016-present (Updated daily)	1 km 10 m	Global Europe
CLMS	**Dry Matter Productivity (DMP)**	SPOT VEGETATION **PROBA-V** **Sentinel-3/OLCI** (present)	1999-June 2020 2014-present (Updated 10 daily)	1 km 300 m	Global
Theia (Fr)	**OSO Land Cover product**	Sentinel-2	2018, 2019, 2020, 2021 (Updated yearly)	10 m (raster) 20 m (vector)	France
Theia (Fr)	**Vegetation variables (GEOV2-AVHRR)**	NOAA AVHRR LTDR	1987-present (Updated 6-yearly)	4 km	Global
Theia (Fr)	**Very High Spatial Resolution (VHSR) Soil Moisture**	Sentinel-1/2	Product on request 2016-2021in France	10 m	France, the EU, and the Mediterran ean basin
ESA (Eu)	**WorldCover**	Sentinel-1/2	2021, 2021	10 m	Global
NASA (US)	**Global Forest Canopy Height**	GEDI	2019	30 m	Global
NASA (US)	**Terra MODIS Vegetation Continuous Fields (VCF)**	Terra Modis	2000-present (Updated yearly)	250 m	Global

Table 6: List of CLMS, French national, European and international freely-available satellite-derived products.

They are widely utilized in environmental monitoring[253] [254], land degradation detection[255] and land use planning[256] [257].

[253] Büttner, G. (2014). CORINE Land Cover and Land Cover Change Products. In I. Manakos & M. Braun (Eds.), *Land Use and Land Cover Mapping in Europe: Practices & Trends* (pp. 55–74). Springer Netherlands. (https://doi.org/10.1007/978-94-007-7969-3_5)
[254] Feranec, J., Soukup, T., Hazeu, G., & Jaffrain, G. (2016). *European Landscape Dynamics: CORINE Land Cover Data*. CRC Press.
[255] Bajocco, S., De Angelis, A., Perini, L., Ferrara, A., & Salvati, L. (2012). The Impact of Land Use/Land Cover Changes on Land Degradation Dynamics: A Mediterranean Case Study. *Environmental Management*, *49*(5), 980–989. (https://doi.org/10.1007/s00267-012-9831-8)
[256] Feranec, J., Jaffrain, G., Soukup, T., & Hazeu, G. (2010). Determining changes and flows in European landscapes 1990–2000 using CORINE land cover data. *Applied Geography*, *30*(1), 19–35. (https://doi.org/10.1016/j.apgeog.2009.07.003)
[257] Abbott, E. H., Ballard, J. H., English, J. T., Isaacson, D., Sivavec, T. M., & Turpening, R. M. (2002). Environmental remote sensing for monitoring plant health. *Center for Research and Technology Development, (Publication) CRTD, American Society of Mechanical Engineers*, *61*, 105–114. Scopus.

Vegetation data, including vegetation variables, indices, and soil moisture measurements, are essential soil indicators as well. LAI, defined as one-half the total green leaf area per unit of horizontal ground surface, is an important structural property of vegetation. It can be used to describe plant canopy structure[258] [259], understand vegetation change[260], and model land surface processes[261]. Furthermore, FCover, which refers to the green fractional vegetation cover, can effectively quantify the spatial extent and amount of vegetation; therefore, this indicator is good for the monitoring of ecosystems and agriculture management[262] [263]. Moreover, NDVI, the most commonly used indicator of the greenness of the biomes, is used to assess the vegetation type[264], forest management[265] [266], land use monitoring[267] [268]. Moreover, several vegetation products related to the water content of the top or depth soil are also available (e.g., European SMOS geo-located soil moisture products, US SMAP soil moisture products), especially for water management, weather forecasting, and ecological modelling[269].

---

[258] Goel, N. S., & Qin, W. (1994). Influences of canopy architecture on relationships between various vegetation indices and LAI and Fpar: A computer simulation. *Remote Sensing Reviews*, *10*(4), 309–347. (https://doi.org/10.1080/02757259409532252)

[259] Stenberg, P., Linder, S., Smolander, H., & Flower-Ellis, J. (1994). Performance of the LAI-2000 plant canopy analyzer in estimating leaf area index of some Scots pine stands. *Tree Physiology*, *14*(7-8–9), 981–995. (https://doi.org/10.1093/treephys/14.7-8-9.981)

[260] Nemani, R. R., Running, S. W., Pielke, R. A., & Chase, T. N. (1996). Global vegetation cover changes from coarse resolution satellite data. *Journal of Geophysical Research: Atmospheres*, *101*(D3), 7157-7162. (https://doi.org/10.1029/95JD02138)

[261] Sabater, J. M., Rüdiger, C., Calvet, J.-C., Fritz, N., Jarlan, L., & Kerr, Y. (2008). Joint assimilation of surface soil moisture and LAI observations into a land surface model. *Agricultural and Forest Meteorology*, *148*(8), 1362–1373. (https://doi.org/10.1016/j.agrformet.2008.04.003)

[262] Carlson, T. N., Perry, E. M., & Schmugge, T. J. (1990). Remote estimation of soil moisture availability and fractional vegetation cover for agricultural fields. *Agricultural and Forest Meteorology*, *52*(1), 45–69. (https://doi.org/10.1016/0168-1923(90)90100-K)

[263] Chu, D. (2020). Fractional Vegetation Cover. In D. Chu (Ed.), *Remote Sensing of Land Use and Land Cover in Mountain Region: A Comprehensive Study at the Central Tibetan Plateau* (pp. 195–207). Springer. (https://doi.org/10.1007/978-981-13-7580-4_10)

[264] Smith, G., Kleeschulte, S., Soukup, T., Garcia, R., Banko, G., & Combal, B. (2021). An Operational Service for Monitoring Grassland Dominated Natura2000 Sites with Copernicus Data. *2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS*, 731–734. (https://doi.org/10.1109/IGARSS47720.2021.9554934)

[265] Maselli, F. (2004). Monitoring forest conditions in a protected Mediterranean coastal area by the analysis of multiyear NDVI data. *Remote Sensing of Environment*, *89*(4), 423–433. (https://doi.org/10.1016/j.rse.2003.10.020)

[266] Wang, Q., Adiku, S., Tenhunen, J., & Granier, A. (2005). On the relationship of NDVI with leaf area index in a deciduous forest site. *Remote Sensing of Environment*, *94*, 244–255. (https://doi.org/10.1016/j.rse.2004.10.006)

[267] Usman, M., Liedl, R., Shahid, M. A., & Abbas, A. (2015). Land use/land cover classification and its change detection using multi-temporal MODIS NDVI data. *Journal of Geographical Sciences*, *25*(12), 1479–1506. (https://doi.org/10.1007/s11442-015-1247-y)

[268] Baeza, S., & Paruelo, J. M. (2020). Land Use/Land Cover Change (2000–2014) in the Rio de la Plata Grasslands: An Analysis Based on MODIS NDVI Time Series. *Remote Sensing*, *12*(3), Article 3. (https://doi.org/10.3390/rs12030381)

[269] Hunt, E. D., Hubbard, K. G., Wilhite, D. A., Arkebauer, T. J., & Dutcher, A. L. (2009). The development and evaluation of a soil moisture index. *International Journal of Climatology*, *29*(5), 747–759. (https://doi.org/10.1002/joc.1749)

Despite their various applications, CLMS products share some common features. Most CLMS products are derived from European satellites, such as the Sentinel family (1,2,3), SPOT-VEGETATION, and PROBA-V. Additionally, with the recently launched satellite (e.g., Sentinel), the spatial resolution of new-released products is improved significantly (e.g., FAPAR, Plant Phenology Index).

Besides CLMS products, national products are derived by services set up by EU countries, such as the Theia product centre in France products which provide similar but more precise data (for example, the OSO land cover map and CORINE Land Cover distinguish 6 and 7 different vegetation types. However, OSO identifies only those types of vegetation in France, which makes it more suitable for this country) and at a higher spatial resolution (usually 10m). Compared to European-scale products, national data with high resolution can offer more accurate soil study results, especially when concentrating on small study areas. It is, therefore, common for French researchers to use Theia data to seek high-accuracy results[270] [271].

Additionally, products from other international agencies not proposed by CLMS or any European services are used as supplementary data in European soil studies, such as the Global Ecosystem Dynamics Investigation (GEDI), and VCF from NASA[272] [273].

It should be added that there is also the Google Earth Engine (GEE) service[274,275], which provides collections of European satellite images (Sentinel 1, 2, 3 and 5), images of American satellites (Landsat 4, 5 , 7, 8 and 9; Modis) as well as numerous processed data (digital terrain models and their topographical derivatives, land use classifications, demographic data, interpolated meteorological data, night light intensity, etc.). The GEE service allows you to perform processing of data shared in the web cloud and quickly visualize the results using JS or Python scripts run from a web browser, starting from cloud masking to create complex machine learning models.

[270] Stoian, A., Poulain, V., Inglada, J., Poughon, V., & Derksen, D. (2019). Land Cover Maps Production with High Resolution Satellite Image Time Series and Convolutional Neural Networks: Adaptations and Limits for Operational Systems. *Remote Sensing*, *11*(17), Article 17. (https://doi.org/10.3390/rs11171986)

[271] Yang, X., Qin, Q., Yésou, H., Ledauphin, T., Koehl, M., Grussenmeyer, P., & Zhu, Z. (2020). Monthly estimation of the surface water extent in France at a 10-m resolution using Sentinel-2 data. *Remote Sensing of Environment*, *244*, 111803. (https://doi.org/10.1016/j.rse.2020.111803)

[272] Tommaso, S. D., Wang, S., & Lobell, D. B. (2021). Combining GEDI and Sentinel-2 for wall-to-wall mapping of tall and short crops. *Environmental Research Letters*, *16*(12), 125002. (https://doi.org/10.1088/1748-9326/ac358c)

[273] Schwartz, M., Ciais, P., Ottlé, C., De Truchis, A., Vega, C., Fayad, I., Brandt, M., Fensholt, R., Baghdadi, N., Morneau, F., Morin, D., Guyon, D., Dayau, S., & Wigneron, J.-P. (2024). High-resolution canopy height map in the Landes forest (France) based on GEDI, Sentinel-1, and Sentinel-2 data with a deep learning approach. *International Journal of Applied Earth Observation and Geoinformation*, *128*, 103711. (https://doi.org/10.1016/j.jag.2024.103711)

[274] Gorelick N. ; Hancher M., Dixon M., Ilyushchenko S., Thau D., Moore R., 2017, Google Earth Engine : Planetary Scale Geospatial Analysis for Everyone. Télédétection. Environ. 202, 18-27. (https://doi.org/10.1016/j.rse.2017.06.031)

[275] Zhao Q., Yu L., Li X., Peng D., Zhang Y., Gong P., 2021, Progress and Trends in the Application of Google Earth and Google Earth Engine. Remote Sens, 13, 3778. (https://doi.org/10.3390/rs13183778)

V.5. The current use of satellite-based Earth Observation in the dashboard of the EUSO

Table 7 presents the EO data that are currently used by the EUSO dashboard. The product that is the most exploited is the CORINE Land Cover (CLC) map that is used as ancillary data to estimate (i) water, wind, harvest and tillage erosions, (ii) mercury; zinc and phosphorus excess, (iii) Soil Organic Carbon (SOC), as well as threat to biological functions, showing that the Land Cover is one of the primary main driver of soil surface properties. CLC maps are currently available at 100 m resolution. It can be noted that complementary data at higher resolution (coming from SPOT4, IRS LISS) were also used for these mapping purposes. However, with the launch of SENTINEL-2 since 2017 and other commercial constellations (e.g., PLANETSCOPE), there is high potential to obtain LULC maps at spatial resolution higher than 10m (like the ESA Worldcover map for example).

Digital Elevation Models (DEM) are also mandatory for the estimation of many soil characteristics (water and tillage erosions; copper, mercury, zinc and phosphorus excess). The product currently used is delivered by the NASA (SRTM and ASTER sensors), with a spatial resolution of 25 m. However, the Copernicus Global Land Service provides a DEM at 30 m resolution (GLO-30) every year since 2019 using Tandem-X data that could be considered as a good alternative.

Products characterizing the status of the vegetation at the soil surface are also often used and are of two kinds:

- Vegetation indices derived from the NASA MODIS products used to estimate water, wind and tillage erosions; or copper, mercury, zinc and phosphorus excess. In the process of these estimations, vegetation indices are mainly used to detect bare soil. It can be noticed however that the CLMS delivers similar products from European Sensors;
- Fractional Vegetation cover is used to quantify the amount of vegetation occurring at the Earth surface (water, tillage and post-fire erosions). The Copernicus Global Land Service is the only provider of such a product (that are derived from European sensors such as VEGETATION, PROBAV, or SENTINEL-3).

Finally, fire products from the CLMS are also used to evaluate post-fire erosion and thermal infrared data from the USGS LANDSAT mission are exploited for Mercury Excess. The European LSTM (launch in 2028, 50 m resolution) together with the French TRISHNA (launch 2025, spatial resolution 30m) missions could therefore be good candidates for this purpose.

Some soil indicators (soil compaction soil salinization, peatland degradation) do not use directly EO data while some of them (salinization, peatland) use maps derived from EO ((irrigated areas, FAO peatland map, UNEP). It can also be noticed that soil nutrients indicators require the combined use of ground observation (e.g., LUCAS points) with EO data are used to ensure more robust spatial interpolation.

SOIL DEGRADATION INDICATOR	EO Product available: CLMS	EO Product available: Galileo EGNOS	EO Product available: Other	Sensor used to derive the product	Auxiliary data used to estimate the indicator (Please complete this information only when Earth Observation (EO: satellite, UAV, airborned sensor) are involved)	Current spatial resolution/ revisit frequency
Soil erosion						
Water erosion	Yes	No	Yes	NSRTM, SPOT 4/5, SPOT VEGETATION, RapidEye, IRS P6 LISS II	Land cover, vegetation statistics, digital elevation model	100m / not specified
Wind erosion	Yes	No	Yes	MODIS, Landsat/Terra	Bare soil (%), snow cover, land cover, field boundaries	100m / not specified
Harvest erosion	Yes	No	Yes	SPOT 4/5, RapidEye, IRS P6 LISS II	Land cover	100m / not specified
Tillage erosion	Yes	No	Yes	Sentinel–1, MERIS, SRTM, ASTER, Landsat-5 MSS/TM, Landsat-7 ETM, SPOT-4/5, IRS P6 LISS III, MODIS	Land cover, digital elevation model, land management, vegetation statistics	100m / not specified
Post-fire erosion	No	No	Yes	MERIS, PROBA-V, Sentinel-3/OLCI and SLSTR, Sentinel-2	Burnt area, vegetation statistics, land cover	25m /annual
Soil pollution						
Copper	Yes	No	Yes	IRS P6 LISS III, RapidEye, MODIS, SRTM, ASTER	Land cover, vegetation statistics (evi), digital elevation model	500m / not specified
Mercury	Yes	No	Yes	IRS P6 LISS III, RapidEye, MODIS, SRTM, ASTER, Landsat	Land cover, vegetation statistics (evi), digital elevation model, reflectance, surface temperature	100m / not specified
Zinc	No	No	Yes	SPOT-4/5, IRS P6 LISS III, SRTM, ASTER, Landsat 7	Land cover, digital elevation model, vegetation statistics	250m / not specified
Soil nutrients						
Nitrogen surplus	No	No	No			LUCAS points
Phosphorus deficiency	Yes	No	Yes	SRTM, ASTER, MODIS, IRS P6 LISS III, RapidEye	Land cover, digital elevation model, vegetation statistics, reflectance	LUCAS points
Phosphorous excess	Yes	No	Yes	SRTM, ASTER, MODIS, IRS P6 LISS III, RapidEye	Land cover, digital elevation model, vegetation statistics, reflectance	LUCAS points
Loss of soil organic carbon						
Distance to maximum SOC level	Yes	No	No	SPOT-4/5, IRS P6 LISS III, RapidEye, Sentinel-2 and Landsat-8	Land cover	500m / 4-6 years
Loss of soil biodiversity						
Potential threat to biological functions	Yes	No	No	IRS P6 LISS III, RapidEye	Land cover	4-6 years
Soil compaction						
Susceptibility to soil compaction	No	No	No			500 m / Not specified
Soil salinization						
Secondary salinization risk	No	No	Yes			500 m / Not specified
Loss of organic soils						
Peatland degradation risk	No	No	Yes			1 km / Not specified
Soil consumption						
Soil sealing	Yes	No	Yes	Sentinel–2	Impervious built-up layers	10m / every 3 years

Table 7: Earth Observation product currently used by the EUSO dashboard (personal communication, Arwyn Jones, Cristina Arias Navaroo, and Timo Breure, 20th March 2024)

V.6. An example: estimating diffuse water erosion using RUSLE model

In this subsection, we present an example comparing RUSLE application for a mixed landscape in France (the area around Dijon), using either European data (JRC RUSLE-2015), or national French database with notably finer spatial and temporal resolutions. As detailed in subsection **IV.6.** (Table 4), we first validated our RUSLE implementation by benchmarking the different factors with the 2015 JRC map when it was possible (e.g., when exactly the same input data were still available). These results relate therefore to the LS and C factor only. We then generated the RUSLE map in 2018 using either European or French data.

R factor estimation: The map of R factor near Dijon issued from JRC rain erosivity assessment (RUSLE-2015) is presented in **Figure 6(a)**, while the map of the same factor issued from COMEPHORE

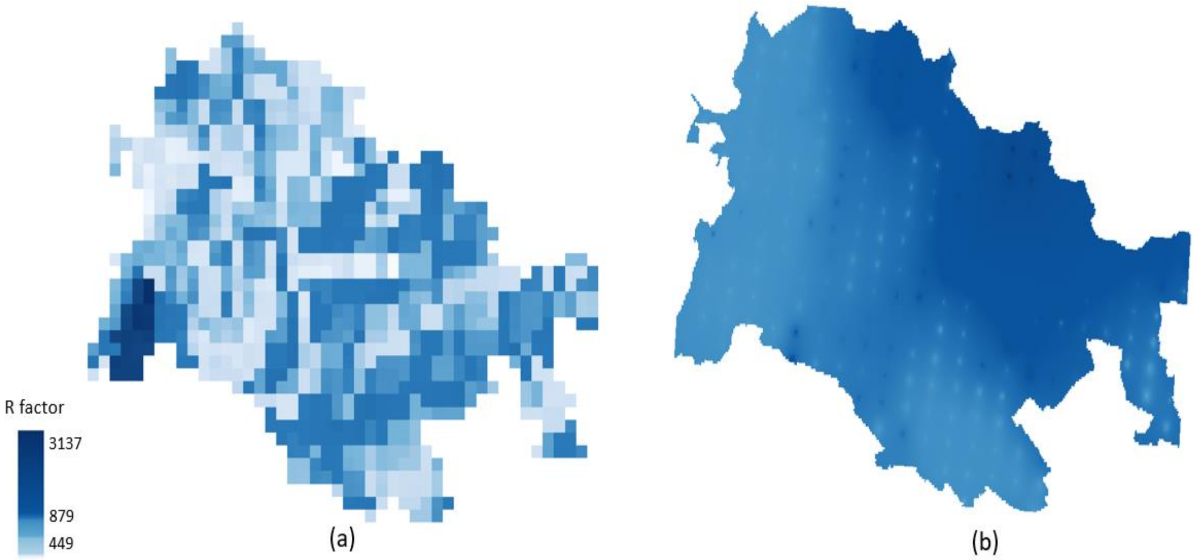


Figure 6: R factor estimated in **(a)** JRC RUSLE 2015 (using data from Météo-France DP/SERV/FDP) and in **(b)** RUSLE 2018 (using data from COMEPHORE).

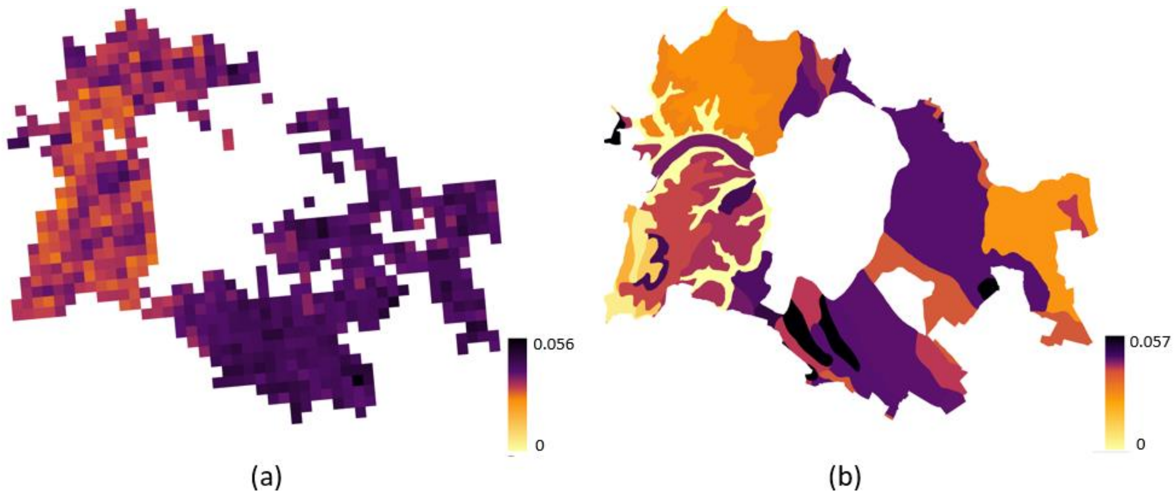


Figure 7: K factor estimated in **(a)** JRC RUSLE 2015 (data from LUCAS and ESDAC) and in **(b)** RUSLE 2018 (data from French DoneSol database)

database (RUSLE-2018) is presented in **Figure 6(b)**. The R factor estimated by the JRC in (RUSLE-2015) and the R factor calculated in this study (RUSLE-2018) are different: the R factor 2018 is significantly higher than the R factor 2015. The main explanation is that Dijon experienced an important 2018 rainy year. This highlights the need of frequent updates of soil erosion maps. Moreover, our rain erosivity map provides more details about the identification of spatial patterns; for example, the northeast is more exposed to rain erosivity than the west. In contrast, except for some high values found in the southwest, the RUSLE-2015 R factor shows abrupt spatial discontinuities, due to the low resolution of the meteorological data available, which provides a less realistic map than the one obtained with COMEPHORE, making it more challenging to read.

K factor estimation: K factors were calculated according to the equation presented in **Table 3** (see sub-section **IV.6.**) by the JRC using the Land Use and Coverage Area frame Survey (LUCAS) and the Europe Soil Database (ESDAC) (RUSLE-2015) (**Figure 7(a)**), while we used the French national database DoneSol[276] (RUSLE 2018) (**Figure 7(b)**).

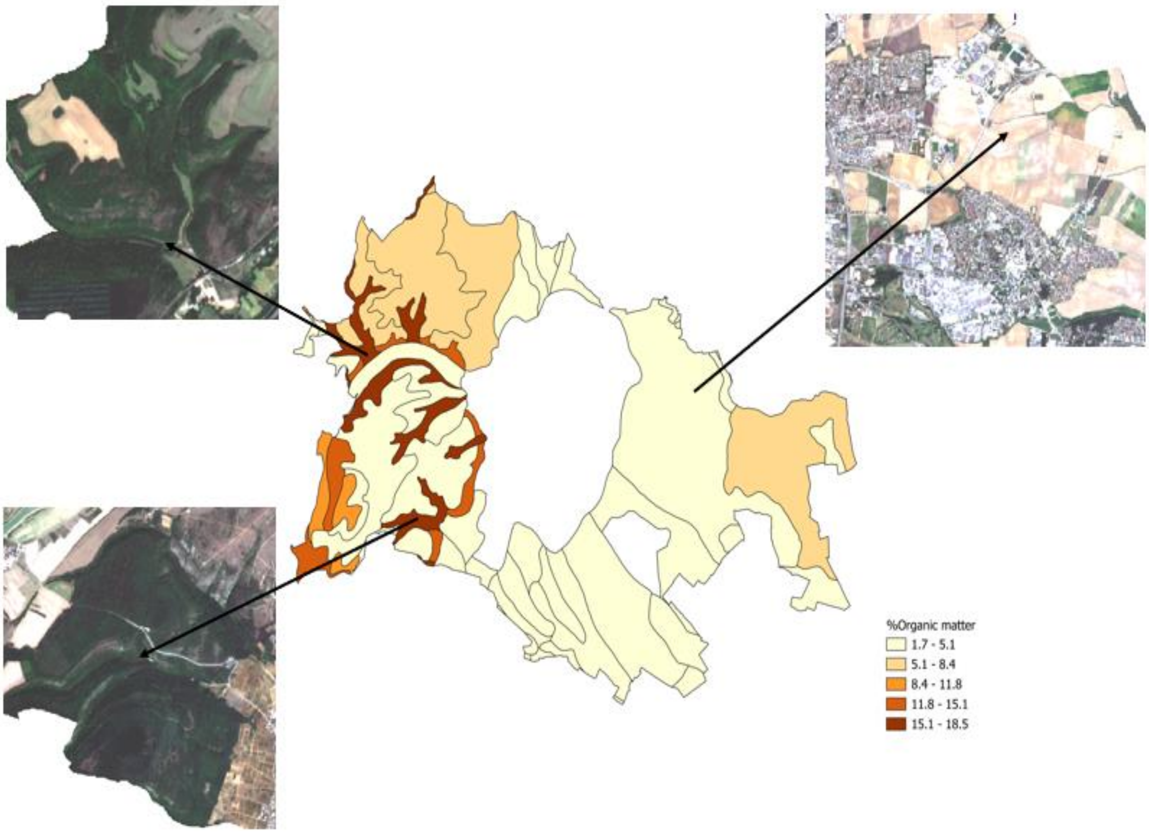


Figure 8: SOC map (in % Organic matter. (Zones with high organic matter contents are forest areas or permanent grassland areas, with higher levels along watercourses)

[276] The French datadabase of the French GIS Sol. Interface de saisie de la base nationale: DoneSolWeb. (n.d.). Retrieved June 4, 2024, from https://www.gissol.fr/outils/donesol-web-336

According to **Figure 7**, there are some similarities between the two soil erodibility maps: the area west of Dijon has lower erosion rates than the area east of Dijon. However, our study generated by using data from the DoneSol national database shows more spatial variations of the erodibility. Also, the minimum and maximum values are very close between the two maps (maximum value of O.056 for JRC RUSLE-2015 and 0.057 for RUSLE-2018). The results show that the East and Southwest of the city covered by agricultural lands, have the lowest soil erodibility rate, which is likely related to the organic matter content map **(Figure 8)**.

LS factor estimations: the maps issued from three calculation procedures are presented, with the initial result of the JRC (RUSLE-2015) (**Figure 9(a)**), the calculated LS factor using the same input data as the JRC in 2015 (**Figure 9(b)**), and the LS factor calculated using the French database (RUSLE-2018) (**Figure 9(c)**). The general trends indicate a greater chance of erosion in the Northwest of Dijon due

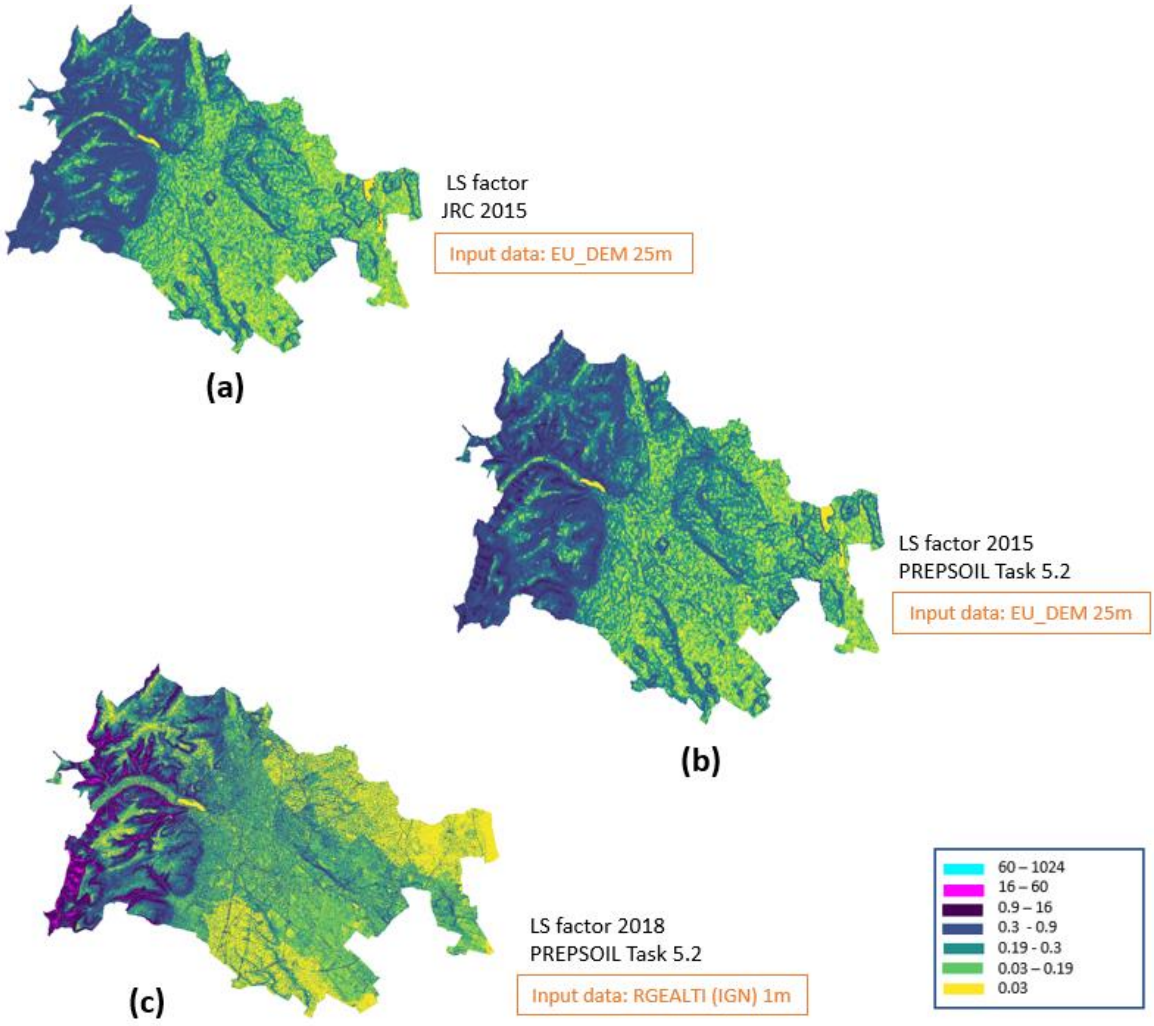


Figure 9: LS factor estimated either **(a)** by the JRC (RUSLE-2015), **(b)** in this work using same input data as the JRC, or **(c)** in this work with input data from French databases (RUSLLE-2018).

to the complex and diverse relief in natural or semi-natural areas. The three maps are generally similar (Figure 9), especially the two 2015 maps (Figure 9(a) and (b)), but RUSLE-2018 offers more detailed information due to its 1 m spatial resolution.

Nevertheless, it is crucial to consider the differences between the maps, despite using the same processing method and similar input data: for instance, some small details such as the road were taken into account in LS factor 2018 (Figure 10(b)) but not in the JRC LS factor (Figure 10(a)).
Moreover, compared to the JRC LS factor (Figure 11(a)), the RUSLE-2018 (Figure 11(b)) LS factors exhibit significantly higher maximum values. The difference could be attributed to the influence of complex topographic conditions, such as a notable drop in altitude (e.g., cliff and valley), which magnified the high-value trend in our studies. Furthermore, the occurrence of values above 16 (referring to the JRC LS factor map) is primarily concentrated in the Northwest, while the LS values of the two maps are broadly similar in the eastern plain.

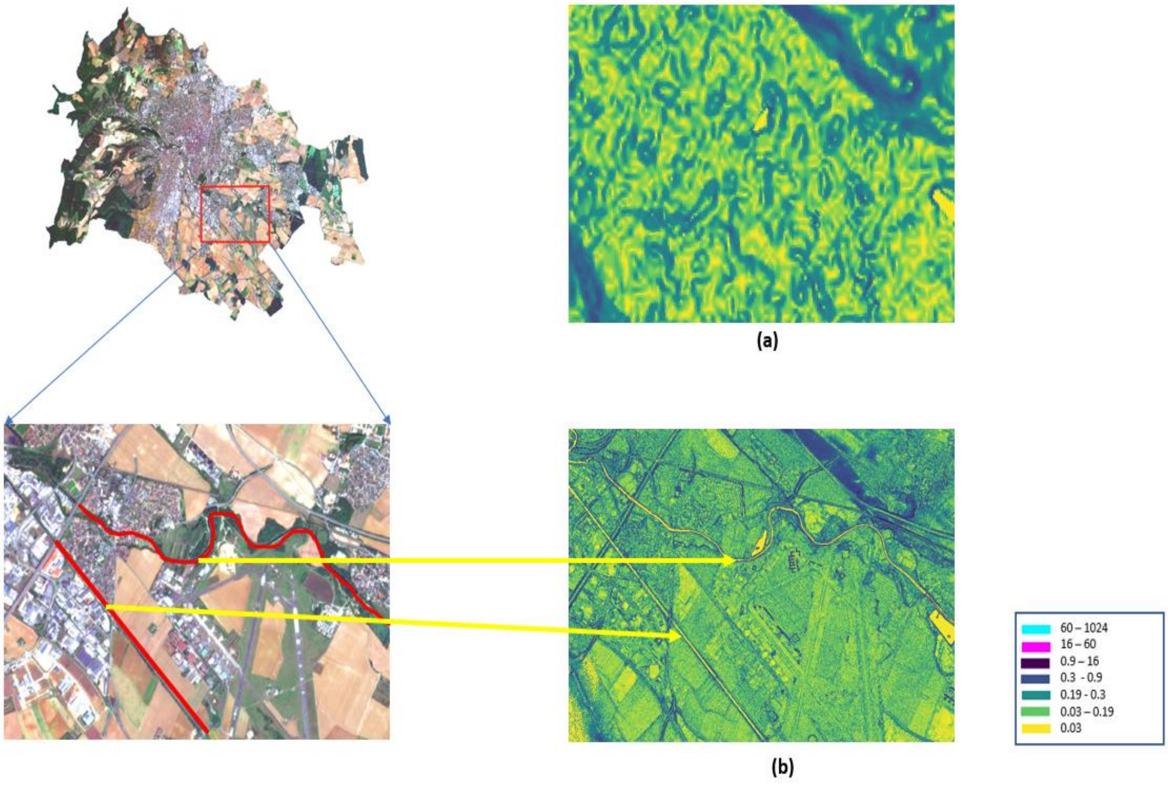


Figure 10: Comparison over a small geographical area of LS factor estimated either (a) initial JRC calculations (RUSLE-2015), or (b) LS factor 2018 (data from French databases) (RUSLE-2018).

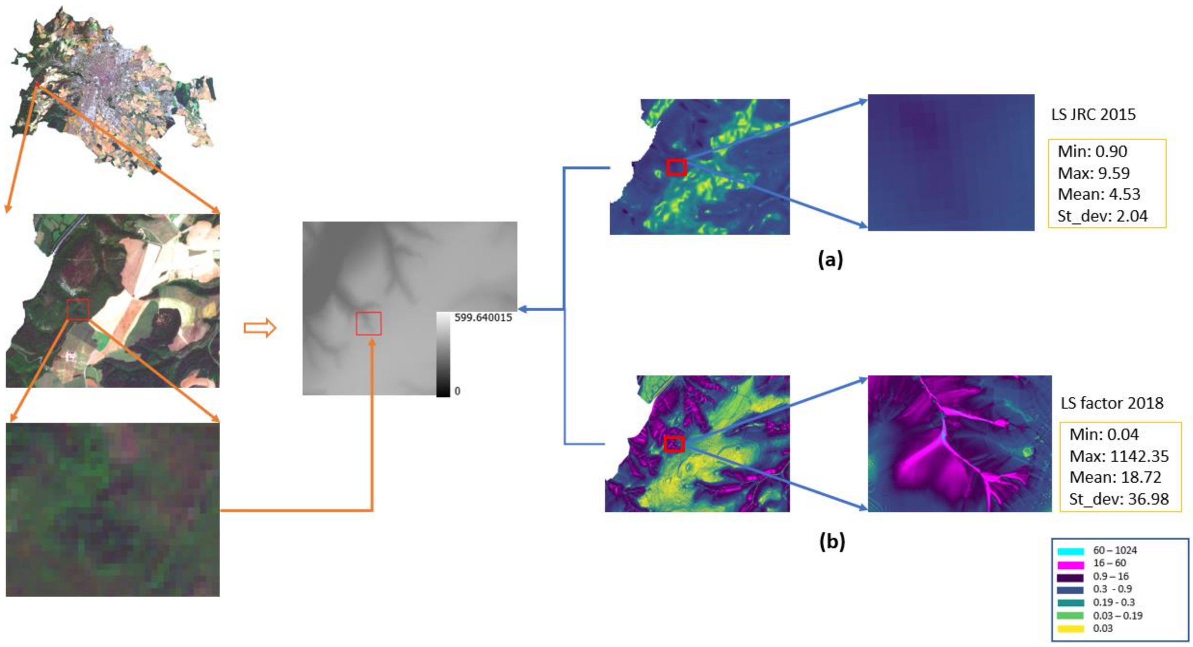


Figure 11: Example of high values. Comparison of **(a)** initial JRC calculations, **(b)** LS factor 2018 (data from French databases)

C factor estimations: C maps issued from the JRC in 2015 (RUSLE-2015) and from this study calculations (RUSLE-2018) are presented in **Figure 12(a)** and **Figure 12(b)**, respectively.

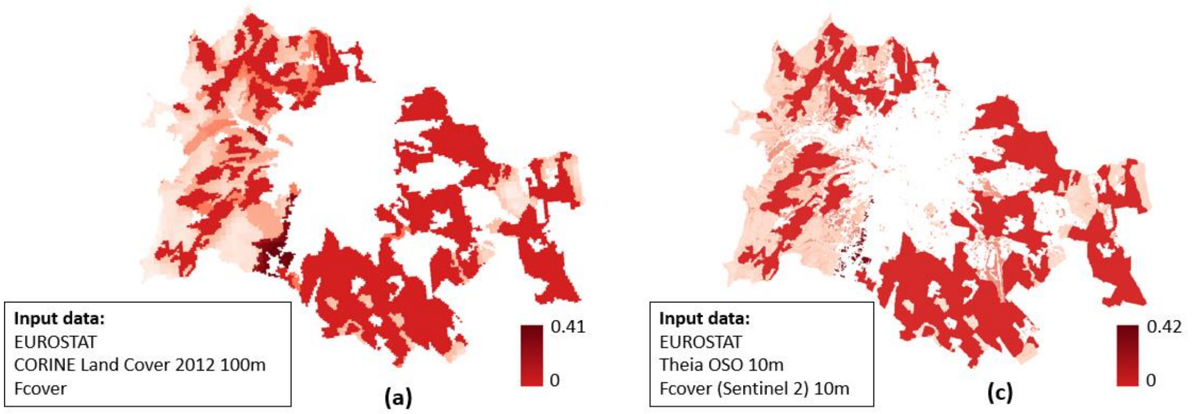


Figure 12: C factor estimated from **(a)** initial JRC calculations (RUSLE-2015), and **(b)** this study calculations (RUSLE-2018) with input data from French databases.

There was a remarkable similarity between JRC map (RUSLE-2015) and our calculations using JRC data for 2015 (results not shown) that validated the processing methods and data type we used. But the calculations performed in this study using French data (RUSLE-2018) provides more spatially detailed C factor estimation (**Figure 12(b)**). The vineyard in the south of the study area remains the most exposed to soil erosion, followed by non-irrigated arable land and agricultural areas with significant natural vegetation. In contrast, the vegetated areas are most protected from soil erosion. This highlights the significant role of agricultural practices, such as crop planting and tillage, in influencing the C factor and, consequently, soil erosion.

As already written, we used **the P factor** generated by the JRC (0.9627) due to lack of accessible and suitable information, time limits and complexity of calculation.

By combining R, K, LS, C and P estimations, soil water erosion maps are obtained for Dijon city in 2018, using either European data (e.g. JRC like) or National ones (this study) (**Figure 13**).
The two erosion maps **(Figure 13 (a) and (b))** share similarities in the spatial pattern; they accurately identify areas of high erosion in the west, characterized by complex relief, and in the east, predominantly arable land. Conversely, the least affected areas are the natural vegetation in the plain. However, the RUSLE 2018 map reveals more detailed information about soil erosion in a small study area due to its fine spatial resolution. Despite the commonalities, the values of the two maps differ significantly. The RUSLE 2018 map shows distinctly higher values than the JRC map because the R and LS factors we generated previously were also higher than the initial JRC factors.

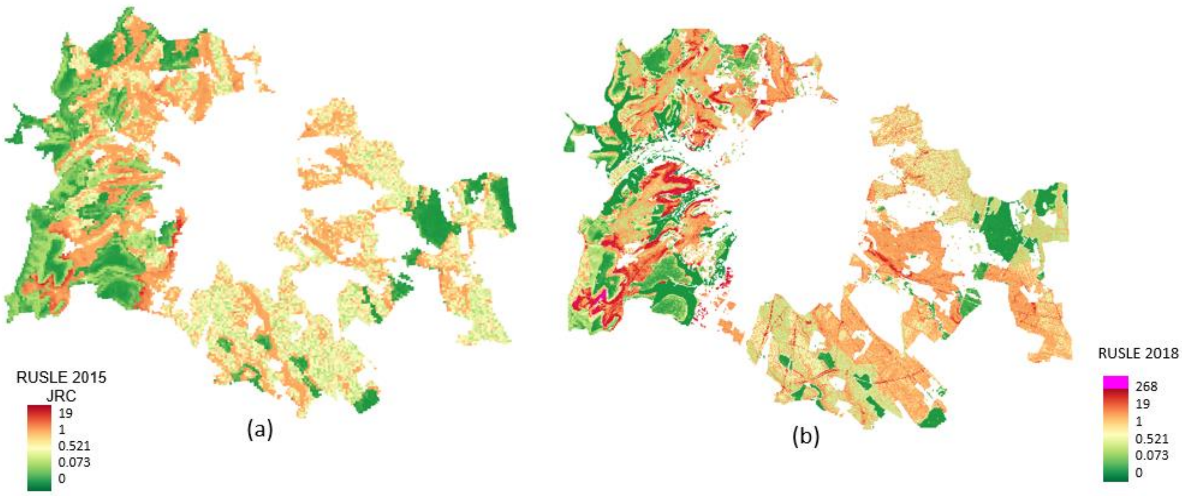


Figure 13: Soil water erosion map of Dijon (in t ha^{-1} $year^{-1}$). Comparison of **(a)** initial JRC 2015 soil erosion map, and **(b)** 2018 soil erosion map generated using French data with a better spatial resolution.

The high maximum value (i.e., value > 20 t ha^{-1} $year^{-1}$) or the very low value (close to 0) **(Figure 14)** are primarily found in small areas, especially in the west, where there are complex and diverse reliefs. A very low value could be found in the highly vegetated areas around the riverbeds, while the high maximum value is usually located at the plateau's edge. These values are caught mainly through the LS factor in our work thanks to the high spatial resolution data, which is able to detect more subtle variations in the landscape.

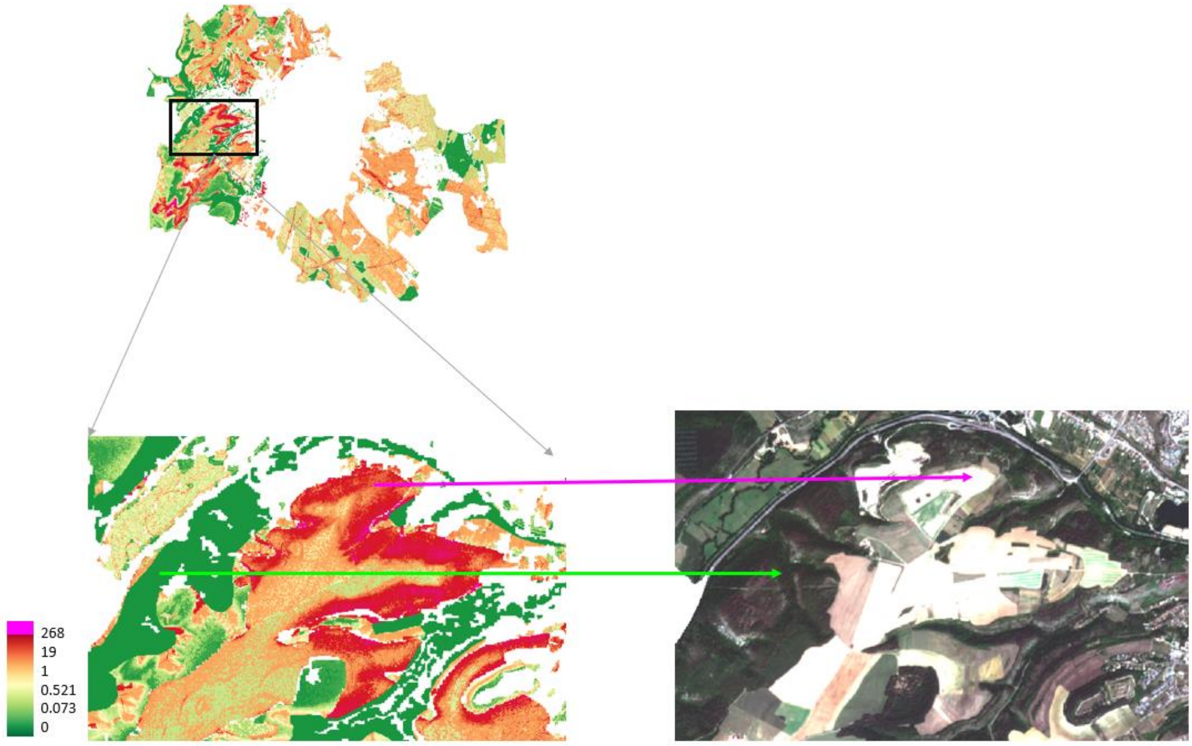


Figure 14: Example of high maximum value. The violet arrows indicate the high maximum value (>19), and the green arrows indicates the very low value (close to 0).

Thus, this part of the work using as an example the estimation of soil water erosion using satellite data serving as input data to a model (RUSLE) leads us to the following conclusions:

- By integrating different measures of causal factors (e.g. rainfall, soil type, topography, soil cover and management practices), the RUSLE model makes it possible *a priori* to assess their individual and collective impact on soil water erosion. In our study area, topography (LS factor) is probably the most influential factor, but the results also show the impact of human activities through land cover, management and practices aimed at limiting erosion (C and P factors). They underline the need for management strategies adapted to anthropised areas. However, it is important to remember that the RUSLE model is an empirical model (see subsection V.2.c.) and that the quality of the resulting estimates of water erosion depends very much on the quality of the model's parameterisation in contexts close to those analysed;
- The ease with which the RUSLE model can be understood and the availability of open-source codes for processing input data make it easy to use and attractive to decision-makers. The RUSLE model can also be fed with a variety of input data, including remote sensing data and CLMS products, which are generally available free of charge. Their very wide spatial coverage, high spatial resolution and high revisit frequencies are assets for a good estimate of erosion;
- While the aim of the JRC was to assess water erosion on a European scale, we used more precise data (high spatial and temporal resolution) to estimate water erosion at more local scales. We

generated a soil erosion map of the area around the city of Dijon with a spatial resolution of 10 m (some types of water erosion - gully erosion, for example - can only be detected with very high spatial resolution);

- We note that one of the intrinsic limitations of the RUSLE model is that it provides an annual estimate without taking into account the correlations or the absence of correlation of rainfall with the vegetation cover of agricultural soils (through the R and C factors). On this particular point, we should point out that there are other models that take this into account (MESALES, PESERA, STREAM, WaterSed...). The use of one of these latter models requires input data with high temporal resolution, which can be the case with EO data, albeit with certain limitations linked to the presence of clouds.

V.7. Obstacles to greater use of EO and measures to reduce them; workshops and virtual discussion group

Between 22 April and 17 May 2024, 4 workshops were held in Norway (22 April 2024), Poland (8 May 2024), France (14 May 2024), and the Czech Republic (17 May 2024). They were organised in the same way and their final objectives were to address the following two points:

- Identify the bottlenecks (scientific, technological, technical, skills, etc.) to greater use of satellite EO, as well as CLMS and/or Galileo/EGNOS products, for soil monitoring;
- Propose measures to reduce/minimise these difficulties.

A summary of each of the workshops is presented in **Annexe V**.

	Population (Millions of inhabitants)	"Average" number of participants to the workshop	Main participant professional profiles
Norway	5.5	17	Scientists (16) Public sector (1)
Poland	36.8	41	Scientists (30) Public sector (9) Private sector (2)
The Czech Republic	10.7	23	Scientists (6) Private sector (13, *including 12 farmers*) NGOs (4)
France	68.0	31	Scientists (14) Public sector (6) Private sector (5) NGOs+others (5)

Table 5: Size of the population of the countries in which workshops were organised and composition of the workshops in terms of participants.

Here we summarise their main conclusions. Insofar as this seemed relevant and possible given the number of participants at each workshop (between 17 in Norway and 41 in Poland) (**Table 5**), we tried to identify what might be more specific to certain groups (scientists, people from the public sector, people from the private sector, representatives of NGOs), or certain countries. Indeed, there is a probable link between the size of the country's population and the size of its scientific community, which indirectly impacts the existence of certain skills or cross-disciplinary skills in certain small countries.

Skills ranging from remote sensing to agriculture, forest and soil expertise do exist in all the Member States involved in Task 5.2, including the least populated (Norway, Czech Republic), even if all workshops identify the need to develop new skills (e.g., on UAV as satellites cannot meet all needs (Norway); on processing the links between EO data and soil characteristics (physical and chemical) and processing Sentinel 1 data (The Czech Republic); passing on these skills to stakeholders other than just scientists (France)). However, participants in the Polish workshop strongly emphasised the lack of appropriate skills to analyse remote sensing data and the need to increase skills in this area. There are several reasons for this, probably in addition to a specific Polish context in this area: (1) the need for specialist knowledge to interpret the data, familiarity with remote sensing data analysis tools and software, and the programming skills required to process the data efficiently; (2) the very rapid evolution of the technologies used in remote sensing (sensors, etc.) and data processing, and the need for continuous updating of knowledge to be able to use EO data; and (3) the need to provide continuous support and maintenance of remote sensing infrastructure to avoid data loss in case of system failure etc.), and the high cost of data acquisition and processing.
To cope with these skills shortages, participants at the Polish workshop suggested (i) providing training to 'de-emphasise' this area, and (ii) organizing as many courses as possible in Poland, initially free, and focusing on acquiring and interpreting satellite data.

Probably linked in part to the small size of Norway population and its scientific community, the Norwegian workshop identified as weaknesses (i) a lack of knowledge among policy-makers about the potential of EO for soil monitoring, due to a lack of dialogue with the research community, (ii) a lack of collaboration between researchers, particularly between experts in remote sensing and soil experts, and (iii) a lack of interactions between scientists and people likely to use Earth observation data (farmers and other end users). Lack of collaboration between scientists is seen as a threat; for example, it can lead to incomplete databases.
One strong suggestion is to avoid competition and encourage collaboration between scientists. Opportunities that could help bring experts in remote sensing and soil experts closer together include (i) the possibility to make data collection more efficient, (ii) the possibility of substituting EO to field measurements and reducing the huge costs associated to the last ones, and (iii) the identification and development of indicators based on remote observations, which are the more low-hanging fruit. Note that the participants to the Czech workshop also mention the need to promote interdisciplinary research to integrate EO data with soil physical and chemical properties, to strengthen collaborations among experts and institutions to share knowledge and resources, with the creation of platforms for

continuous exchange of best practices and innovations. Beyond that, scientists need to work on sensors and satellites with farmers and other end-users of EO data. The Norwegian workshop had been very useful to get an overview of what others were working with, opening up for new collaborations. The participants agreed that the participant list and the power point presentation (including the presentations of the participants) should be shared among the group afterwards, so that it would be possible to find and contact each other's. Several of the participants to the Norwegian workshop expressed an interest for more meetings across disciplines, with policymakers to help developing the opportunities for using EO for soil monitoring in Norway, and opened to more stakeholder groups could have been present, for example farmers (Perhaps to co-design solutions and research, as happens in citizen sciences or living labs). Participants to the French workshop also mentioned the need to call on partners from different horizons, with different skills and different vocabularies to devise solutions that add value to EO data.

For French scientists in particular, the inaccessibility of data on soil properties at depth using direct remote sensing is an obstacle to the wider use of remote sensing.
They suggest three types of solution to overcome this problem in the short or medium term (long-term solution was not envisaged, e.g., with P-band wavelength sensors at the resolution of interest):

- Better couple *in situ* data and available covariates (accessible imagery proxies) with the operational models of interest for each type of potential threat;
- Encourage the widespread use of airborne gamma-ray spectrometry, which provides an integrated 60 cm parameterization of soil texture and certain other signatures such as fertilizer applications. Other European countries are also very interested in gamma-ray spectrometry, notably Denmark (all people working on peat are very interested in gamma-ray spectrometry because it enables easy detection of whether there is at least 50 cm of peat or not);
- Use process-based model inversion, e.g., using vegetation proxies such as NDVI or others to try and infer soil water holding capacity.

For French and Czech scientists, another bottleneck to wider use of remote sensing data is that of scale: for a given soil process or property, what resolution and coverage are appropriate?

- Basically, what grain of information should we have on the soil in relation to the resolution and remote sensing support available? We have to use rather punctual soil information (mainly from soil pits, 1 m^2) to calibrate or validate remote sensing models the resolution of which is ranging 100 m^2 - 1 km^2? This is not trivial;
- The geographical "laws" (or drivers) of distribution change with scale. On which overall coverage do we calibrate relationships? Soil carbon, for example, has completely different controlling factors depending on the scale envisaged (global, continental or regional): the main driving variables change (e.g. at world scale climate is the main controlling factor, followed by land use; at small national scale land-use and soil texture are dominant, at field scale, soil texture, and soil and crops management practices are dominant), therefore relevant models change with scale, and the variables are more and more uneasy to capture as detailed maps are required).

Scientists propose two types of approach to deal with this problem in the case of soil carbon:

- The first one is to use imagery to delimit areas that will enable the *ad-hoc* model to be applied upstream to spatialise a carbon estimate that is representative of these areas, with a sampling of areas that is well representative of this zoning and well designed in both geographical and feature spaces;
- The second one would be to increase the harvesting of *in situ* soil data from a variety of laboratories, or even to encourage public policy to impose procedures for the transfer of analyses, for example when fields are transferred from one farmer or owner to another, so as to accumulate field soil data. This solution is not linked to the technology available, but as field-scale analyses often come from a composite sample gathered on a rather large area (say 1 ha to 50 ha), it allows to have a soil support integrating the within and inter pixels variability on a consistent area. Note that a database of such soil agronomic analyses already exists in France, gathering several millions of analyses since 1990. But the collection of results is a voluntary process from the labs. There is no constraining obligation.This approach would allow to better match soil observations with the resolution of the sensors available, depending on the scale at which we are working.

Of course, we need to support R&D to improve spatial resolution.

Another important bottleneck mentioned during the French workshop is the lack of standardisation. People of the public sector mentioned the lack of harmonisation (in concrete terms the heterogeneity of methods and products, with satellite products whose definitions are sometimes not in agreement with those of users). People in the private sector noted that advice based on EO data varies with the producers of that advice and the treatment chains they apply: for example, cloud cover limits the data that can be collected over vast territories, leading some operators to mobilize the data in spite of everything, correcting them but without really informing the user of what has been done. Participants to the Czech workshop mentioned cloud coverage affecting the quality of data, particularly those of Sentinel 2, and the non-stabilised character of protocols and standards. To cope with these problems, they expressed the need for interoperability between the various products, the need of standardized methods and procedures (e.g. what to do if there are a lot of clouds) which can guarantee a certain product quality, and requiring operators / data producers to provide a confidence interval to assess product quality. The need to identify and quantify uncertainties was also expressed by people representing NGOs. And participants to the Czech workshop proposed to cope with these problems by supporting R&D for cloud cover mitigation techniques, develop and implement technologies to improve data processing capabilities (including artificial intelligence: machine learning and deep learning), advocate for standardized protocols that are stable and adaptable to technological advancements

Other technological and technical bottlenecks have been mentioned: Participants to the Czech workshop mentioned handling and processing large volumes of data, the prevalence of paid commercial platforms, and the evolving data and digital policies. They propose to cope with these problems by supporting R&D for cloud cover mitigation techniques, develop and implement technologies to improve data processing capabilities (including artificial intelligence: machine and deep learning), advocate for standardized protocols that are stable and adaptable to technological advancements, engage with policymakers to influence favourable data and digital policies (moderate effort can significantly influence the operational environment). Participants to the French workshop regret that information on non-agricultural soils (forests, etc.) is not always accessible, and that it is sometimes only available at temporal and spatial resolutions that are not fine enough, due to the fact that these soils are rarely bare. Some participants to the French workshop wonder whether citizen science (CS) could not be used as complementary information to remote sensing (as covariates). Others have high hopes for hyperspectral imaging.

Although French scientists are aware of this, it is mainly people in the public sector or the private sector and people representing NGOs who report a problem with access to EO data and services (CLMS, Galileo/EGNOS) during the French workshop. People of the public sectors mention (i) a lack of knowledge and skills to know what can be done with remote sensing, and (ii) a general lack of visibility of what is available, where the data can be accessed, and sometimes the price of the data, which can hamper accessibility. People in the private sector mention that end-users' lack of knowledge and skills in relation to existing products, but also in relation to what they can do with the products supplied. People representing NGOs or who do not fall into any of the other categories (i.e. Scientists, people of the public sector, people of the private sector) also mentioned difficulties in accessing services and data (with a labyrinthine character due in part to the plethora of data on offer, which is not easy to find one's way around) and the need for expertise that is not necessarily shared within the associative sector, particularly when it comes to coupling remote sensing with other environmental covariates, which can yield very interesting results.
To tackle these problems, they expressed (i) the need to raise awareness among product users, to support these users and to train them in the use of available tools, (ii) the need for exchanges between scientists and local authorities (currently considered insufficient or even non-existent), but also between field workers and database users, and (iii) the need for a collaborative web space to facilitate interaction between stakeholders, e.g. a universal web portal or an adapted website. And scientists also not that there is a major need to train users of remote sensing data so that they understand what types of media they can exploit and, consequently, to communicate on how to identify the limits to the use of PROXYS derived from remote sensing. Some of these ideas were already mentioned before. The participants to the Czech workshop suggest (i) to develop a comprehensive training program to build expertise in EO data processing and interpretation, (ii) to conduct workshops and courses to enhance skills in Sentinel 1 and Sentinel 2 data handling, and (iii) to develop potential for partnerships with educational institutions and online platforms (for relatively low cost and high impact).

The final problem that needs to be mentioned and not underestimated is the risk of ‘deluding ourselves’ into thinking that remote sensing can solve everything, especially with artificial intelligence.

VI. Conclusion

Soils contribute to the achievement of several Sustainable Development Goals (SDG) through their contribution to various ecosystem services, well beyond their role in food production. They are subject to a variety of threats and can be degraded very quickly, even though they are formed over very long periods of time. Any sustainable soil management policy must include soil monitoring (health, quality, functions, properties, degradation), but monitoring based on in situ characterisation and sampling is costly in human and financial terms, leading to studies of a very limited number of sites, with revisit times of several years. Besides large-scale initiative ground sampling such as LUCAS, Earth Observations (EO) can help to reduce these problems. In this report, we deal successively with (i) the state of scientific knowledge (mini-review of the literature, expert opinions, objectives of current European projects), (ii) the technological resources that can be mobilised (inventory of current and planned vectors, sensors, products and services; current use of EO data for the EUSO dashboard; impact of data choices on the estimation of an indicator - erosion - by way of example), and (iii) identification of the obstacles to greater use of Earth observations for soil monitoring and the need to adopt measures to reduce/minimise these difficulties.

On a scientific, technological and technical level, EO provides access to a wide range of information thanks to different vectors (satellite, airborne sensors, Unmanned Aerial Vehicle (UAV)), different sensors (radar, passive microwave, multispectral, hyperspectral, LiDAR, gamma-ray spectrometry) and a wide range of data processing (digital soil mapping using EO data as environmental covariates; assessing spatial, spectral or temporal heterogeneities after classification or using a continuous approach based on radiative transfer, etc.), including the increasing use of artificial intelligence (AI) (machine learning (ML) and deep learning (DL)). Much hope is pinned on hyperspectral imagery, gamma-ray spectrometry and LiDAR observations access new information on soil depth, chemical composition and canopy structure (particularly agro-ecological infrastructure). Among the subjects currently being explored are numerous studies on the links between aerial or soil surface biodiversity and landscape heterogeneity, taking into account various agroecological infrastructures (including hedgerows). The study of links between landscape heterogeneity and soil biodiversity is suggested by the links mentioned above, as well as by the impact of flora on the latter biodiversity.

There are many EO data resources and products available from various international (NASA, etc.), European (CLMS, Galileo/EGNOS), or national (Théia (France), etc.) services, and new products need to be proposed. Apart from their accessibility, which is often problematic for non-experts in remote sensing, European services do not provide access to everything, as demonstrated by the JRC's use of data from the US National Aeronautics and Space Administration (NASA) and the Indian Space Research Organisation (ISRO). Over and above these limitations, it is important to consider the evaluation of certain indicators based on empirical modeling; these can be very reliable when based on a large number of direct observations (as in the case of RUSLE in the USA), but their transposition to other contexts requires the acquisition of a large number of data specific to these contexts, and we may wonder whether other choices might not be more appropriate, such as the use of the process-based model PESERA (Pan-European Soil Erosion Risk Assessment), which was the official EU model used and deployed by the JRC in the past.

Obstacles to greater use of EO data vary with the national context - including the numbers of remote sensing experts, soil experts, and even experts with dual “EO-soil” skills - and the end users (scientists, people from the public or private sector, NGO representatives). Scientists using this type of data have (relatively) easy access to it, thanks to international, European (CLMS, Galileo/EGNOS), or national services, unlike other end-users. The need for more interaction between EO and soil specialists on the one hand, and between scientists and other end-users on the other, is very often put forward. At the scientific level, the main stumbling blocks (not prohibitive) are related to the limits of information (surface characterization, compatibility of scales, standardisation/harmonization of measurements, etc.); they have high expectations of gamma-ray spectrometry and hyperspectral imaging. In general, people in the public sector or the private sector and people representing NGOs report problems with access to EO data and services, a lack of knowledge and skills to know what can be done with remote sensing, and a general lack of visibility of what is available. A number of solutions need to be explored to solve these problems: raising awareness, supporting and training end-users of EO products and data, encouraging interaction between scientists on the one hand and public authorities and other end-users on the other (meetings, workshops, collaborative web space...); creating new links between education and research.

The rereading of this deliverable by people not involved in PREPSOIL Task 5.2 has highlighted ethical issues not included in the Grant Agreement, but which we feel are important. The use of EO technologies can raise a number of questions, not least because such data can provide information about people's private lives. But ethical issues go far beyond this; they concern the relationship between public authorities, the people who own and/or manage the data, scientists, other stakeholders and every citizen. They concern respect for people's privacy, data security and equity (**Figure 15**). In the short time between the emergence of these questions and the official submission of this Deliverable, it has not been possible for us to interact sufficiently with the JRC and the EEA to obtain answers to some of them, but it is clear that most would remain unanswered today or with answers that are probably unsatisfactory from an ethical point of view. We suggest that they be taken up by others.

Avignon (France), 27 June 2024

Pierre Renault

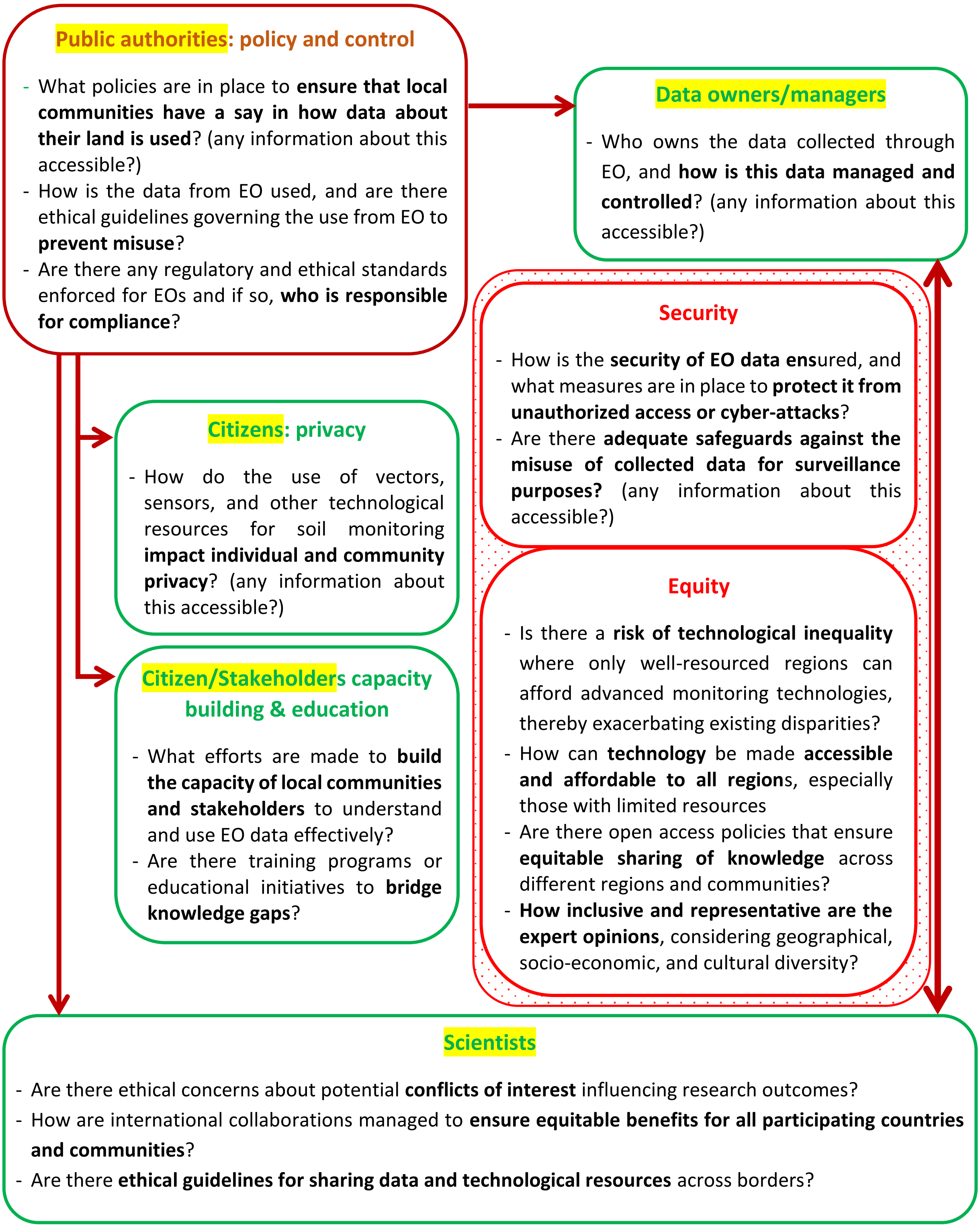


Figure 15: Ethical dimensions of the interactions between public authorities, data owners/managers, scientists, other stakeholders and all the citizen with regard to security and equity.

Annexes

Annexe I:

Advanced search under SCOPUS

The last advanced search, the results of which are summarised at the beginning of subsection V.1., was carried out on 8 May 2024 using SCOPUS. Below is a list of the questions asked and their results (in green). Some questions gave rise to an exhaustive description of the evolution of publications over the years. These questions are marked with 2 red asterisks (**), and a table gives the associated values.

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne"))

481,142 documents

TITLE ("earth observation" OR "remote sensing" AND NOT ("satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")))

64,925 documents

TITLE ("satellite" OR "airborne" OR "UAV" OR "drone" AND NOT ("earth observation" OR "remote sensing" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")))

217,184 documents

TITLE ("radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne") AND NOT ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone"))

173,302 documents

TITLE (("radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND ("satellite" OR "airborne" OR "UAV" OR "drone"))

14,479 documents

TITLE ("earth observation" OR "remote sensing")

76,770 documents

TITLE ("satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne"))

416,217 documents

TITLE ("earth observation" OR "remote sensing" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne"))

263,958 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone")

307,840 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND TITLE ("soil" OR "crop*" OR "vegetation" OR "forest" OR "landscape")

22,882 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND TITLE ("crop*" OR "vegetation" OR "forest" OR "landscape")

17,409 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND TITLE ("soil")

6,136 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND TITLE ("crop*" OR "vegetation" AND NOT ("forest" OR "landscape"))

7,960 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND TITLE ("forest" AND NOT ("crop*" OR "landscape"))

7,811 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND TITLE ("landscape")

1,595 documents

TITLE ("earth observation" OR "remote sensing" OR "satellite" OR "airborne" OR "UAV" OR "drone" OR "radar" OR "passive microwave" OR "multispectral" OR "hyperspectral" OR "LiDAR" OR ("gamma*" AND "airborne")) AND TITLE ("hedgerow*")

16 documents

TITLE ("satellite" OR "airborne" OR "UAV" OR "drone") AND TITLE ("soil")

1,946 documents

TITLE ("satellite") AND TITLE ("soil") **

1,332 documents

TITLE ("airborne") AND TITLE ("soil") **

381 documents

TITLE ("UAV" OR "drone") AND TITLE ("soil") **

257 documents

TITLE ("radar") AND TITLE ("soil") **

956 documents

TITLE ("passive microwave") AND TITLE ("soil") **

329 documents

TITLE ("multispectral") AND TITLE ("soil") **

223 documents

TITLE ("hyperspectral") AND TITLE ("soil") **

835 documents

TITLE ("LiDAR") AND TITLE ("soil") **

67 documents

TITLE ("gamma*" AND "airborne") AND TITLE ("soil") **

23 documents

Table A1-1: Evolution over the years of the number of publications including in their titles ”soil” and either a vector type or a sensor type.

Year	Satellite	Airborne sensor	UAV / Drone	Radar	Passive microwave	Multi-spectral	Hyper-spectral	LiDAR	Gamma-spectro.
1952		1							
1953		0							
1954		0							
1955		0							
1956		0							
1957		0							
1958		0							
1959		0							
1960		0							
1961		1							
1962		1							
1963		0							
1964		0							
1965		0							
1966		0							
1967		0							
1968		0							
1969		0							
1970		0							
1971		1		1					

1972		0		0		1			
1973		2		1		1			1
1974		0		1	1	1			0
1975	2	0		0	1	0			0
1976	1	2		2	0	1			0
1977	2	2		1	2	1			0
1978	0	0		3	0	0			0
1979	2	3		0	1	2			0
1980	3	4		2	2	9			0
1981	2	4		5	2	2			3
1982	4	2		7	3	2			0
1983	3	6		5	6	1			2
1984	7	0		6	5	1			0
1985	0	3		7	5	1			0
1986	5	4		8	4	0			0
1987	2	4		3	2	1			0
1988	5	1		8	3	1			0
1989	4	4		2	1	3			0
1990	3	4		4	2	1			0
1991	5	3		3	2	0			0
1992	9	5		8	6	2			0
1993	7	5		2	4	2			0
1994	3	3		8	2	0			0
1995	11	9		12	6	0			1
1996	5	9		23	7	1			1
1997	6	8		15	4	1			4
1998	5	7		13	5	1	1		0
1999	7	4		13	4	0	4		0
2000	9	11		18	6	3	1		0
2001	5	7		11	11	2	3		0
2002	5	9		30	5	3	4		0
2003	10	5		21	5	1	4		0
2004	17	8		29	4	0	9		0
2005	24	7		21	4	1	11		0
2006	13	4		19	5	0	4	1	1
2007	17	8		21	10	3	9	0	0
2008	24	6		28	13	2	18	0	0
2009	21	10	1	24	7	1	10	0	1
2010	22	9	0	32	12	5	18	2	0
2011	25	11	0	31	14	1	23	1	0
2012	42	13	1	31	14	0	28	6	1
2013	43	8	1	43	9	1	24	3	0
2014	46	17	2	47	20	4	39	4	1
2015	40	13	2	33	16	6	29	6	0
2016	71	14	4	32	19	5	44	3	0
2017	75	12	6	44	6	9	41	4	2
2018	85	17	9	47	16	11	53	4	2
2019	113	12	29	46	10	24	66	5	0
2020	104	15	30	42	9	20	63	7	2

2021	103	16	41	48	9	24	81	7	0
2022	142	21	53	49	10	24	94	7	1
2023	128	20	59	33	9	28	128	6	
2024	45	6	19	13	6	9	26	1	

Advanced requests for the columns entitled:

- Satellite: TITLE ("satellite") AND TITLE ("soil")
- Airborne sensor: TITLE ("airborne") AND TITLE ("soil")
- UAV / Drone: TITLE ("UAV" OR "drone") AND TITLE ("soil")
- Radar: TITLE ("radar") AND TITLE ("soil")
- Passive microwave: TITLE ("passive microwave") AND TITLE ("soil")
- Multispectral: TITLE ("multispectral") AND TITLE ("soil")
- Hyper-spectral: TITLE ("hyperspectral") AND TITLE ("soil")
- LiDAR: TITLE ("LiDAR") AND TITLE ("soil")
- Gamma-seprctrometry: TITLE ("gamma*" AND "airborne") AND TITLE ("soil")

Annexe II:

Survey form for obtaining information on EU projects with an EO component

&

Informed consent form

CSA PREPSOIL

Survey of European projects dealing with soil health monitoring using satellite-based Earth Observations

This survey is to take stock of past, current and recently approved European projects dealing with the use of satellite Earth observation and airborne sensors (aircraft or drones) to monitor soil health.
In particular, its aims are to identify:

- results that are already well consolidated;
- work in progress that is likely to advance certain achievements;
- scientific issues relating to the sensor component, as well as to the data processing component and its use as a PROXI of soil properties/characteristics/indicators of soil health;
- topics that have not yet been addressed and that could be considered a priority.

Thank you in advance for taking the time to answer this question on behalf of the project you represent as a leader or as someone heavily involved in the satellite or airborne Earth observation sector.
Please, don't forget to sign and send us the Informed Consent Form, attached to the e-mail sent to you.
Sincerely yours,

Pierre Renault (France, INRAE) for all partners involved in this work

Contact for any questions and for returning the completed survey form:
Pierre Renault (INRAE, France): pierre.renault@inrae.fr

Person answering the questionnaire:
• **Last name:** • **First Name:** • **Professional e-mail:** • **Responsibility within the project:** • **Informed consent agreement signed:** ☐ yes ☐ no
Project identity:
• **Name/acronym of the project:** • **Complete title of the project:** • **Project framework (EJP Soil, Horizon Europe, H2020 …):** • **Type of project (CSA, RIA, IA …):** • **Start date:** • **End date:**

Summary of the projet (a simple copy/paste)
Main objectives:
• **Main objectives of the project (1 short sentence or statement per objective):** o Objective 1: o Objective 2: o Objective 3: o • **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):** o Objective 1: o Objective 2: o Objective 3:

- ◦

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**
  - **1st:**
  - **2nd:**
  - **3rd**:
  -
- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing?
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product?
  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest?
  - What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?
  - **1st:**
  - **2nd:**
  - **3rd**:
  -
- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  - Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  - Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  - Gaps to be filled / challenges to be overcome to reduce any weaknesses:
  - Additional comments:

Interactions with stakeholders:
• Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? ☐ yes ☐ no • If yes: Can you mention the main interactions and their main conclusions? ○ Interaction 1: ○ Interaction 2: ○
Main results of your project related to the use of satellite-based Earth Observation:
• Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)? *(PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)* • Result 1: • Result 2: • Result 3: • … • .

INFORMED CONSENT FORM

PREPSOIL Data Policy
Project duration: 01/07/2022 - 30/06/2025

You have been invited to take part in the European project "PREPSOIL - Preparing the ground for healthy soils: Building capacities for engagement, outreach, and knowledge".
Before taking a decision on whether you wish to participate or not, please read this document carefully. Please feel free to ask all the questions you may have to ensure that you have full understanding of the purpose and proceedings of the project.

Please contact **Pierre RENAULT**, INRAE, pierre.renault@inrae.fr, XX.XX.XX.XX.XX for any questions you may have.

At all times, we assure full compliance with relevant national and EU legislation on data protection and ethical standards.

1. The Prepsoil Project
Prepsoil is a European project that aims to prepare the ground for the European mission "A soil deal for Europe" (EU Soil Mission).

Prepsoil supports the implementation of the Mission by creating awareness and knowledge on soil needs among stakeholders in regions across Europe. The project widens the understanding of Living Labs as a vehicle for engaging stakeholders in soil improvements in different land use types (agriculture, forestry, urban, etc.) and creates understanding of how different approaches to soil monitoring may support the transition to sustainable land use.

Prepsoil also engages with soil ambassadors and soil advocates, and gather information on soil education by establishing a one-stop-shop for soil literacy, communication, and engagement as a state-of-the-art web platform.
You can read more about Prepsoil on its website: https://prepsoil.eu/

2. Data collected and purposes and legal basis for collecting and processing your data
You are asked to participate in a survey carried out as part of WP5 of Prepsoil. This survey is organised/prepared by Pierre RENAULT from the INRAE (France).
The objectives of the survey are to identify the main European projects on Earth Observation (satellite, airborne sensors, UAVs) and their specific features.

Responses and opinions that you will provide during this survey as a stakeholder will **only be used internally, and in a secured way, to carry out the activity for the objectives described above**.
Data collected during this survey will be used for the duration of the project and will be processed during the phase of data analysis. These data will be included in project reports, deliverables and possibly promotional materials after anonymisation to a level that does not interfere with the quality of the work.

Your personal data are also collected. The personal data we collect are your name, your position and the name, nature (e.g., research, policy, NGO, etc.) and website of your organisation, your e-mail address, your country and the geographic coverage of your professional activity and information regarding your field of expertise (focus on land uses and possibly networks you are related to).

Your personal data will be processed:

- As part of the survey, to ensure good representation of different stakeholders. After anonymisation, information about the nature of your organisation, geographic coverage and your field of expertise will be included in project reports, deliverables and possibly promotional materials to give an overview of the type of stakeholders engaged.
- To involve you as a stakeholder in Prepsoil activities beyond your participation in the survey. In this context, your personal data will be used more specifically to:
  - identify the best way to involve you, depending on the needs of the project and your profile
  - contact you to define together your possible involvement beyond this survey, according to your availability and interest, and in line with the needs of the project.

The legal basis for the processing of personal data is defined in Art. 6 of the General Data Protection Regulation (GDPR). No use for commercial purpose will be made with your data.

3. Recipients of your Data

a. Recipients of your Personal Data

Only Prepsoil project members will have access to your personal data. Prepsoil project members are identified in the following list of entities:

- TRUST-IT, ESTABLISHED IN VIA FRANCESCO REDI 10 56124 PISA, ITALY, VAT NO. AND FISCAL CODE 01958380501
- COMMPLA SRL, ESTABLISHED IN VIA FRANCESCO REDI 10 56124 PISA, ITALY. VAT NO. 01958380501
- AARHUS UNIVERSITET ESTABLISHED IN NORDRE RINGGADE 1 8000 AARHUS C, DENMARK
- STICHTING WAGENINGEN RESEARCH ESTABLISHED IN DROEVENDAALSESTEEG 4 6708 PB WAGENINGEN, NETHERLANDS
- SVERIGES LANTBRUKSUNIVERSITET ESTABLISHED IN ALMAS ALLE 8 750 07 UPPSALA, SWEDEN
- **INRAE : INSTITUT NATIONAL DE RECHERCHE POUR L'AGRICULTURE, L'ALIMENTATION ET L'ENVIRONNEMENT** ESTABLISHED IN 147 RUE DE L'UNIVERSITE 75007 PARIS CEDEX 07, FRANCE
- ASSOCIATION DE COORDINATION TECHNIQUE AGRICOLE ESTABLISHED IN 149 RUE DE BERCY, 75012 PARIS, FRANCE
- NIBIO - NORSK INSTITUTT FOR BIOOKONOMI ESTABLISHED IN HOEGSKOLEVEIEN 7 1430 AAS, NORWAY
- LEIBNIZ-ZENTRUM FUER AGRARLANDSCHAFTSFORSCHUNG (ZALF) E.V. ESTABLISHED IN EBERSWALDER STR. 84 MUENCHEBERG, GERMANY
- EUROPEAN NETWORK OF LIVING LABS IVZW ESTABLISHED IN PLEINLAAN 9 1050 BRUSSEL, BELGIUM
- LESPROJEKT SLUZBY SRO ESTABLISHED IN MARTINOV 197 27713 ZARYBY, CZECHIA
- STICHTING DELTARES ESTABLISHED IN BOUSSINESQWEG 1 2629 HV DELFT, NETHERLANDS
- AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS ESTABLISHED IN CALLE SERRANO 117 28006 MADRID, SPAIN
- INSTYTUT UPRAWY NAWOZENIA I GLEBOZNAWSTWA, PANSTWOWY INSTYTUT BADAWCZY ESTABLISHED IN CZARTORYSKICH 8 24 100 PULAWY, POLAND
- COMITE DES ORGANISATIONS PROFESSIONNELLES AGRICOLE DE L'UNION EUROPEENNE COPA ASSOCIATION DE FAIT ESTABLISHED IN RUE DE TREVES 61 1040 BRUXELLES, BELGIUM
- ASSOCIATION DES VILLES ET REGIONS POUR LA GESTION DURABLE DES RESSOURCES ESTABLISHED IN AVENUE D'AUDERGHEM 63 1040 BRUXELLES, BELGIUM

- FUNDACION FUNDECYT - PARQUE CIENTIFICO Y TECNOLOGICO DE EXTREMADURA ESTABLISHED IN AVENIDA DE ELVAS CAMPUS UNIVERSITARIO ED 06071 BADAJOZ, SPAIN
- OKOLOGIAI MEZOGAZDASAGI KUTATOINTEZET KOZHASZNU NONPROFIT KFT ESTABLISHED IN MELCZER UTCA 47 1174 BUDAPEST, HUNGARY
- RE SOIL FOUNDATION ESTABLISHED IN CORSO DUCA DEGLI ABRUZZI 24, 10129 TORINO, ITALY

b. Recipients of other data
Only INRAE, INSTYTUT UPRAWY NAWOZENIA I GLEBOZNAWSTWA, PANSTWOWY INSTYTUT BADAWCZY, LESPROJEKT, STICHTING WAGENINGEN RESEARCH, SVERIGES LANTBRUKSUNIVERSITET, NIBIO - NORSK INSTITUTT FOR BIOOKONOMI, and the JRC -JOINT RESEARCH CENTRE- EUROPEAN COMMISSION will have access to the other data (responses, opinions) collected through the survey in a non-anonymised form, in order to process these data for the purposes described in section 2.

4. Other Recipients of Personal Data
Your personal data may be shared with consortia of other projects related to the European Soil Deal for Europe, provided that it is only used to involve relevant stakeholders in these projects and that no commercial use is made of your personal data.
One of these projects would be the project Na100ns, that will organise national engagement activities to foster the development of Living-Labs to address regional soil needs and early matchmaking for cross-regional living-labs clusters.
If the case arises that these consortia need to use your personal data for purposes other than the one mentioned above, the coordinators of these consortia will be responsible for contacting you in advance and requesting the necessary authorisations.

5. Retention of your Data
a. Retention of Personal Data
Personal Data processed for the purposes mentioned in section 2 will be stored on Acta SharePoint, up to one year after the end of the project on 2025, June 30. Data within Acta SharePoint will be protected against unauthorised access by creation of individual access to the recipients described in section 3.
Personal data will be also stored for the duration of the project on the collaborative SharePoint platform set up by Aarhus University, coordinator of the Prepsoil project. The SharePoint platform is dedicated to the Prepsoil project and only members of the Prepsoil consortium have access to it. Data within this online collaborative platform will be protected against unauthorised access by means of standard Aarhus University Login (external account login and password).

Copies on local devices will be allowed by the recipients described in section 3 for the purpose and duration of data processing only.

b. Retention of other Data
Responses and opinions expressed during the survey will be recorded and stored digitally on the servers of INRAE, and shared space for PREPSOIL consortium.

The security of your personal data is important to us but remember that no method of transmission over the Internet, or method of electronic storage, is 100% secure. While we strive to use means to protect your personal data, we cannot guarantee its absolute security.

6. Data subjects' rights
You have specific rights as a 'data subject' under Chapter III (Articles 14-25) of Regulation (EU) 2018/1725.

In particular, you have the right to access your personal data, and, to rectify them, in case your personal data are inaccurate or incomplete.
Where applicable, you have the right to erase your personal data, to restrict the processing or the sharing of your personal data, to object to the processing or the sharing of your personal data, and the right to data portability.

You can exercise your rights by sending a written request to the contact identified in section 7.

7. Contact information
In case you have any questions about the collection or processing of your personal data, legal issues, or if you want to exercise your rights of access, rectification, erasure, restriction, data portability, or objection, you can send an email in your local language or in English (with a copy of an ID document if you want to exercise your rights) to INRAE (Pierre RENAULT, pierre.renault@inrae.fr).

8. Amendments
Acta and organisation identified in section 5b reserve the right to amend this notice partly or fully, or simply to update its content, e.g., because of changes in applicable law.
You will be informed by e-mail of such changes as soon as they are introduced.

9. Consent

You are free to accept or refuse to take part in this survey and to the collection and processing of your data as part of the survey, as described in section 2. If you accept to take part, you have the right to decline to answer any questions, or to withdraw from the survey at any moment without providing a reason for it.

Regardless your involvement in the survey, you are free to accept or refuse the collection and processing of your personal data beyond the scope of the [survey/interview/workshop] as described in section 2. If you accept you are free to exercise your rights to object to the processing or sharing of your personal data at any time, as well as all your other rights as described in section 6.

Regardless your involvement in Prepsoil activities, you are free to accept or refuse that your data may be shared with consortia of other projects related to the European Soil Deal for Europe, as described in section 4. If you accept, you are free to withdraw your authorisation at any time and to exercise your rights as described in section 6.

☐ **I give my informed consent to take part in this survey and agree to the collection and processing of my data, as part of this survey, as described in this document.**

☐ **I give my informed consent to the collection and processing of my data, beyond the scope of this survey, for the purpose of involving me as a stakeholder in other activities of Prepsoil, as described in this document.**

☐ **I give my informed consent to my data being shared with consortia of other projects related to the European Soil Deal for Europe Mission, provided that it is only used to involve relevant stakeholders in these projects and that no commercial use is made of my personal data.**

Name and surname of stakeholder
Place, date and signature of stakeholder

Annexe III:

Answers to the survey form for obtaining information on EU projects with an EO component

- SensRes (EJP Soil);

Person answering the questionnaire:

- **Last name:** XXXXX
- **First Name:** XXXXX
- **Professional e-mail:** XXX@XX
- **Responsibility within the project:** **Co-coordination**
- **Informed consent agreement signed:** ☒ yes ☐ no

Project identity:

- **Name/acronym of the project:** SensRes
- **Complete title of the project:** Sensor data for downscaling digital soil maps to higher resolutions (SensRes)
- **Project framework (EJP Soil, Horizon Europe, H2020 …):** EJP Soil
- **Type of project (CSA, RIA, IA …):** MT1
- **Start date:** 01/02/2021
- **End date:** 30/07/2024

Summary of the projet (a simple copy/paste)

Soil maps for large areas often fail to account for local variation in soil properties, due to their coarse resolutions. However, remote and proximal sensors can provide highly detailed soil information at a local level. We therefore propose a method to downscale large-extent soil maps using sensor data. We will test the method for agricultural fields in seven European countries, using proximal sensors, drone images and satellite images. The mapped soil properties will include soil organic carbon, soil texture and locally important soil properties. We will test drone and satellite images of bare soils and vegetated fields, and we will test the effect of fusing data from different sensors. We will also test the potential for using the downscaled soil maps in practical applications.

Main objectives:

- **Main objectives of the project (1 short sentence or statement per objective):**
  - Objective 1: Develop an open access model to downscale soil properties to field level.
  - Objective 2: Test different proximal and remote sensing approaches for downscaling.
  - Objective 3: Apply the approach in different climate conditions in Europe
- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  - Objective 1: Test the use of Sentinel 2 imagens for the downscaling process
  - Objective 2:

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**

- **1st:** Soil organic carbon
- **2nd:** Soil texture (clay and silt)
- **3rd**: We will use the soil organic carbon and soil texture to create high resolution maps of potential sequestration of carbon.

- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing?
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product?
  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest?
  - What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?

- **1st:** We make our own processing.
- **2nd:** We are using Sentinel 2 data from bare soils.
- **3rd**: We are working at ~1m resolution and it would nice to have free higher resolution images of other remote sensing products.

- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    In our case, the satellite-based Earth Observation does not improve the model performance since the 10 m resolution is still quite coarse for our filed analysis.
  - Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    Please see the answer above.
  - Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    -
  - Gaps to be filled / challenges to be overcome to reduce any weaknesses:
    -
  - Additional comments: Available and ready for download bare soil composites could help to improve our model

Interactions with stakeholders:

- Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? ☐ yes ☐ no
- If yes: Can you mention the main interactions and their main conclusions?
  - Interaction 1:
  - Interaction 2:

Main results of your project related to the use of satellite-based Earth Observation:

- Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)?

  (PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)

  - Result 1: The model for downscaling soil properties is the main output of our project and can be applied depending on data availability. The model is available online here (https://github.com/anbm-dk/soilscaler).
  - Result 2: Proximal sensors provide the best performance for the models, but drone images with full bare soil conditions is also important for the downscaling process.
  - Result 3:

- STEROPES (EJP Soil);

Person answering the questionnaire:

- **Last name:** XXXX
- **First Name:** XXXX
- **Professional e-mail:** XXX@XX
- **Responsibility within the project:** co-coordinator (with Johanna Wetterlind, SLU)
- **Informed consent agreement signed:** ☒ yes ☐ no

Project identity:

- **Name/acronym of the project:** STEROPES
  - **Complete title of the project:** Stimulating novel Technologies from Earth Remote Observation to Predict European Soil carbon
- **Project framework (EJP Soil, Horizon Europe, H2020 …):** EJP Soil
  - **Type of project (CSA, RIA, IA …):** medium-sized internal project
- **Start date:** 1st February 2021
- **End date:** 1st July 2024

Summary of the projet (a simple copy/paste)

Conventional high-detail soil maps are static and often based on obsolete data in relation to the time of use. STEROPES intends to overcome these limitations putting the use of satellite time series forward, to test their potential to predict cropland soil organic carbon content over various pedoclimatic conditions and cropping systems across Europe.
First, models will be constructed from the reflectance image spectra of optical satellite series, notably Sentinel-2 (ESA), based on a number of diversified areas for which soil organic carbon samples are already available. The second phase of the project will be dedicated to analysing the influence of various factors on SOC prediction performance: soil moisture, texture, dry vegetation due to management practices, salinity. Then, for the sites where satellite information may not enable to derive acceptable predictions, other ancillary data will be considered at a more detailed scale, using geophysical proxies to reduce the uncertainty associated with these predictions.

Main objectives:

- **Main objectives of the project (1 short sentence or statement per objective):**
  - Objective 1: assess robustness of spectral models according to agroecosystems/soil types
  - Objective 2: assess/account for disturbing/influencing soil surface factors
  - Objective 3: incorporate results from objectives 1 & 2 into spatial models
- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  - Objective 1: -
  - Objective 2:-
  - Objective 3:-

  Comment: All tasks deal with Earth observations

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations
From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**
  - **1st:** soil organic carbon content of the topsoil (SOC) for digital soil assessment
  - **2nd:** soil moisture content of the topsoil
  - **3rd**: soil texture of the topsoil
  - **4th**: soil salinity of the topsoil
  - **5th**: dry or green vegetation residues on the soil surface
- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing?
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product?
  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest?
  - What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?
  - **1st:** Théia CNES data platform or satellite data from Google Earth Engine, own soil datasets
  - **2nd:** Théia CNES data platform or satellite data from Google Earth Engine, own soil datasets
  - **3rd**: Théia CNES data platform or satellite data from Google Earth Engine, own soil datasets
  - **4th**: Théia CNES data platform or satellite data from Google Earth Engine, own soil datasets
  - **5th**: Théia CNES data platform or satellite data from Google Earth Engine, own soil datasets
- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    Strengths : reduced need of reference soil data and easier update of soil maps

    Specifying the strengths and weaknesses of EO for assessing SOC is precisely the main expected outcome of the project (still in progress). The following review papers have been published to anticipate what is known so far from the literature:
    Vaudour et al., 2022. https://doi.org/10.3390/rs14122917
    Richer-de-Forges et al., 2023. https://doi.org/10.3390/rs15123070
  - Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    Weaknesses (see above mention): need of recently collected reference soil data (accuracy depends on many factors, including the density and spatial scale of the reference dataset); possible need of covariates
  - Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    Risks (see above mention): Issues of cloud frequency and soil roughness
    Lack of recent and sufficiently dense soil data analyses
    Need to harmonize SOC determination methods

- Gaps to be filled / challenges to be overcome to reduce any weaknesses:
  Gaps: Tackle the agroecosystems in which bare soil is hardly appearing because of agricultural choices (generating soil roughness and/or partially vegetated surfaces)
  Accuracy/uncertainty of estimates according to available data and specific pedoagroecosystems
- Additional comments:
  Gaps currently under study in the framework of STEROPES and also in the framework of the SANCHOsTHIRST ‘s project of EJP SOIL (external) for vineyards and of the MELICERTES project (PEPR “Agroécologie et numérique”-France2030) for soil roughness

Interactions with stakeholders:

- Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? ☒ yes ☐ no
- If yes: Can you mention the main interactions and their main conclusions?
  - Interaction 1: in the form of national workshops held separately by the project representatives (for instance, Sweden, Switzerland, Spain and Portugal). Conclusions: encouragements and interest for this research.
  - Interaction 2:
  -

Main results of your project related to the use of satellite-based Earth Observation:

- Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)?

  (PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)
  - Result 1: review of past studies relying on satellite remote sensing for the purpose of SOC mapping point out its potential (https://doi.org/10.3390/rs14122917)
  - Result 2: median reflectance and 90th percentile reflectance are amongst the best strategies for temporal mosaicking of Sentinel-2 bare soil reflectance in relationship with accuracy/uncertainty of SOC and clay content at local scale (Castaldi et al 2023 doi10.1016/j.isprsjprs.2023.03.016)
  - Result 3: soil moisture maps derived from Sentinel-1 and Sentinel-2 are useful for temporal mosaicking of S2 time series to predict SOC (Urbina-Salazar et al., 2023 doi10.3390/rs15092410)
  - Result 4: jointly with Sentinel-2 bands and indices, gamma-ray data are important co-covariates to predict clay, hence SOC (Urbina-Salazar et al., 2023 doi10.3390/rs15092410)
  - Result 5: when retrieving soil moisture from Sentinel-1, limitations arise over certain crops and the accuracy is sensitive to the first soil thin layer (Bazzi et al., 2024 doi.org/10.3390/w16010040)
  - Result 6: deep learning approaches combining lab spectra and times series of image spectra might yield better performance than image spectra only (Zayani et al., 2023 doi.org/10.3390/rs15174264)

- AI4SoilHealth (Horizon Europe (RIA));

Person answering the questionnaire:
• **Last name:** XXXX • **First Name:** XXXX • **Professional e-mail:** XXX@XX • **Responsibility within the project:** WP5 lead • **Informed consent agreement signed:** ☑ yes ◻ no
Project identity:
• **Name/acronym of the project:** AI4SoilHealth • **Complete title of the project:** AI4SoilHealth: Accelerating collection and use of soil health information using AI technology to support the Soil Deal for Europe and EU Soil Observatory • **Project framework (EJP Soil, Horizon Europe, H2020 …):** Horizon Europe • **Type of project (CSA, RIA, IA …):** RIA • **Start date:** 1st January 2023 • **End date:** 31 December 2026
Summary of the projet (a simple copy/paste)
The objective of AI4SoilHealth is to co-design, create and maintain an open access European-wide digital infrastructure, compiled using state-of-the-art Artificial Intelligence (AI) methods combined with new and deep soil health understanding and measures. The AI-based data infrastructure functions as a Digital Twin to the real-World biophysical system, forming a Soil Digital Twin. This can be used for assessing and continuously monitoring Soil Health metrics by land use and/or management parcel, supporting the Commission's objective of transitioning towards healthy soils by 2030. The project is divided into seven (7) work-packages including: (WP2) Policy and stakeholder engagement - networking and synchronising with EU and national programmes, (WP3) Soil health methodology and standards - developing/testing methodology to be used by WPs 4-6, (WP4) Soil health in-situ monitoring tools and data - developing field and laboratory solutions for Observations & Measurements, (WP5) Harmonised EU-wide soil monitoring services - developing the final suite of tools, data and services, (WP6) Multi-actor engagement pilots - organizing field-works and collect users' feedback, (WP7) Soil literacy, capacity building and communication - organizing public campaigns and producing educational materials. Key deliverables include: 1) Coherent Soil Health Index methodology, 2) Rapid Soil Health Assessment Toolbox, 3) AI4SoilHealth Data Cube for Europe, 4) Soil-Health-Soil-Degradation-Monitor, and 5) AI4SoilHealth API and Mobile phone App. Produced tools will be exposed to target-users (including farmer associations in >10 countries), so their feedback is used to improve design/functionality. Produced high-resolution pan-European datasets will be distributed under an Open Data license, allowing easy access by development communities. AI4SoilHealth will provide an effective Soil Health Index certification system to support landowners and policy makers under the new Green Deal for Europe.
Main objectives:
• **Main objectives of the project (1 short sentence or statement per objective):**

- Objective 1: Identify key policy and living lab stakeholder requirements for a pan-EU Soil Health Index, using this input as the initiation for the co-design of the Soil Health Indicator framework and digital infrastructure (WP2).
- Objective 2: Develop a robust framework for indicator selection and testing. Starting with the eight proposed Mission Board indicators ("A Soil Deal for Europe") and identifying new and proxy measures for a more harmonized approach to soil health monitoring and simulation of soil processes (WP3).
- Objective 3: Develop a sensor-fusion-based soil health assessment toolbox of the future (spectroscopy, genomics and in-situ measurements). Test methods suitable for stakeholder implementation with potential for incorporation in national monitoring and LUCAS soil (WP4).
- Objective 4: Develop a flexible progressive web app-based cyberinfrastructure termed "AI4SoilHealth" (including Soil Health Data Cube) to serve users with current data at farm scale (30m spatial resolution or finer) with a secure API (Application Programming Interface) (WP5).
- Objective 5: Develop and deploy the AI4SoilHealth EO (Earth Observation)-based Soil-Health and Soil-Degradation Monitor to be assessed against ground based networks of measurements, working with real soil managers (reporting soil health state & threats), compatible with LUCAS soil methodology (WP5).
- Objective 6: Test, harmonize and benchmark the proposed indicators for a range of soil types, land use types and climate zones in the EU and Associated Countries (pilots) and define the acceptable limits or thresholds; update indicators as a result of feedback following monitoring campaigns or data inputs (WP6).
- Objective 7: Increase soil literacy, promote the value of soil health also from an economic aspect (soil ecosystem services) and connect researchers, advisors, SMEs, industry and the AI4SoilHealth tools (WP7).

- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  - Objective 1: Compare derivation of NDVI density curves using daily Planet Fusion & monthly Sentinel-2 images during a growing season.
  - Objective 2: Test fitting and using spatiotemporal ML models to predict dynamic soil properties such as soil carbon, pH, soil nutrients and similar.
  - Objective 3: Assess the state and change of soil properties/soil health indicators through time. Produce trend maps and detect areas across pan-EU with potentially significant soil degradation.

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**
  - **1st:** soil chemical properties from LUCAS soil;
  - **2nd:** soil physical soil properties and soil types (WRB 2022)
  - **3rd**: experimental soil variables designed and collected in the project e.g. soil enzyme concentrations, soil erodibility etc.

Soil health indicators of interest: 1) presence of pollutants, excess nutrients and salts, 2) soil organic carbon stock, 3) soil structure including soil bulk density and absence of soil sealing and erosion, 4) soil biodiversity, 5) soil nutrients and acidity (pH), 6) vegetation cover, 7) landscape heterogeneity, 8) forest cover;

- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing? **NO**
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product? **YES we use CLMS data as covariates for soil property mapping**.
  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest? **YES we are building a large data cube with all covariate layers; available at: https://github.com/AI4SoilHealth/SoilHealthDataCube**
  - What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use? **30 to 10 m resolution; monthly to 10-day temporal granularity**
-
- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    RE: We currently use Landsat time-series 2000–2022 bimonthly indices (described in: https://www.researchsquare.com/article/rs-4251113/v1). Advantage of this data is that we have almost 25 years of data so that we can determine long-term trends and understand which are the key drivers of soil degradation and how change in land use affects soil properties. Also, having bimonthly data allows us to follow crop rotations and quantify effects of seasonal events e.g. floods, drought, forest fires etc.
  - Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    RE: The Landsat data has limited quality and spatial resolution. Also, a lot of artefacts due to poor cloud / snow masks can be visible especially in winter months (November to March). Artifacts can propagate to predictions i.e. totally pollute predictions of soil properties. Sentinel-2 images are about 5–10 times more detailed and come with less artifacts, however, these are more expensive to process because of the higher data volume + they are only available for 2016+.
  - Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    RE: We noticed consistently 2 things that affect predictive soil mapping of dynamic soil properties: (1) inter-annual variability in biophysical indices is often result of climatic oscillations and this does not affect changes in soil properties, but it is a problem and needs to be filtered out as it becomes visible in the predictions, (2) most of EU countries have a wealth of soil data, but unfortunately (and even though this data has been paid from national or EU funding), this data is being kept by researchers and government agencies. The effort to collate and use this (we are talking only about the legacy data i.e. older than 5 years) is significant and

without it is difficult to fully understand what is the maximum potential of using EO images for soil monitoring.

- Gaps to be filled / challenges to be overcome to reduce any weaknesses:
  RE: What would be useful if some other project could produce cloud-free Sentinel-2 bimonthly products for pan-EU (including annual bare-earth spectral products) and make it available as open data. In addition, we are hoping to use some of the DRL products (e.g. https://doi.org/10.1016/j.rse.2017.11.004) and products from other Horizon Soil projects. In our project we share our data and outputs as soon as we produce them. It would be nice if other groups would do the same!
- Additional comments:
  We had quite some issues with defining "pan-EU". There are several subsets of "pan-EU" so we have finally decided to use the broadest definition (include western Balkans, Ukraine and Turkey, UK and Switzerland), but this comes at a cost! Many GIS layers (e.g. CORINE land cover) we use are only available for some countries and need to be gap-filled.

Interactions with stakeholders:

- Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? ☑ yes □ no
- If yes: Can you mention the main interactions and their main conclusions?
  - Interaction 1: **We are having a group visit to JRC ESDC in June 2024 and will discuss these issues in detail; Conclusions will follow.**
  - Interaction 2: **We are planning an open workshop in April 2025 and will invite stakeholders from JRC, EEA, but also from industry / commercial businesses; Conclusions will follow.**

Main results of your project related to the use of satellite-based Earth Observation:

- Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)?

  (PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)
  - Result 1: **We have discovered that gully erosions can be successfully mapped using Landsat indices (https://www.kaggle.com/competitions/esa-eo4soilprotection-2024-predicting-erosion-cat/);**
  - Result 2: **We have discovered that the Eurostat data can be compared with results we get directly from Landsat / Sentinel-2 biophysical indices (https://doi.org/10.21203/rs.3.rs-4251113/v1)**
  - Result 3: **We have discovered that LUCAS points are most likely the best source of data for testing predictive mapping, but the delay to get the data to researchers (outside JRC) is really significant — for example the 2021/2022 soil samples are still not available and the release date is unknown.**
  - …

- BENCHMARKS (Horizon Europe (RIA));

Person answering the questionnaire:
• **Last name:** XXXX • **First Name:** XXXX • **Professional e-mail:** XXX@XX • **Responsibility within the project:** Management on research focussing on spatial and sensor applications • **Informed consent agreement signed:** X yes ☐ no
Project identity:
• **Name/acronym of the project:** BENCHMARKS • **Complete title of the project:** Building a European Network for the Characterisation and Harmonisation of Monitoring Approaches for Research and Knowledge on Soils • **Project framework (EJP Soil, Horizon Europe, H2020 …):** Horizon Europe. HORIZON-MISS- 2021-SOIL-02-02] — [Validating and further developing indicators for soil health and functions] • **Type of project (CSA, RIA, IA …):** HORIZON-RIA - HORIZON Research and Innovation Actions • **Start date:** 01-01-2023 • **End date:** 01-01-2027
Summary of the projet (a simple copy/paste)
BENCHMARKS is a Horizon Europe funded project, aims to develop a transparent, harmonised, and cost-effective integrated soil health monitoring framework (ISHMF) for measuring soil health across Europe. The acronym BENCHMARKS stands for "Building a European network to advance soil research, monitor soil health and advocate for sustainable land use". The resulting ISHMF will be co-developed by the project team and stakeholders engaged within the 24 European local case studies (LCS) and landscape case studies covering multiple land-use types: agriculture, forestry and urban. The ISHMF will consider both multi-scale and multi-user requirements for the development of the monitoring framework. Throughout the project, BENCHMARKS will support the Joint Research Centre (JRC) and EU Soil Observatory (EUSO) in development of a Soil Health Dashboard (SHD). The ISHMF will serve as basis for the SHD, which provides assessment, evaluation, and support for land managers and other BENCHMARKS stakeholders at various scales. Working with a range of stakeholders such as land managers, legislators, value chain businesses, NGOs and policy makers, BENCHMARKS will define a monitoring system that is pertinent to the objective of assessment, applicable to the land use, and logistically feasible. Key outcomes of the project will include a harmonized and cost-effective framework for measuring soil health, a review of proposed indicators from the EU Soil Mission and BENCHMARKS, the ISHMF, the SHD and scientific underpinning of soil health incentivization schemes for value-chain businesses.
Main objectives:
• **Main objectives of the project (1 short sentence or statement per objective):** 1. Co-develop a coherent Integrated Soil Health Monitoring Framework 2. Test and validate the SH&F mission indicators as well as the alternative/additional indicators proposed by BENCHMARKS for the different land uses (agriculture, forestry and urban) and for the different scales (local, landscape, region, Europe).

3. Develop a European-wide sampling framework, methodology and protocols, which can serve to support relevant EU policy (and global initiatives including; LULUCF), regulation and monitoring needs.
4. Support the development of a Soil Health Dashboard with the Joint Research Centre (JRC).
5. Make sure to follow the FAIR principles to ensure that project data and protocols are actively made available to the large variety of stakeholders.
6. Develop and implement communication, dissemination and exploitation activities to ensure that the outputs of the project are relevant, understandable and applicable for the various stakeholders.

- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  - Objective 1: Using satellite data for soil sampling designs, at local and broader scales
  - Objective 2: Testing the applicability of various sensors (drone, satellite) for retrieving context-specific soil health indicators, at local and broader scales
  - Objective 3: Using of a wide range of satellite data for predictive mapping using machine learning (AI)

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**
  - **1st:** Direct retrieval of soil variables from bare soil (e.g. soil organic matter).
  - **2nd:** Indicators derived from the land surface (e.g. vegetation traits) which serve as proxy indicator for soil variables, soil functions and soil health, representing spatial and temporal variability.
  - **3rd**: Indicators derived from the land surface (e.g. trends in land productivity and meteorological data) which serve as indicator for drivers of change in soil functions and soil health.
- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing?
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product?
  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest?
  - What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?
  - Drone imaging and processing is done by ourselves.
  - Sentinel and Landsat data is obtained through google earth engine, processing is further done by ourselves.
  - PlanetScope data is obtained through the European Space Agency, processing is done by ourselves.
- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    - Soil sampling design: Reducing sampling numbers and thus costs by optimizing the sampling design using environmental variables.
    - Spatial variability: Using drone imaging for assessing within field variability of a wide range of soil health indicators in different land use system. Using satellite-based EO data for assessing context-specific variability of soil health in different land use systems across Europe.
    - Soil monitoring: Context-specific mapping and monitoring of key (proxy) indicators and drivers.

- Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  - The accuracy will depend on the scale of assessment, the land use system (e.g. forest, agriculture, urban) and the spatial and spectral resolution of the employed sensors. Not all proxies may proof to be sufficiently accurate or pertinent for soil health monitoring. This is further studied within BENCHMARKS, results are not yet available.
  - Validation of modelled soil variables requires sampling (ground truthing) and sufficient up-to- date soil data is required. This is challenging for large scale assessments.
- Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  - We do not foresee any risks or threats.
- Gaps to be filled / challenges to be overcome to reduce any weaknesses: The main challenges are having sufficient soil property (chemical, physical and biological) data, either from field sampling campaigns or from legacy data for large-scale assessments. If legacy data is being used (e.g. existing national soil information systems), harmonization of soil information originating from various European countries will be a major challenge. Soil biological data is typically not widely available and thus for large-scale modelling the datasets may be too scarce.
- Additional comments: none

Interactions with stakeholders:

- Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? X yes ☐ no
- If yes: Can you mention the main interactions and their main conclusions?

During the past months we have organised multistakeholder workshops, one for each case study. We are currently analysing the results, they will be available soon. Below a summary of the process:
To ensure the success of the Integrated Soil Health Monitoring Framework (ISHMF), BENCHMARKS recognizes the significance of adopting a user-centric approach. BENCHMARS emphasizes the active involvement of a diverse range of stakeholders within the 24 LCS to achieve this objective.
By engaging with stakeholders, BENCHMARKS aims to understand and address their specific needs within a collaborative framework. BENCHMARKS seeks to gather valuable insights and perspectives from various actors involved in soil and land management, including land managers, policy makers, scientists, and local communities. These stakeholders bring their knowledge, expertise, and decision-making power, which are essential for ensuring the relevance and acceptance of BENCHMARKS outcomes.
The engagement with stakeholders within the 24 LCS enables us to customize the ISHMF to their specific contexts, ensuring its practicality and usability. By incorporating stakeholders' inputs and feedback, the project can develop a framework that meets their practical needs, facilitates informed decision-making, and promotes effective soil management practices.
Through this collaborative effort, BENCHMARKS aims to co-create a robust and user-oriented ISHMF that reflects the collective wisdom and expertise of stakeholders. By actively involving stakeholders throughout the development process, BENCHMARKS fosters ownership, enhance the framework's effectiveness, and ultimately contribute to sustainable soil health management across Europe.

Main results of your project related to the use of satellite-based Earth Observation:

- Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)?
  (PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)
  - For the sampling design there is not a specific deliverable. At the moment, the sampling is ongoing and thus not results are yet available concerning the use of satellite-based Earth Observation for monitoring soil health.
  - The most recent version of the sampling design was also discussed with the JRC in order to contribute to the updated LUCAS Soil Module, potentially introducing new parameters and sampling protocols.

- MARVIC (Horizon Europe (RIA)) & OrCaSa (Horizon Europe (CSA));

Person answering the questionnaire:

- **Last name:** XXXX
- **First Name:** XXXX
- **Professional e-mail:** XXX@XX
- **Responsibility within the project:** co-WP leader or the ORCASA and MARVIC projects
- **Informed consent agreement signed:** X yes ☐ no

Project identity:

- **Name/acronym of the project:** **ORCASA and MARVIC projects**
- **Complete title of the project:** "Operationalising the International Research Cooperation on Soil Carbon" (ORCASA) and "Developing and testing a framework for the design of harmonized, context-specific Monitoring, Reporting and Verification systems for soil Carbon and greenhouse gas balances by Agricultural activities" (MARVIC)
- **Project framework (EJP Soil, Horizon Europe, H2020 …):** **Horizon Europe**
- **Type of project (CSA, RIA, IA …):** MARVIC: RIA & OrCaSa: CSA
- **Start date:** 1st June 2023 for MARVIC, 1st September 2022 for OrCaSa
- **End date:** 31 May 2027 for MARVIC, 31 August 2025 for OrCaSa

Summary of the projet (a simple copy/paste)

ORCASA

To reach the targets of the Paris Agreement commitments for land degradation neutrality, for biodiversity, and to support the EU Green Deal, Europe needs to join its research and innovation forces on soil carbon with those around the globe in a coordinated manner. To scale up efforts for conserving and increasing soil carbon stocks and harness the co-benefits for climate change mitigation and adaptation, soil health and food security international coordination of research efforts is essential. In this context the EC supported a 1st Coordination action (CIRCASA) led by INRAE which brought together over 100 key stakeholders and 500 scientists from around the world who formalised an interest in establishing an International Research Consortium (IRC) on Soil Carbon built around an initial strategic research and innovation agenda (SRIA) focusing on agricultural soils. Operationalising the IRC requires further mobilization of the international community of stakeholders working on agricultural soil carbon but also other land uses and therefore expanding the initial SRIA as well as developing with international funding bodies an implementation plan and a central knowledge platform offering services to this community.

The main goal of ORCaSa is therefore to launch and roll out the initial operational phases of the IRC on Soil Carbon so that by 2024 the IRC has established an international position as the coordinator of soil carbon research and innovation and related issues at global level offering a unique SRIA and implementation plan, supporting knowledge platform and enable the preparation of a disruptive low cost international recognized MRV system. To reach this overall goal, ORCaSa brings together European partners and 6 regional nodes covering the 5 continents around an ambitious 3-year work plan working hand in hand with the international every step of the way.

MARVIC

The EC has set the ambition to become climate neutral by 2050. As not all greenhouse gas (GHG) emissions can be avoided, such as GHGs from biological processes in agriculture, carbon removal will become increasingly important to meet the neutrality targets set. Besides carbon capture and storage by industry, carbon sequestration in the land use sector will need to compensate for the remaining emissions. In this respect, reliable yet cost-effective systems to monitor, report and verify efforts by land managers become increasingly important. This is particularly relevant for the international GHG inventory reporting, and for the development of payment systems to reward land managers for sequestering carbon and reducing GHG emissions by carbon farming (CF). The interest in CF schemes is substantial, as illustrated by the large number of (pilot) payment schemes that have been initiated in recent years. Most of the schemes are experimenting on relatively small geographical areas with a relatively small number of land managers involved. In the 'Sustainable carbon cycles communication' that was launched in December 2021, the EC has expressed the challenging ambition that 'every land manager should have access to verified emission and removal data by 2028 to enable a wide uptake of CF'. MARVIC has been specifically designed to generate instruments and knowledge that enable fulfilling this ambition. The main goal of MARVIC is to develop and test a reliable Framework for the design of harmonized, context-specific MRV systems ('MRV Framework') for assessing carbon stock changes in soils and woody biomass and soil GHG emissions. The development of a generic MRV Framework, applicable to all agricultural land-use activities, is essential for boosting faith in public and private CF schemes in Europe.

Main objectives:

- **Main objectives of the ORCASA project (1 short sentence or statement per objective):**
  - Objective 1: prepare the launch of the International Research Consortium on Soil Carbon
  - Objective 2: Define a strategic research and innovation agenda
  - Objective 3: develop a knowledge platform
  - Objective 4: Propose a unified methodological framework for MRV and a first prototype of operational SOC monitoring
- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective): Only WP4 that is about MRV deals with satellite observations**
  - Objective 1: analyse how to use EO data in the Monitoring and verification components of MRV Objective 2: develop a prototype of operational processing chain for Monitoring SOC stock changes at cropland involving EO data assimilation in a coupled crop-soil model (AgriCarbon-EO processing chain)
  - Objective 3: produce data layers involving EO data related to C budget components for the Impact4soil platform

- **Main objectives of the MARVIC project (1 short sentence or statement per objective):**
  - Objective 1: boost faith in European public and private carbon farming (CF) schemes by developing and testing an MRV Framework that will provide, to any public or private CF scheme developer a standardized approach for designing MRV systems that (i) are in line with the EU carbon removal certification regulation, (ii) have an optimal trade-off between costs and accuracy, (iii) take into account the local context, (iv) reduce administrative burden and (v) consider risks of non-permanence
  - Objective 2: For achieving accurate yet cost-effective MRV systems with minimum administrative burden, MARVIC investigates how different building blocks of (farm) data, sampling strategies,

benchmark sites, models and remote and proximal sensing technologies could efficiently be connected into operational processing chains (OPCs)

- Objective 3:

- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  - Objective 1: analyse how to use EO data in the Monitoring and verification components of MRV
    Objective 2: develop prototypes of Operational processing chain for Monitoring SOC stock changes for different land use types (cropland, grassland, peatland, agroforestry). Some of them will involve EO data assimilation in a coupled crop-soil models
  - Objective 3: Use EO data to develop methods for optimal soil and biomass sampling for validation of the operational processing chains but also for the Verification component of MRV.

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application? (both for ORCASA & MARVIC projects)**
  - **1st:** soil organic carbon stock changes for MRV purposes
  - **2nd:** soil organic C content and stocks
  - **3rd**: soil texture, soil bulk density
  - **4th**: all the other components of the carbon budget (CO2 fluxes, biomass, yield) for MRV purposes
  -
- **For each of targeted soil variables/characteristics/indicator(s):**

  - Are these products available from a service or do you make your own processing?

  In ORCASA:

  - For SOC content and stocks we use SoilGrids or LUCAS spatialised products + we plan to use our own superficial SOC content map based on EO data (collaboration with E. Vaudour, INRAE from ECOSYS) + we do in situ measurements of SOC stocks
  - For SOC stock changes we produce our own spatialised products based on the AgriCarbon-EO processing chain

  In MARVIC:

  - For SOC content and stocks we use both soil products (e.g. SoilGrids, LUCAS spatialised products) + our own superficial SOC content and stocks map based on EO data and other methods (e.g. gama ray, spectral informations…)
  - For SOC stock changes we produce our own spatialised products based on several processing chains (e.g. AgriCarbon-EO, Remote-C…)

  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product?

    For both projects:

    - We are using Sentinel 2 data to estimate 1) crop leaf area index that we assimilate in crop model to estimate C budget components (CO2 fluxes, biomass, yield, SOC pools…), 2) superficial SOC content maps

  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest?

    For both projects:

    - We use climatic data (e.g. ERA5), soil property maps (Soilgrids, Lucas), plots contours and type (LIPS data) activity data provided by the farmers

- What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?

- **1st:** 10 m resolution for all products
- **2nd:** annual estimates of soil organic C stock changes, biomass (aboveground, belowground) and yield
- **3rd**: daily estimates of CO_2 fluxes, biomass (aboveground, belowground)
-

- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**

Not Easy to answer this question because soil health covers many aspects. Therefore I will consider some indicators that be related to soil earth according to me

- Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  We use optical satellite data to map superficial permanent soil properties (e.g. C content, albedo) but only when the soil is bare. We also explore the use of radar (active) satellite data to provide info on superficial soil water content but they are more complex to use than optical data.
  We also use satellite data to produce information on vegetation development such as biomass phenology, soil coverage that can be used as a proxy of soil fertility and/or soil water holding capacity
  Mostly we use satellite data to produce time series of biophysical products (e.g. Leaf Area Index) that we assimilate in crop models to better estimate biomass input to the soil but also soil water content dynamics.
  Last we use optical satellite data to map agricultural practices (soil work, cover crops…) that will impact soil health (erosion, SOC content…)
- Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  We start working on the combined use of optical and radar satellite data to produce continuous times series of biophysical indicators (e.g. leaf area index, LAI) to be assimilated in crop/soil models in order to avoid gap in observations during cloudy periods.
  We also analyse the potential of higher resolution satellite data assimilation in crop/soil models from private constellations such as Planet to improve the biomass & soil C estimates.
- Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
  When using only optical data (e.g. Sentinel 2) the main risk is related with long cloudy periods that prevent from seeing the agricultural practices and plant development. In such situations EO data cannot be used to assimilate LAI time series in crop models to force them to reproduce biomass development, C inputs to the soil and changes in SOC.
- Gaps to be filled / challenges to be overcome to reduce any weaknesses:
  To overcome the risk mentioned above we analyse different options for using radar satellite data in combination of optical ones as radar data are not sensible to clouds
- Additional comments:
-

Interactions with stakeholders:

• Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? x yes ☐ no
• If yes: Can you mention the main interactions and their main conclusions?
  ○ Interaction 1: we organised for both projects (ORCASA & MARVIC) workshops on MRV and we asked various stakeholders in which contexts EO data couldn't be used for MRV (cloudy areas, size of the parcels, slopes…) and how EO should be used in the Monitoring and Verification components of the MRV process
  ○ Interaction 2:
  ○

Main results of your project related to the use of satellite-based Earth Observation:

• Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)?
(PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)
  • Result 1: Development of the AgriCarbon-EO processing chain assimilating EO data in a model to Monitor SOC stock changes (ORCASA & MARVIC)
  • Result 2: assessment of how EO data could be used in the MRV process for M and V (see ORCASA's Deliverable 4.1: https://www.isric.org/sites/default/files/ORCASA_D4-1_FinalDeliverable_InReviewByEU_0.pdf)
  • Result 3: We have developed a methodological framework on how to use EO data to monitor SOC stock changes
  • …

- MRV4SOC (Horizon Europe (RIA));

Person answering the questionnaire:

On behalf of the MRV4SOC consortium and partners working with RS data and tools (AUTH, CZU, DLR, GFZ, ISRIC, TAU, UCL)

- **Last name:** XXXX
- **First Name:** XXXX
- **Professional e-mail:** XXX@XX
- **Responsibility within the project:** Coordinator
- **Informed consent agreement signed:** x yes ☐ no

Project identity:

- **Name/acronym of the project:** MRV4SOC.
- **Complete title of the project:** Monitoring, Reporting and Verification of Soil Organic Carbon and Greenhouse Gas Balance
- **Project framework (EJP Soil, Horizon Europe, H2020 …):** Horizon Europe
- **Type of project (CSA, RIA, IA …):** RIA
- **Start date:** 1st June 2023
- **End date:** 31 may 2026

Summary of the project (a simple copy/paste)

MRV4SOC aims at designing a comprehensive, robust, and cost-effective Tier 3 approach, accounting for changes in as many C pools as possible, to estimate GHG and full C budgets, coupling C and N cycles, quantify Soil Organic Carbon (SOC) accumulation, and assess the results of traditional management practices and C farming. The main challenges addressed in MRV4SOC are: i) monitoring changes in SOC accumulation due to climate change and socio-economic pressures; ii) accounting for C and N cycles in full C budgets; iii) development of scientifically-sound, standard, and transparent Tier 3 methodology at different scales, iv) implementation of high-quality in-situ and RS data for testing methods and scale-up purposes; iv) standardisation of Monitoring, Reporting, and Verification schemes to ensure transparency, robustness, and cost-effectiveness; and v) a lack of trust in Voluntary Carbon Markets. To overcome these challenges, MRV4SOC will develop 6 specific objectives, which will be measurable, verifiable, and monitored through KPIs pointing at specific targets. MRV4SOC proposes a comprehensive 3-year work plan that ranges from the assessment of C pools in 9 land use/ land cover classes located in 14 Demonstration Sites (DS); to the potential integration of the approach. MRV4SOC aims at designing a comprehensive and robust Tier 3 approach accounting for changes in as many C pools as possible (above-ground biomass, below ground-biomass, litter, dead wood, soil organic carbon, and harvested wood products) fully aligned with national GHG reporting. MRV4SOC seeks to develop solutions applicable for different spatio- temporal scales and climate change scenarios and validated for a wide variety of ecosystems in arid, temperate, and continental climate zones in collaboration with local stakeholders. The proposed approach will help establish reliable and transparent C farming credits within a cost-effective monitoring, reporting, and verification (MRV) methodological framework.

Main objectives:

- **Main objectives of the project (1 short sentence or statement per objective):**
  - Objective 1: To measure long-term SOC accumulation in 9 EU representative LULC classes.
  - Objective 2: To assess how C farming practices drive C flux dynamics in the 9 LULUCF classes.
  - Objective 3: To assess the impact of climate change on SOC accumulation associated with C farming practices.
  - Objective 4: To develop a robust, transparent, standard, and cost-effective MRV to facilitate results-based payments.
  - Objective 5: To seek out revenue opportunities to unlock results-based payments.
  - Objective 6: To increase stakeholders' faith in Voluntary Carbon Markets.
- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  - Objective 1: Analysis and Preparation of RS Data Inputs for Modelling Approaches
  - Objective 2: Testing the Effect of RS and other Widely Available Data as Input for the GHG Budget Models

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**
  - **1st:** SOC (operational)
  - **2nd:** Bare soil composites (operational)
  - **3rd**: Soil texture, pH and Total N
  - **4th**: Cover crops and Yield
  - **5th**: fCover, fPAR and LAI

All the aforementioned indicators will be produced via RS techniques and will be used as enhanced input datasets into the physical process-based modelling supporting the Tier 3 MRV methodologies.

- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing?
    - Own processing, the processing chain of some of these products will be built upon the results obtained from the ESA Worldsoils project (https://world-soils.com/).
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product?
    - N/A yet, further information below.
  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest?
    - Yes (ground truth data), meta data (climate, GPS, topography, parent material)
  - What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?
  - **1st:** SOC, Sentinel-2, 1 ha globally, 10 m pixel size in Europe, once a year (summer season).
  - **2nd:** Same as 1
  - **3rd**: Same as 1
  - **4th**: Same as 1
  - **5th**: Same as 1

- **SWOT analysis applied to the use of satellite - based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    - Spatial, spectral and temporal resolution
    - Large scale applications/wide coverage
    - Most of the datasets for soil health monitoring are open and freely available.
    - Global cover
    - Non-invasive
    - Standardized ground truth data
    - QA of satellite data
  - Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    - In many cases very coarse spatial resolutions
    - Cloud cover problem
    - Data processing
    - Deterioration of satellite sensor
    - Atmosphere attenuation
    - Harmonization of spectral libraries
  - Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    - The overall cost of acquiring and processing the big amount of data.
    - Risks/threats related to data quality, calibration and validation of satellite derived soil health indicators may impact the accuracy and the reliability of monitoring which potentially may lead to incorrect decision-making and planning.
    - Data sharing, privacy, and data ownership rights may pose challenges to the effective utilization of satellite-based EO for soil health monitoring
    - Lack of ground truth data
  - Gaps to be filled / challenges to be overcome to reduce any weaknesses:
    - Spatial, temporal and spectral resolution improvements
    - Cloud cover efficiency
    - Data processing efficiency
    - Cost reduction in the cases where the satellite data are not open
    - Validation and calibration to ensure the accuracy and the reliability of satellite-derived soil health indicators, including ground-truthing measurements and calibration against field-based data.
    - Provide training and capacity-building programs to enhance the skills and expertise of stakeholders in remote sensing and EO techniques, particularly in regions with limited resources or technical expertise.
  - Additional comments:

Interactions with stakeholders:

- Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? x yes ☐ no
- If yes: Can you mention the main interactions and their main conclusions?
  - Interaction 1: Two workshops have been organised so far, but they were related to identify Carbon farming barriers and enablers. One workshop was organised in Belgium and another one in Spain. Further workshops will be organised in other regions such as Italy and Czech Republic. However, we are not planning to discuss the usefulness of EO products.
  - Interaction 2: CREDIBLE Focus Groups, MRV4SOC is contributing to the discussions regarding Earth Observation in those Focus Groups. We will deliver a presentation of the 27th of May.

Main results of your project related to the use of satellite-based Earth Observation:

- Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)?

  (PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)
  - Result 1:
  - Result 2:
  - Result 3:
  - …

- ProbeField (EJP Soil);

Person answering the questionnaire:
• **Last name:** XXXX • **First Name:** XXXX • **Professional e-mail:** XXX@XX • **Responsibility within the project:** co-coordinator • **Informed consent agreement signed:** ✓☐ yes ☐ no
Project identity:
• **Name/acronym of the project:** Probefield • **Complete title of the project:** A novel protocol for robust in field monitoring of carbon stock and soil fertility based on proximal sensors and existing soil spectral libraries • **Project framework (EJP Soil, Horizon Europe, H2020 …):** EJP Soil • **Type of project (CSA, RIA, IA …):** • **Start date:** Nov 2021 • **End date:** Oct 2024
Summary of the projet (a simple copy/paste)
Quick and simple soil analyses directly in the field through proximal sensing has the potential to substantially gear up the number of samples analysed. With focus on visible and near infrared spectroscopy (Vis-NIRS) ProbeField will work to make this happen. The Vis-NIR technique has many advantages required for field analyses of soil properties. There are, however, drawbacks to be overcome. In contrast to spectroscopy in the lab on prepared samples, variable moisture and structure in the field will hamper reliability of analyses. ProbeField will test and suggest physical and mathematical procedure to manage these problems. A wide range of soil properties will be analysed and 3D mapping will be performed to estimate for example carbon stocks. A best practice protocol will be produced.
Main objectives:

• **Main objectives of the project (1 short sentence or statement per objective):**
  ○ Objective 1: Identify and recommend best practices for spectral soil sampling and measurement in the field.
  ○ Objective 2: Enable the application of lab-based soil spectral libraries to field-obtained soil spectra for in-field soil properties' estimation
  ○ Objective 3: Evaluate accuracy and cost estimates for single and combined methods, and the best practice advice for converting 1 or 2D measurements into 3D information on soil properties.
• **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  ○ Objective 1: We mainly intend to use drone-based cameras to assist in digital soil mapping.
  ○ Objective 2:
  ○ Objective 3:

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**
  - **1st:** Soil texture
  - **2nd:** Carbon
  - **3rd**: Nutrients
  -
- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing?
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product?
  - Do you need auxiliary data to estimate your variable/indicator/characteristic of interest?
  - What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?
  - **1st:** -
  - **2nd:** Covariates mainly based on proximal sensing and drone-borne cameras
  - **3rd**: 2*2 Sq m, revisit frequency can be variable
  -
- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    Not applicable
  - Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    Not applicable
  - Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:
    Not applicable
  - Gaps to be filled / challenges to be overcome to reduce any weaknesses:
    Not applicable
  - Additional comments: Not very relevant for our project as we mainly employ proximal soil sensing and drone based camera data. We have limited use of the Satellite-based data.

Interactions with stakeholders:

- Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? ✓☐ yes ☐ no
- If yes: Can you mention the main interactions and their main conclusions?
  - Interaction 1: Proximal sensing has many advantages but it can be expensive to avail of such services
  - Interaction 2:
  -

Main results of your project related to the use of satellite-based Earth Observation:
• Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)? *(PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)* • Result 1: https://www.sciencedirect.com/science/article/pii/S0016706123003130 • Result 2: https://bsssjournals.onlinelibrary.wiley.com/doi/10.1111/sum.12952 • Result 3: https://www.tandfonline.com/doi/full/10.1080/05704928.2022.2128365 • …

- SANCHO's THIRST (EJP Soil);

Person answering the questionnaire:
• **Last name:** XXXX • **First Name:** XXXX • **Professional e-mail:** XXX@XX • **Responsibility within the project:** Coordinator • **Informed consent agreement signed:** X yes ☐ no
Project identity:
• **Name/acronym of the project:** SANCHOSTHIRST • **Complete title of the project:** Cover cropS ANd soil health and climAte CHaNge adaptatiOn in Semiarid woody crops. THe RemOte SensIng and furTHer scenaRIoS projecTions • **Project framework (EJP Soil, Horizon Europe, H2020 …):** EJP SOIL • **Type of project (CSA, RIA, IA …):** RIA • **Start date:** 31/07/2023 • **End date:** 31/07/2026
Summary of the projet (a simple copy/paste)
Traditional tillage (TT) in woody crops in the Mediterranean environment is a paradigmatic example of the effect of unsustainable management on soil degradation due to erosion and the loss of organic carbon (SOC), nutrients, and biodiversity. The use of cover crops (CC) increases the SOC and produces a cascade of benefits in soil structure, water storage, or biodiversity. However, in semi-arid areas, farmers are reluctant to use CC. To involve them, research must clearly highlight the current state of degradation of soils in woody crops and the feasibility, with pros and cons, of CC as a sustainable management practice. This project is based on four pillars: 1. Deepen the knowledge of agro-ecosystem functions in woody crops with TT and CC. For this purpose, farms with soils managed by different practices will be used to test the following functions: Carbon sequestration will be carried out with an innovative approach, considering the source and dynamics of SOM, inferred by 13C and 14C analysis. This approach will reveal the age of SOC at different soil depths, providing important insights into C sequestration efficiency. The stability of SOM will be inferred by visible spectroscopy analysis for determining the aromaticity of the degree of maturation. Microbiological activity plays a crucial role in C dynamics. It is related to ecosystem services such as gene pool (provisioning) and nutrient cycling (supporting). The effects of agronomic practices have received very little attention in this regard. β-glucosidase activity, linked to fungi and bacteria, will be used for this purpose. The water content changes (regulating services), the most important reason for rejecting the use of CC, will be considered, studying the effects of CC on soil moisture, and water status in vines and olive trees. Yield in vineyards and olive trees (provisioning services) with and without CC will be measured. 2. A global perspective of ecosystem services provided by CC will be obtained by the identification and quantification of the ecosystem services indicators and the development of a composite indicator through a fuzzy logic procedure.

3. Improving Remote sensing tools by considering disturbing factors that have been found to affect the spectral response (texture, roughness, iron oxide compounds). This research will help to reduce the uncertainty of SOC and water content predicted by models obtained with satellite imagery. Monitoring soil conditions will be performed in 30 to 40 active farms including field sampling campaigns and Sentinel-2 acquisitions. Normalized spectral indices; geostatistical methods; regression model approaches, and thermal and radarbackscattering models will be used.

4. Temporal modeling to describe future scenarios of doing business as usual will be done using the STICS (SimulateurmulTIdisciplinaire pour les Cultures Standard) model, although requiring many parameters it has already been tested under different climates and managements. Experimental farms will provide information for modeling.

Strong emphasis will be placed on raising awareness and encouraging its adoption. Over the project, a high-quality video documentary will be produced to be disseminated on different platforms and TV channels in different languages. Sampling, results, and opinions of farmers and researchers will be gathered. The potential and limitations of CC in semi-arid areas will be revealed.

Main objectives:

- **Main objectives of the project (1 short sentence or statement per objective):**
  - Objective 1: Create an inventory of vineyards and olive groves (30-40) to monitor soil health
  - Objective 2: Establish the effect of Cover crops on the efficiency of carbon sequestration
  - Objective 3: Identification and quantification of ecosystem services
  - Objective 4: Modelling long term effects of cover crops
  - Objective 5: Improve remote sensing tools
  - Objective 6: Dissemination and demonstration campaigns
- **When only a few tasks/WPs deal with the use of satellite observations of the Earth, main objectives of these tasks/WP (1 short sentence or statement per objective):**
  - Objective 1: develop and validate SOC predictions from satellite imagery and/or UAV with hyperspectral camera combined with ground data.
  - Objective 2: Influence of texture
  - Objective 3: Influence of iron oxides
  - Objective 4: Influence of soil moisture

In the following, the questions concern tasks involving the use of Satellite-based Earth Observations

From a technical point of view:

- **What type(s) of soil variables/characteristics/indicator(s) does the project focus on, and for which application?**
  - **1st:** Soil moisture
  - **2nd:** Soil organic carbon
  - **3rd**: Soil texture, types of clays, minerals and Fe oxides
- **For each of targeted soil variables/characteristics/indicator(s):**
  - Are these products available from a service or do you make your own processing? Both
  - If you are using services supplying the RS product (Copernicus Land Monitoring Service; Galileo/EGNOS; Other), could you please indicate this service and the sensors used to derive your product? Currently we are not using this type of services, but we plan to use Copernicus.

- Do you need auxiliary data to estimate your variable/indicator/characteristic of interest? No
- What would be your ideal spatial resolution and revisit frequency for the indicator in question and its use?

- **1st:** 5 x 5 m, at least 10 x 10 m;
- **2nd:** revisit frequency, one week is fine.
-

- **SWOT analysis applied to the use of satellite-based EO for soil health monitoring:**
  - Strengths of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:

    Different spectral and/or geostatistical methods will be used to develop and validate SOC predictions from satellite imagery and/or UAV with hyperspectral camera combined with ground data. Spectral models based on regression approaches (MLR, PLSR, QRF, SVM) on spectral data; normalized spectral indices will be constructed.

    The influence of clay content and type of clay minerals on SOC predictions will be studied. For spatial improvement of this relationship, a high density of sampling will be carried out. Different sensors will be used: multispectral, hyperspectral and RGB. The SOC/Clay ratio as soil quality indicator will be assessed and mapped. The influence of iron oxides on SOC predictions will be studied,
  - Weaknesses of satellite-based Earth Observation for estimating the soil health indicators on which your project is working: maybe the resolution
  - Current risk/threats associated with the use of satellite-based Earth Observation for estimating the soil health indicators on which your project is working:

    Multi-effects of these variables can hinder the prediction of SOC
  - Gaps to be filled / challenges to be overcome to reduce any weaknesses:

    Particularly the effects of different types of clays and the iron oxides will be studied
  - Additional comments:

Interactions with stakeholders:

- Does your project include interaction (meetings, workshops, experiments...) with stakeholders to assess whether the solutions you are working on can meet their needs (in terms of purpose, accessibility to data and, if necessary, the ability to process it, etc.)? x yes ☐ no
- If yes: Can you mention the main interactions and their main conclusions?
  - Not yet, these interactions will be done the last year.

Main results of your project related to the use of satellite-based Earth Observation:

- Can you list the main results achieved by your project so far (if the state of progress of the project allows it and if they are communicable (possibly an Internet link to the deliverables of your project validated by the European Commission)?

To date we do not have results. The project started in September 2024 and the activities were related to sampling sites. The group dealing with remote sensing is collecting different images with different sensors.

(PREPSOIL's use of these results will then be limited to mentioning them in a deliverable, specifying which project they come from)

- Result 1:
- Result 2:
- Result 3:

Annexe IV:

Workshops “Earth observation for soil health monitoring; obstacles and proposal in overcoming them”

(Materials and methods)

- Practical instructions (with a report outline);

Workshop objective: To explore the incorporation of Earth Observation data in soil monitoring (objective O10);

(*Beneficiaries must make use of Copernicus and/or Galileo/EGNOS, but other data and services may be used in addition).*

6 KPI for the 6 workshops to be organized by INRAE, IUNG, LESP, WR, SLU and NIBIO, respectively (1 workshop organized by each partner).

Workshop final objectives:

1. Identify bottlenecks (scientific, technological, technical, skills …) to greater use of satellite Earth Observations (EO) and CLMS and/or Galileo/EGNOS products for soil monitoring;
2. Propose measures to reduce/minimize these difficulties, ranking them (subjectively) successively (i) according to their supposed impact on the bottlenecks, and (ii) according to their ease - or even cost - of implementation. (We can imagine that these two criteria will be used by the people in charge of prioritizing these measures).

General organization of workshops:

- **online using a communication platform** (Zoom, Team, Skype...) **and**, if possible, **a whiteboard** (Klaxoon, Miro...) allowing each participant to post Post-It in a framework provided for a SWOT analysis;
- **by inviting a wide range of participants to <u>register in advance</u>** using Google form that enable to download files during registration (e.g. Informed Consent Form), so as to be able to adapt to the size of the group and the type of players present **(launch information and registration at least 1 month before the workshop!)**;
- As far as possible, it would be important to have **approximately 30-50 participants, including both:**
  - **scientists** (i) with expertise in the use of satellite data to observe soils, crops and/or forests, or even landscape heterogeneity, or (ii) specialized in soils and interested in the sustainability of soil management practices;
  - **Public sector stakeholders** in charge of public policies (ministries, agencies …) using and/or interested in using CLMS and/or Galileo/GNEOS products for soil monitoring and/or land cover monitoring, for the purposes of preserving or monitoring soil health (e.g., as part of CAP implementation);
  - **People from NGOs** concerned with protecting the environment and its biodiversity (IUCN…);
  - **People from the private sector** interested in satellite-based EO, e.g. to check compliance with specifications, or for payment for environmental services.
- **Each workshop lasts 1h30, with** around 30 minutes of introductory PPT presentation, 45 minutes of discussion in sub-groups bringing together the same types of stakeholders, and 15 minutes of feedback from the sub-groups to the large group, plus a general conclusion.

Workshop report:

A report of 4-to-6 pages will be written for each workshop. It will include (1) a list of all workshop participants with their characteristics (stakeholder category, employer, working place, free description of their work), (2) a factual summary of the workshop proceedings, highlighting any deviations from the proposed general framework and copies of the white board used for the SWOT analysis (Klaxoon, Miro, Zoom or…), and (3) the main conclusions of the workshop.

To facilitate the writing process, the organizers of each workshop can record the moments when all the participants are together (i.e. the first half-hour of the workshop and the last twenty minutes), explaining the purpose of the recording and suggesting that participants who so wish turn off their webcams or even erase their names.

Informed consent form: We suggest that participants download it during their online registration and tick boxes indicating that they accept it without physically signing it.

Preliminary presentation of the workshop's subject and objective (~ 30')

Introductory PPT: You have to translate the PPT in your local language, adapt it to your national context, and possibly merge tit with additional contributions from participants

If possible, send each participant automatically to another meeting room; if not, give each participant the address to connect to another lounge.

Working in groups with close stakeholders (~ 40')

Introduction (~ 3'): On the principle of SWOT analysis and its customization for the use of satellite-based EO: especially what are internal and external factors;

Initial brainstorming time on your own (~ 5-10'): The suggestion that everyone put on post-it notes what they would like to put in each of the boxes (a very short word or expression).

A time for discussion (~ 20': ~ 5 minutes for each of the 4 boxes of the SWOT analysis): During this phase, the facilitator suggests reconciling/shifting post-its, and asks participants to explain why they have placed a particular post-it (or to propose an example illustrating the post-it and its positioning).
During this time, participants can add post-its if the exchanges suggest other ideas.**:**

A final time of discussion where the group tries to answer collectively to the 2 following questions (~ 10'): Try to focus on the main problems

1. Identify bottlenecks (scientific, technological, technical, skills …) to greater use of satellite Earth Observations (EO) and CLMS and/or Galileo/EGNOS products for soil monitoring;
2. Propose measures to reduce/minimize these difficulties, ranking them (subjectively) successively (i) according to their supposed impact on the bottlenecks, and (ii) according to their ease - or even cost - of implementation. (We can imagine that these two criteria will be used by the people in charge of prioritizing these measures).

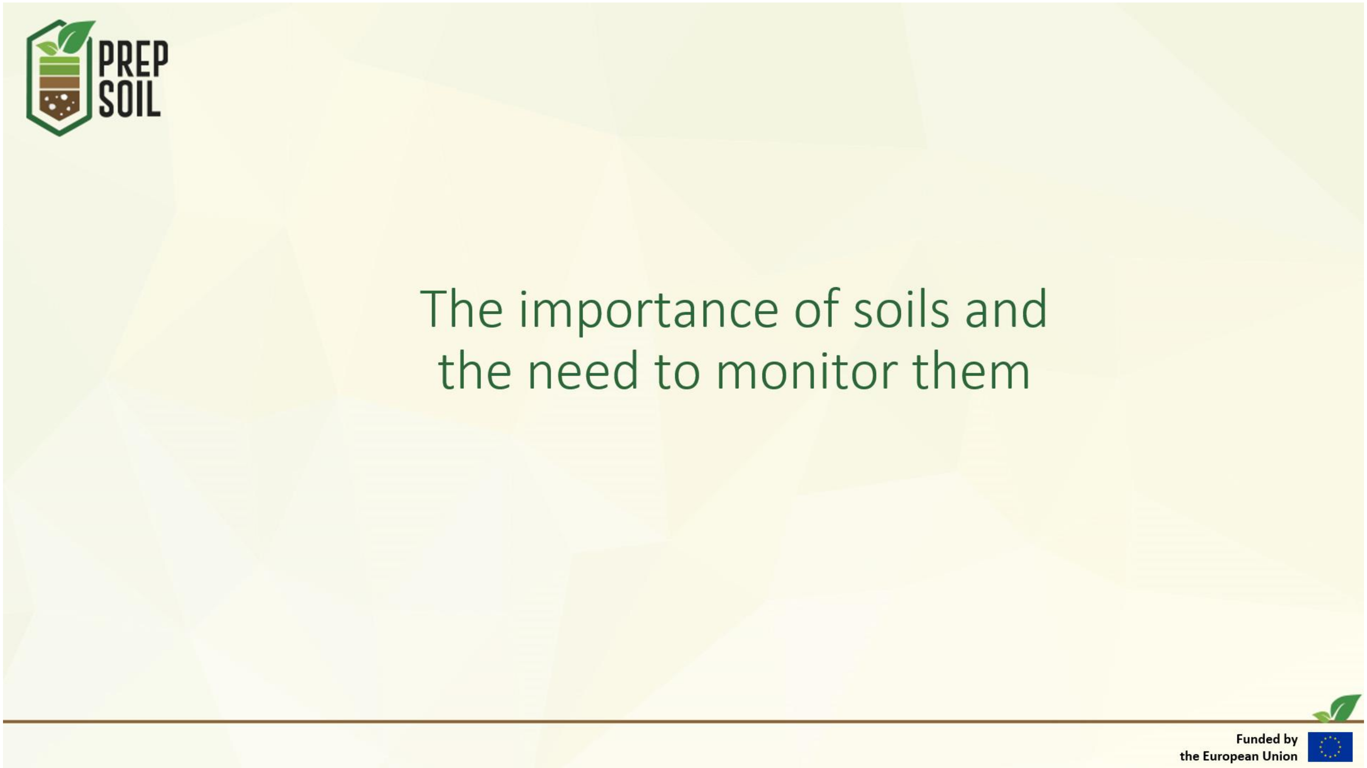
A final time (~ 20'): where the group tries to answer collectively to the 2 following questions by trying to limit itself to 3 cases

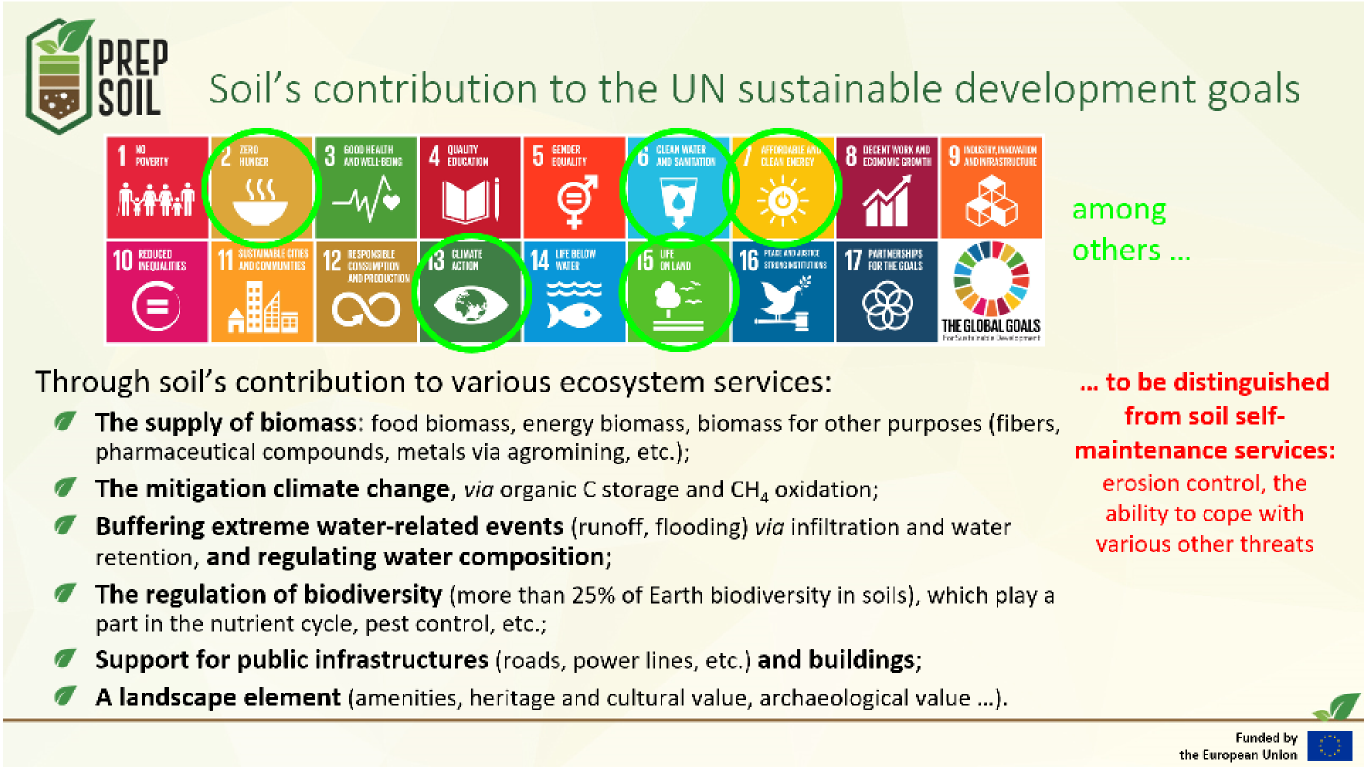
Introduction to the SWOT (Strength-Weakness-Opportunity-Threat) analysis framework:

Ideally, you should have prepared in advance (using MIRO, KLAXOON, Zoom ...) a whiteboard containing the following diagram:

		Useful	Harmful
e.g. - accessibility to data; - Capacity building;	Internal (which you can influence)	Strength	Weakness
e.g. - spatial resolution; - temporal frequency; - - new satellites; - new data and digital policies; - data over longer period enabling to assess temporal trend; - New sensors, new satellites; -other airborne sensors;	External (beyond your control)	Opportunity	Threat

- Introductory slide show (to be translated);




Soil's contribution to the UN sustainable development goals
among others …
Through soil's contribution to various ecosystem services:
The supply of biomass: food biomass, energy biomass, biomass for other purposes (fibers, pharmaceutical compounds, metals via agromining, etc.);
The mitigation climate change, via organic C storage and CH_4 oxidation;
Buffering extreme water-related events (runoff, flooding) via infiltration and water retention, and regulating water composition;
The regulation of biodiversity (more than 25% of Earth biodiversity in soils), which play a part in the nutrient cycle, pest control, etc.;
Support for public infrastructures (roads, power lines, etc.) and buildings;
A landscape element (amenities, heritage and cultural value, archaeological value …).
… to be distinguished from soil self-maintenance services:
erosion control, the ability to cope with various other threats
THE GLOBAL GOALS
Funded by the European Union


Soil's contribution to the UN sustainable development goals
Flood regulation
Climate regulation
Foundation for human infrastructure
Provision of construction materials
Provision of food, fibre and fuel
Habitat for organism
Carbon sequestration
Nutrient cycling
Water purification and soil contaminant reduction
Source of pharmaceuticals and genetic resources
Cultural heritage
Choose between the previous slide and this one (from the FAO).
(I think it's easy to find the figure on the previous slide like this one in your languages. Maybe SDG in the previous slide are easier to read)
GLOBAL SOIL PARTNERSHIP

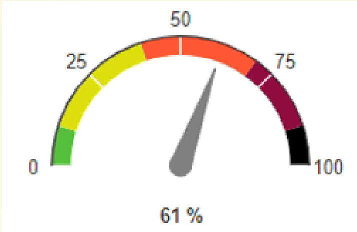
Global and EU soil degradation

At the global level:

Most assessments show that between 20-40% of the global land area is degraded or degrading to varying extents and degrees.

From: https://www.unccd.int/sites/default/files/2022-04/UNCCD_GLO2_low-res_2.pdf

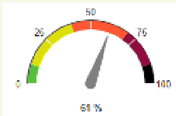
At the EU level



From: https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

Funded by the European Union

Soil: slow pedogenesis *vs* fast degradation



% soil beyond a tolerable threshold

The 10 main independent forms of soil degradation:

- Reduced biodiversity,
- Decrease in organic matter,
- Soil sealing,
- Erosion,
- Compaction,
- Waterlogging/drought,
- Nutrient depletion,
- Acidification,
- Salinization,
- Pollution.

	EU	France
Reduced biodiversity	36.7 %	49.5 %
Decrease in organic matter	52.7 %	40.8 %
Soil sealing	7.3 %	10.1 %
Erosion – Gully erosion	???	???
Erosion – Diffuse water erosion	24.0 %	23.1 %
Erosion – Wind erosion	6.3 %	1.6 %
Erosion – Harvest erosion	3.3 %	6.5 %
Erosion – Tillage erosion	26.5 %	29.8 %

From: https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

- 1 cm of soil formed in 240 years can be eroded away in 1 to 10 years (or during a storm or excavation for building);
- 2 m of soil formed in 48,000 years can be destroyed for urbanization in a matter of minutes.

(C. Valentin, 2024. Personal Comm.; Valentin, C. 2018. Les sols au cœur de la zone critique 5: dégradation et réhabilitation (Vol. 5). ISTE Group.)

Funded by the European Union

The need for soil monitoring to support public policies etc.

But with questions upstream:

- **What should be monitored?**
  - **Soil health?** (linked to their contribution to ecosystem services; Human-oriented);
  - **Soil functions?** (Action of the soil on itself, a wider ecosystem and/or Humans);
  - **Soil elementary processes?** (physical, chemical, or biological);
  - **Soil properties?** (e.g. %clay, pH, bulk density …);
  - **Soil degradation indicators?**

Various links between these categories

- **How?**
  - Sampling and laboratory analysis?
  - *In situ* observations / measurements:
    - Ground measurements?
    - Remote sensing? (Satellite-based EO, UAV, airborne sensors);
  - Combining observations and calculations?

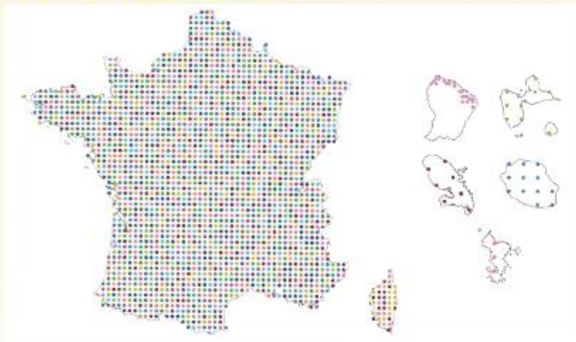
- **For what use in soil management?**
  - Positioning of indicators in a reference framework of possibilities (use of thresholds, etc.), interpretation and possible definition of corrective measures.

Funded by the European Union

Current EU and MS soil monitoring

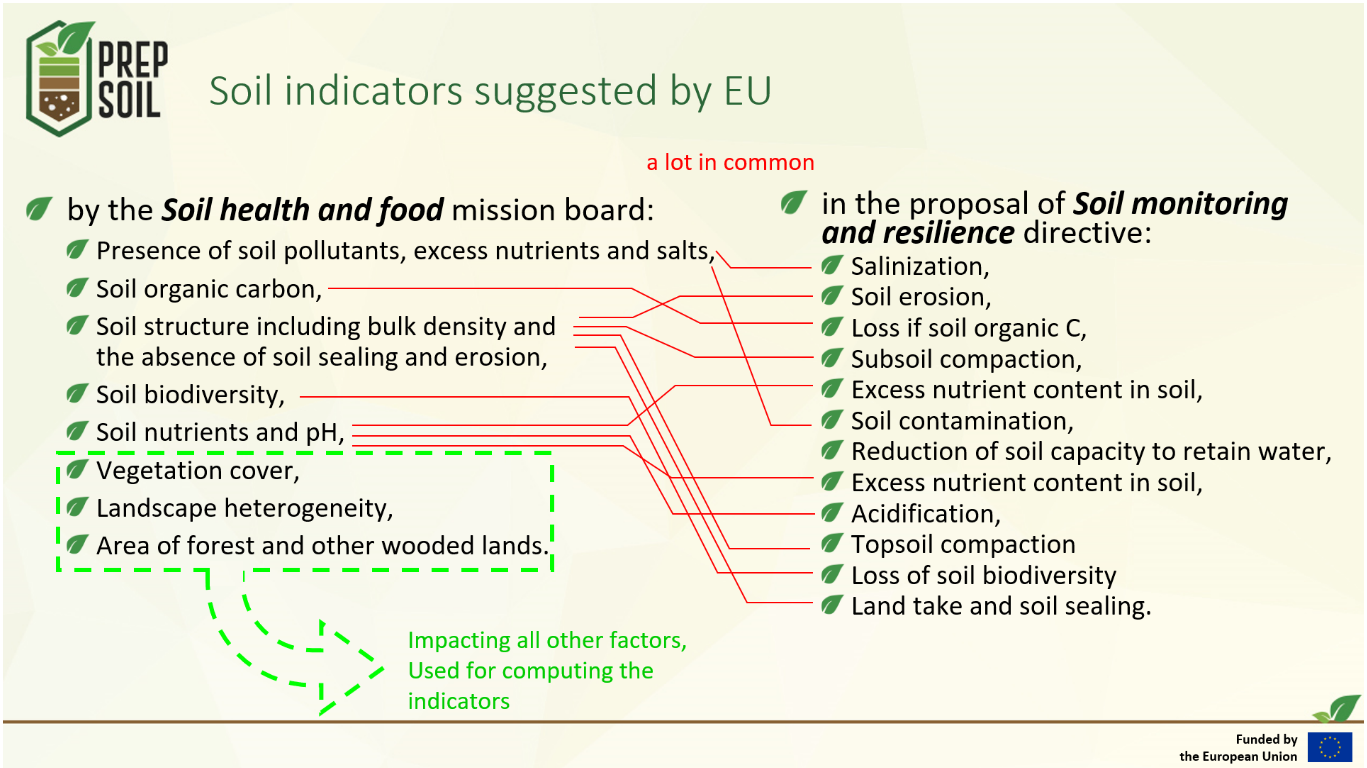
- LUCAS Soil at the EU level:
  - Systematic approach for 25,000 locations across the EU;
  - Harmonized sampling protocol;
  - Standard analytical procedures to measure parameters;
  - Single laboratory;
  - Data from 2009, 2015, 2018, 2021/2022…;
  - EU/Regional statistics, point-based applications;

- At the national level (France):
  - The French program RMQS (*Réseau de Mesure de la Qualité des Sols*): A network of 2,240 sites sampled and analyzed every 15 years



Funded by the European Union


PREP SOIL
Possible contributions of Earth Observation to soil monitoring
Funded by the European Union


PREP SOIL
Soil indicators suggested by EU
a lot in common
by the *Soil health and food* mission board:
Presence of soil pollutants, excess nutrients and salts,
Soil organic carbon,
Soil structure including bulk density and the absence of soil sealing and erosion,
Soil biodiversity,
Soil nutrients and pH,
Vegetation cover,
Landscape heterogeneity,
Area of forest and other wooded lands.
in the proposal of *Soil monitoring and resilience* directive:
Salinization,
Soil erosion,
Loss if soil organic C,
Subsoil compaction,
Excess nutrient content in soil,
Soil contamination,
Reduction of soil capacity to retain water,
Excess nutrient content in soil,
Acidification,
Topsoil compaction
Loss of soil biodiversity
Land take and soil sealing.
Impacting all other factors,
Used for computing the indicators
Funded by the European Union

EUSO already used satellite EO to monitor soil degradation

- EO often used as a covariate in the spatial description instead of directly derive the status of the indicator;
- Large use of EU sensors;

Non-EU sensors

- Few high spatial resolution data used, mainly hectometric

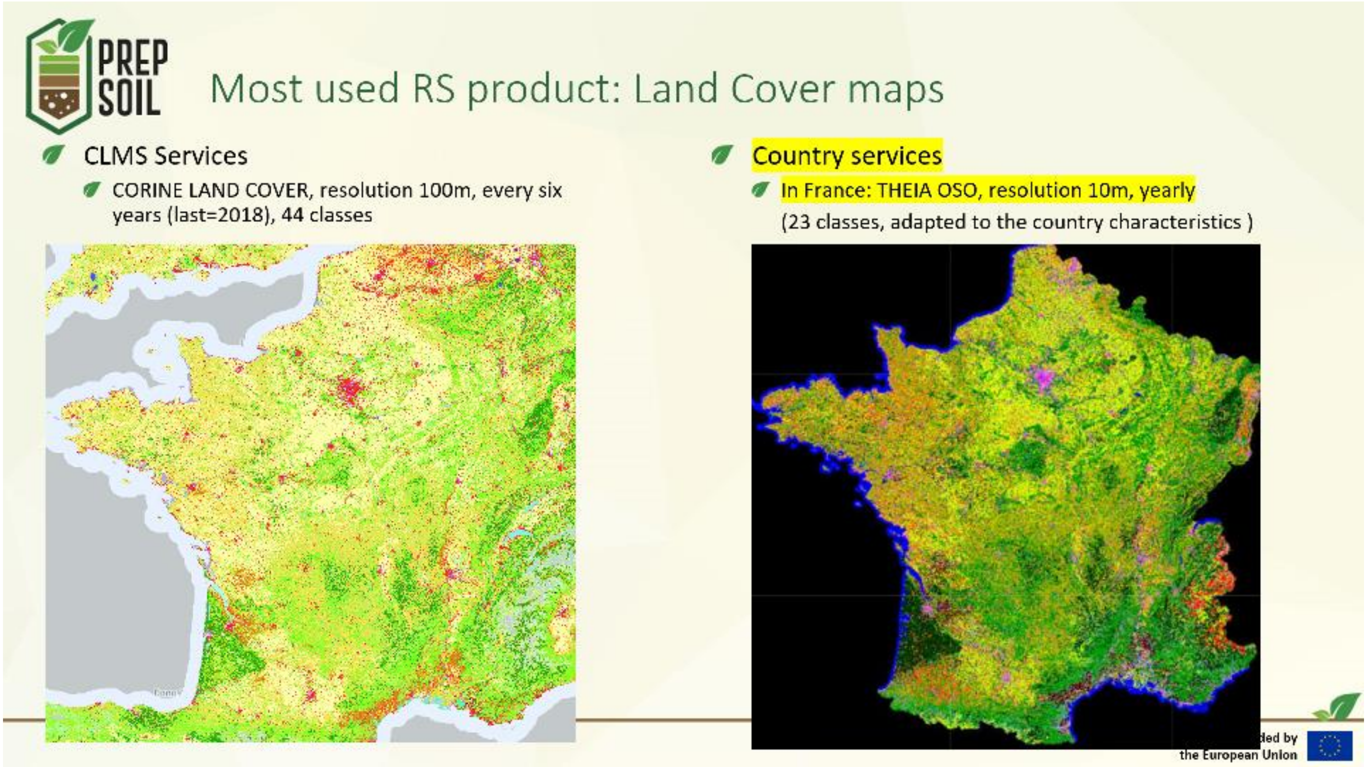
(T. Breure (JRC), personal communication)

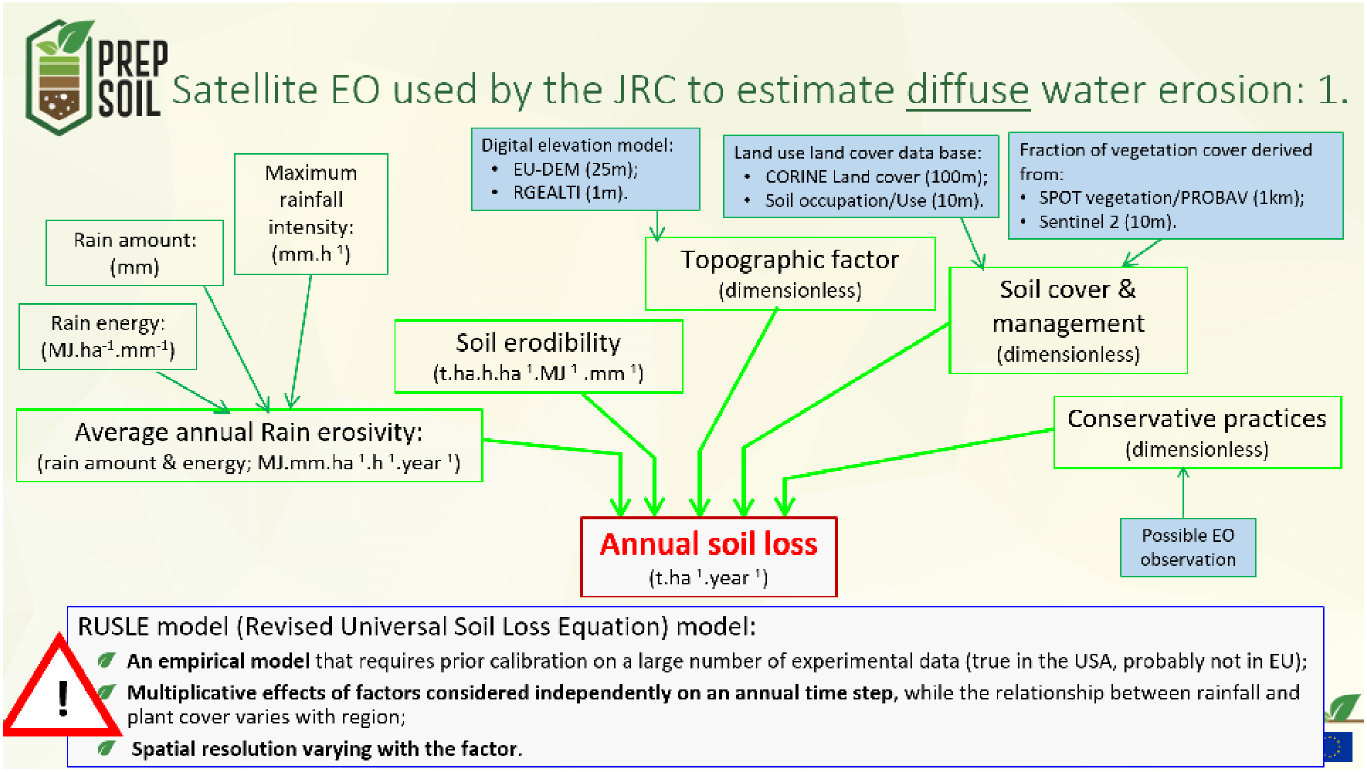
SOIL DEGRADATION INDICATOR	Product available: CLMS	Product available: Galileo/ EGNOS	Product available: Other	Sensor used to derive the product	Auxiliary data used to estimate the indicator (Please complete this information only when Earth Observation (EO: satellite, UAV, airborned sensor) are involved)	Current spatial resolution/ revisit frequency
Soil erosion						
Water erosion	Yes	No	Yes	NSRTM, SPOT 4/5, SPOT VEGETATION, RapidEye, IRS P6 LISS II	Land cover, vegetation statistics, digital elevation model	100 m / not specified
Wind erosion	Yes	No	Yes	MODIS, Landsat/Terra	Bare soil (%), snow cover, land cover, field boundaries	100 m / not specified
Harvest erosion	Yes	No	Yes	SPOT 4/5, RapidEye, IRS P6 LISS II	Land cover	100 m / not specified
Tillage erosion	Yes	No	Yes	Sentinel–1, MERIS, SRTM, ASTER, Landsat-5 MSS/TM, Landsat-7 ETM, SPOT-4/5, IRS P6 LISS III, MODIS	Land cover, digital elevation model, land management, vegetation statistics	100 m / not specified
Post-fire erosion	No	No	Yes	MERIS, PROBA-V, Sentinel-3/OLCI and SLSTR, Sentinel-2	Burnt area, vegetation statistics, land cover	25 m /annual
Soil pollution						
Copper	Yes	No	Yes	IRS P6 LISS III, RapidEye, MODIS, SRTM, ASTER	Land cover, vegetation statistics (evi), digital elevation model	500 m / not specified
Mercury	Yes	No	Yes	IRS P6 LISS III, RapidEye, MODIS, SRTM, ASTER, Landsat	Land cover, vegetation statistics (evi), digital elevation model, reflectance, surface temperature	100 m / not specified
Zinc	No	No	Yes	SPOT-4/5, IRS P6 LISS III, SRTM, ASTER, Landsat 7	Land cover, digital elevation model, vegetation statistics	250 m / not specified
Soil nutrients						
Nitrogen surplus	No	No	No			LUCAS points
Phosphorus deficiency	Yes	No	Yes	SRTM, ASTER, MODIS, IRS P6 LISS III, RapidEye	Land cover, digital elevation model, vegetation statistics, reflectance	LUCAS points
Phosphorous excess	Yes	No	Yes	SRTM, ASTER, MODIS, IRS P6 LISS III, RapidEye	Land cover, digital elevation model, vegetation statistics, reflectance	LUCAS points
Loss of soil organic carbon						
Distance to maximum SOC level	Yes	No	No	SPOT-4/5, IRS PG LISS III, RapidEye, Sentinel-2 and Landsat-8	Land cover	500 m / 4-6 years
Loss of soil biodiversity						
Potential threat to biological functions	Yes	No	No	IRS P6 LISS III, RapidEye	Land cover	4-6 years
Soil compaction						
Susceptibility to soil compaction	No	No	No			500 m / Not specified
Soil salinization						
Secondary salinization risk	No	No	Yes			500 m / Not specified
Loss of organic soils						
Peatland degradation risk	No	No	Yes			1 km / Not specified
Soil consumption						
Soil sealing	Yes	No	Yes	Sentinel–2	Impervious built-up layers	10m / every 3 years

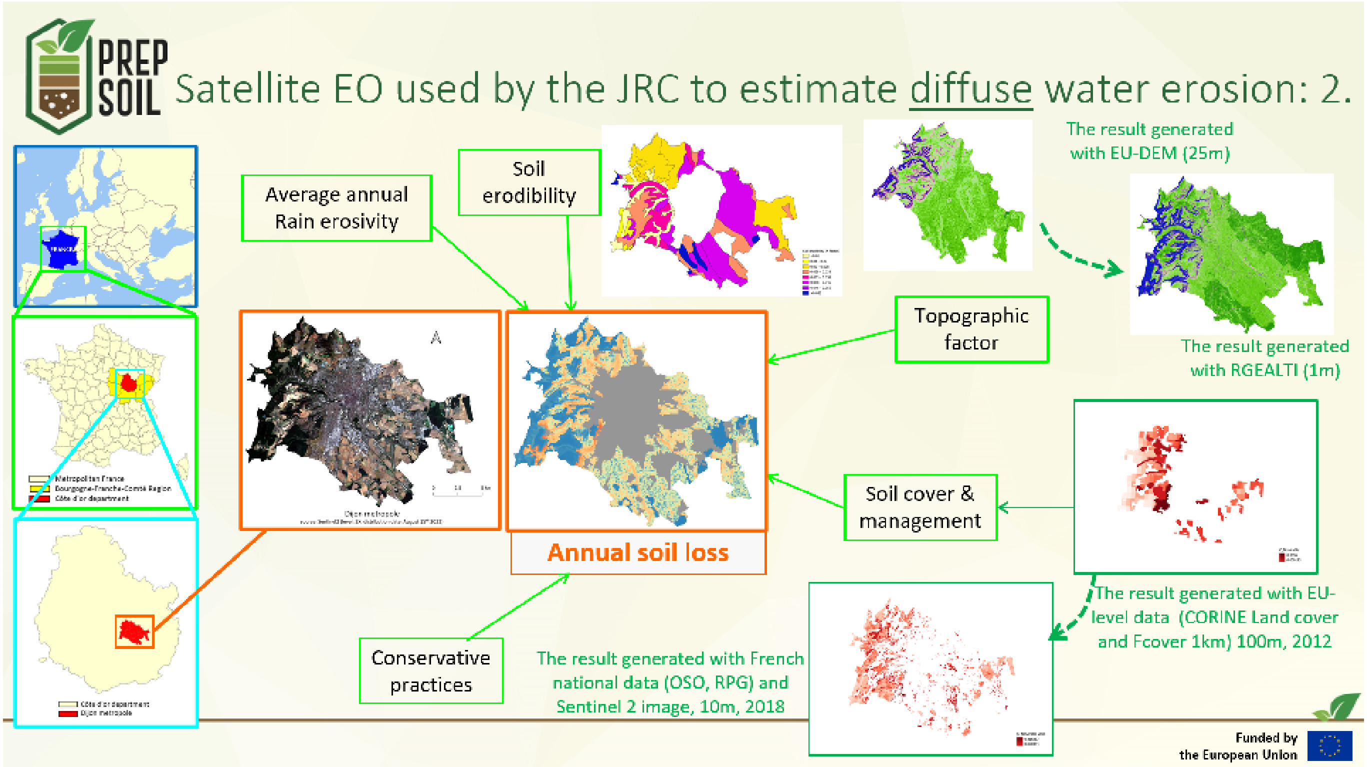
Satellite EO, UAV and airborne sensors to characterize soils

- Soil digital mapping: organic [C] concentration (at bare soil surface), and variations in soil organic C stock (in combination with other data), soil moisture, soil texture;
- erosion estimates;
- Land cover;
- area of forest and other wooded lands (including biodiversity estimate);
- Vegetation fractional cover (F-Cover);
- landscape heterogeneity (and its impact on surface biodiversity), although various heterogeneity metrics must be proposed;
- Topography.

Funded by the European Union


Most used RS product: Land Cover maps
CLMS Services
CORINE LAND COVER, resolution 100m, every six years (last=2018), 44 classes
Country services
In France: THEIA OSO, resolution 10m, yearly
(23 classes, adapted to the country characteristics)

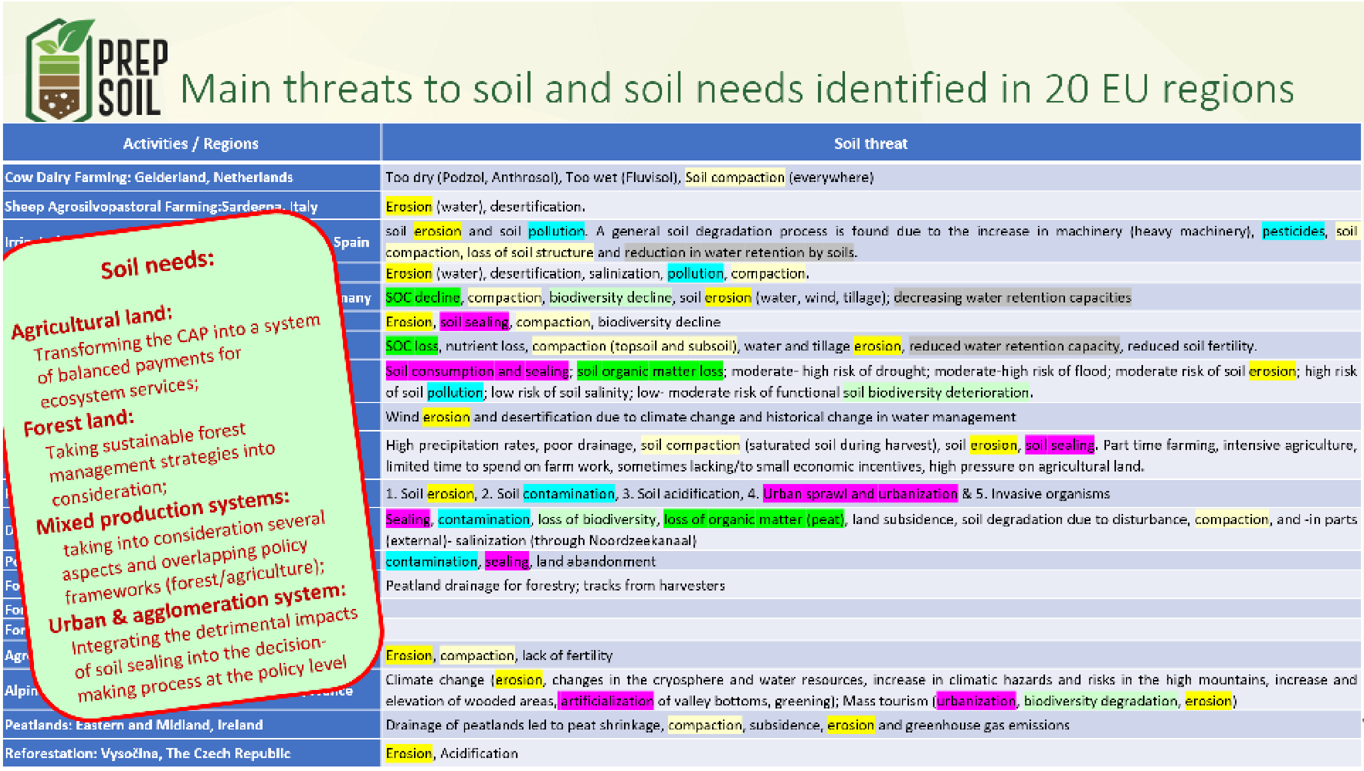

Satellite EO used by the JRC to estimate diffuse water erosion: 1.
Rain amount: (mm)
Maximum rainfall intensity: (mm.h-1)
Rain energy: (MJ.ha-1.mm-1)
Digital elevation model:
• EU-DEM (25m);
• RGEALTI (1m).
Land use land cover data base:
• CORINE Land cover (100m);
• Soil occupation/Use (10m).
Fraction of vegetation cover derived from:
• SPOT vegetation/PROBAV (1km);
• Sentinel 2 (10m).
Topographic factor (dimensionless)
Soil cover & management (dimensionless)
Soil erodibility (t.ha.h.ha-1.MJ-1.mm-1)
Average annual Rain erosivity: (rain amount & energy; MJ.mm.ha-1.h-1.year-1)
Conservative practices (dimensionless)
Possible EO observation
Annual soil loss (t.ha-1.year-1)
RUSLE model (Revised Universal Soil Loss Equation) model:
An empirical model that requires prior calibration on a large number of experimental data (true in the USA, probably not in EU);
Multiplicative effects of factors considered independently on an annual time step, while the relationship between rainfall and plant cover varies with region;
Spatial resolution varying with the factor.



What is what is happening in each country?

Work and expectations of some participants

Funded by the European Union



Activities / Regions	Soil threat
Cow Dairy Farming: Gelderland, Netherlands	Too dry (Podzol, Anthrosol), Too wet (Fluvisol), Soil compaction (everywhere)
Sheep Agrosilvopastoral Farming:Sardegna, Italy	Erosion (water), desertification.
Irri[illegible] Spain	soil erosion and soil pollution. A general soil degradation process is found due to the increase in machinery (heavy machinery), pesticides, soil compaction, loss of soil structure and reduction in water retention by soils.
[illegible]	Erosion (water), desertification, salinization, pollution, compaction.
[illegible]many	SOC decline, compaction, biodiversity decline, soil erosion (water, wind, tillage); decreasing water retention capacities
[illegible]	Erosion, soil sealing, compaction, biodiversity decline
[illegible]	SOC loss, nutrient loss, compaction (topsoil and subsoil), water and tillage erosion, reduced water retention capacity, reduced soil fertility.
[illegible]	Soil consumption and sealing; soil organic matter loss; moderate- high risk of drought; moderate-high risk of flood; moderate risk of soil erosion; high risk of soil pollution; low risk of soil salinity; low- moderate risk of functional soil biodiversity deterioration.
[illegible]	Wind erosion and desertification due to climate change and historical change in water management
[illegible]	High precipitation rates, poor drainage, soil compaction (saturated soil during harvest), soil erosion, soil sealing. Part time farming, intensive agriculture, limited time to spend on farm work, sometimes lacking/to small economic incentives, high pressure on agricultural land.
[illegible]	1. Soil erosion, 2. Soil contamination, 3. Soil acidification, 4. Urban sprawl and urbanization & 5. Invasive organisms
D[illegible]	Sealing, contamination, loss of biodiversity, loss of organic matter (peat), land subsidence, soil degradation due to disturbance, compaction, and -in parts (external)- salinization (through Noordzeekanaal)
Po[illegible]	contamination, sealing, land abandonment
Fo[illegible]	Peatland drainage for forestry; tracks from harvesters
Fo[illegible]	
For[illegible]	
Agr[illegible]	Erosion, compaction, lack of fertility
Alpin[illegible] France	Climate change (erosion, changes in the cryosphere and water resources, increase in climatic hazards and risks in the high mountains, increase and elevation of wooded areas, artificialization of valley bottoms, greening); Mass tourism (urbanization, biodiversity degradation, erosion)
Peatlands: Eastern and Midland, Ireland	Drainage of peatlands led to peat shrinkage, compaction, subsidence, erosion and greenhouse gas emissions
Reforestation: Vysočina, The Czech Republic	Erosion, Acidification

Participant #1 contribution

- Short participant presentation:
  - Title 2:

- The place of the soil in his work:
  - Title 2:

- His expectations regarding soil monitoring, the place of EO, and the workshop itself:
  - Title 2:

Funded by the European Union

Objectives and next steps of the workshops

Funded by the European Union

Objectives: to study the integration of EO data in soil monitoring

- With regard to your needs (spatial resolution, revisit frequency, accuracy), **identify bottlenecks** (scientific, technological, technical, skills ...) **to greater use of satellite Earth Observations** (EO) and CLMS and/or Galileo/EGNOS products for soil monitoring;
- **Propose measures to reduce/minimize these difficulties**, ranking them (subjectively) successively (i) according to their supposed impact on the bottlenecks, and (ii) according to their ease - or even cost - of implementation. (We can imagine that these two criteria will be used by the people in charge of prioritizing these measures)

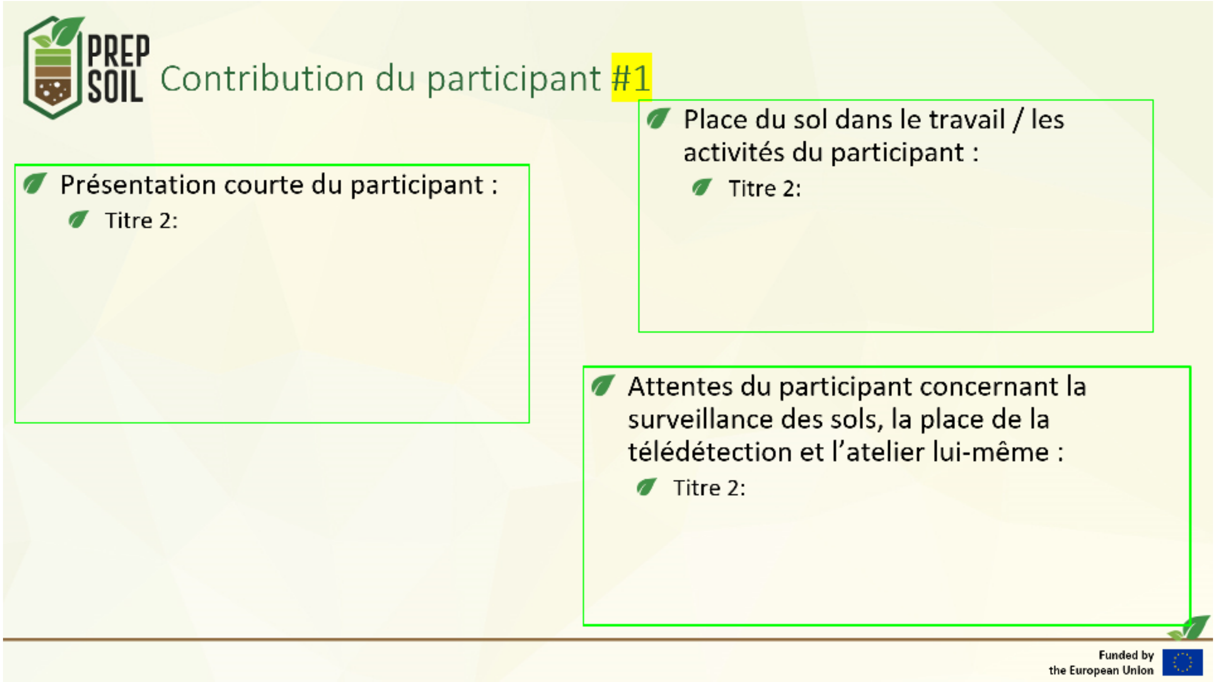
Funded by the European Union

The next stages of the workshop

- Working in subgroups with close stakeholders (e.g. Subgroups of (i) scientists, (ii) public sector stakeholders, (iii) people from NGOs, (iv) people from the private sector:
  - Introduction in subgroups;
  - Initial brainstorming time on your own;
  - A time for discussion;
  - A final time of discussion to answer collectively to the 2 objectives of the workshop
- Large group synthesis and discussion

Funded by the European Union

- Slide template for participants sharing questions (in French);



- Adapted Informed consent form (with highlighted text to modify);

INFORMED CONSENT FORM

PREPSOIL Data Policy
Project duration: 01/07/2022 - 30/06/2025

You have been invited to take part in the European project "PREPSOIL - Preparing the ground for healthy soils: Building capacities for engagement, outreach, and knowledge".
Before taking a decision on whether you wish to participate or not, please read this document carefully. Please feel free to ask all the questions you may have to ensure that you have full understanding of the purpose and proceedings of the project.

Please contact **Pierre RENAULT**, INRAE, pierre.renault@inrae.fr, XX.XX.XX.XX.XX for any questions you may have.

At all times, we assure full compliance with relevant national and EU legislation on data protection and ethical standards.

1. The Prepsoil Project
Prepsoil is a European project that aims to prepare the ground for the European mission "A soil deal for Europe" (EU Soil Mission).

Prepsoil supports the implementation of the Mission by creating awareness and knowledge on soil needs among stakeholders in regions across Europe. The project widens the understanding of Living Labs as a vehicle for engaging stakeholders in soil improvements in different land use types (agriculture, forestry, urban, etc.) and creates understanding of how different approaches to soil monitoring may support the transition to sustainable land use.

Prepsoil also engages with soil ambassadors and soil advocates, and gather information on soil education by establishing a one-stop-shop for soil literacy, communication, and engagement as a state-of-the-art web platform.
You can read more about Prepsoil on its website: https://prepsoil.eu/

2. Data collected and purposes and legal basis for collecting and processing your data
You are asked to participate in a workshop carried out as part of WP5 of Prepsoil. This workshop is organised/prepared by Pierre RENAULT from the INRAE (France).
The objectives of the workshop are to (1) identify bottlenecks to greater use of satellite Earth Observations (EO), UAV, airborne sensors for soil monitoring, and (2) propose measures to reduce/minimize these difficulties.

Responses and opinions that you will provide during this workshop as a stakeholder will **only be used internally, and in a secured way, to carry out the activity for the objectives described above**.
Data collected during this workshop will be used for the duration of the project and will be processed during the phase of data analysis. These data will be included in project reports, deliverables and possibly promotional materials after anonymisation to a level that does not interfere with the quality of the work.

Your personal data are also collected. The personal data we collect are your name, your position and the name, nature (e.g., research, policy, NGO, etc.) and website of your organisation, your e-mail address, your country and the geographic coverage of your professional activity and information regarding your field of expertise (focus on land uses and possibly networks you are related to).

Your personal data will be processed:

- As part of the workshop, to ensure good representation of different stakeholders. After anonymisation, information about the nature of your organisation, geographic coverage and your field of expertise will be included in project reports, deliverables and possibly promotional materials to give an overview of the type of stakeholders engaged.
- To involve you as a stakeholder in Prepsoil activities beyond your participation in the workshop. In this context, your personal data will be used more specifically to:
  - identify the best way to involve you, depending on the needs of the project and your profile
  - contact you to define together your possible involvement beyond this workshop, according to your availability and interest, and in line with the needs of the project.

The legal basis for the processing of personal data is defined in Art. 6 of the General Data Protection Regulation (GDPR). No use for commercial purpose will be made with your data.

3. Recipients of your Data

a. Recipients of your Personal Data

Only Prepsoil project members will have access to your personal data. Prepsoil project members are identified in the following list of entities:

- TRUST-IT, ESTABLISHED IN VIA FRANCESCO REDI 10 56124 PISA, ITALY, VAT NO. AND FISCAL CODE 01958380501
- COMMPLA SRL, ESTABLISHED IN VIA FRANCESCO REDI 10 56124 PISA, ITALY. VAT NO. 01958380501
- AARHUS UNIVERSITET ESTABLISHED IN NORDRE RINGGADE 1 8000 AARHUS C, DENMARK
- STICHTING WAGENINGEN RESEARCH ESTABLISHED IN DROEVENDAALSESTEEG 4 6708 PB WAGENINGEN, NETHERLANDS
- SVERIGES LANTBRUKSUNIVERSITET ESTABLISHED IN ALMAS ALLE 8 750 07 UPPSALA, SWEDEN
- **INRAE : INSTITUT NATIONAL DE RECHERCHE POUR L'AGRICULTURE, L'ALIMENTATION ET L'ENVIRONNEMENT** ESTABLISHED IN 147 RUE DE L'UNIVERSITE 75007 PARIS CEDEX 07, FRANCE
- ASSOCIATION DE COORDINATION TECHNIQUE AGRICOLE ESTABLISHED IN 149 RUE DE BERCY, 75012 PARIS, FRANCE
- NIBIO - NORSK INSTITUTT FOR BIOOKONOMI ESTABLISHED IN HOEGSKOLEVEIEN 7 1430 AAS, NORWAY
- LEIBNIZ-ZENTRUM FUER AGRARLANDSCHAFTSFORSCHUNG (ZALF) E.V. ESTABLISHED IN EBERSWALDER STR. 84 MUENCHEBERG, GERMANY
- EUROPEAN NETWORK OF LIVING LABS IVZW ESTABLISHED IN PLEINLAAN 9 1050 BRUSSEL, BELGIUM
- LESPROJEKT SLUZBY SRO ESTABLISHED IN MARTINOV 197 27713 ZARYBY, CZECHIA
- STICHTING DELTARES ESTABLISHED IN BOUSSINESQWEG 1 2629 HV DELFT, NETHERLANDS
- AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS ESTABLISHED IN CALLE SERRANO 117 28006 MADRID, SPAIN
- INSTYTUT UPRAWY NAWOZENIA I GLEBOZNAWSTWA, PANSTWOWY INSTYTUT BADAWCZY ESTABLISHED IN CZARTORYSKICH 8 24 100 PULAWY, POLAND
- COMITE DES ORGANISATIONS PROFESSIONNELLES AGRICOLE DE L'UNION EUROPEENNE COPA ASSOCIATION DE FAIT ESTABLISHED IN RUE DE TREVES 61 1040 BRUXELLES, BELGIUM

- ASSOCIATION DES VILLES ET REGIONS POUR LA GESTION DURABLE DES RESSOURCES ESTABLISHED IN AVENUE D'AUDERGHEM 63 1040 BRUXELLES, BELGIUM
- FUNDACION FUNDECYT - PARQUE CIENTIFICO Y TECNOLOGICO DE EXTREMADURA ESTABLISHED IN AVENIDA DE ELVAS CAMPUS UNIVERSITARIO ED 06071 BADAJOZ, SPAIN
- OKOLOGIAI MEZOGAZDASAGI KUTATOINTEZET KOZHASZNU NONPROFIT KFT ESTABLISHED IN MELCZER UTCA 47 1174 BUDAPEST, HUNGARY
- RE SOIL FOUNDATION ESTABLISHED IN CORSO DUCA DEGLI ABRUZZI 24, 10129 TORINO, ITALY

b. Recipients of other data
Only INRAE, INSTYTUT UPRAWY NAWOZENIA I GLEBOZNAWSTWA, PANSTWOWY INSTYTUT BADAWCZY, LESPROJEKT, STICHTING WAGENINGEN RESEARCH, SVERIGES LANTBRUKSUNIVERSITET, NIBIO - NORSK INSTITUTT FOR BIOOKONOMI, and the JRC -JOINT RESEARCH CENTRE- EUROPEAN COMMISSION will have access to the other data (responses, opinions) collected through the workshops in a non-anonymised form, in order to process these data for the purposes described in section 2.

4. Other Recipients of Personal Data
Your personal data may be shared with consortia of other projects related to the European Soil Deal for Europe, provided that it is only used to involve relevant stakeholders in these projects and that no commercial use is made of your personal data.
One of these projects would be the project Na100ns, that will organise national engagement activities to foster the development of Living-Labs to address regional soil needs and early matchmaking for cross-regional living-labs clusters.
If the case arises that these consortia need to use your personal data for purposes other than the one mentioned above, the coordinators of these consortia will be responsible for contacting you in advance and requesting the necessary authorisations.

5. Retention of your Data
a. Retention of Personal Data
Personal Data processed for the purposes mentionned in section 2 will be stored on Acta SharePoint, up to one year after the end of the project on 2025, June 30. Data within Acta SharePoint will be protected against unauthorised access by creation of individual access to the recipients described in section 3.
Personal data will be also stored for the duration of the project on the collaborative SharePoint platform set up by Aarhus University, coordinator of the Prepsoil project. The SharePoint platform is dedicated to the Prepsoil project and only members of the Prepsoil consortium have access to it. Data within this online collaborative platform will be protected against unauthorised access by means of standard Aarhus University Login (external account login and password).

Copies on local devices will be allowed by the recipients described in section 3 for the purpose and duration of data processing only.

b. Retention of other Data
Responses and opinions expressed during the survey will be recorded and stored digitally on the servers of INRAE, and shared space for PREPSOIL consortium.

The security of your personal data is important to us but remember that no method of transmission over the Internet, or method of electronic storage, is 100% secure. While we strive to use means to protect your personal data, we cannot guarantee its absolute security.

6. Data subjects' rights

You have specific rights as a 'data subject' under Chapter III (Articles 14-25) of Regulation (EU) 2018/1725.
In particular, you have the right to access your personal data, and, to rectify them, in case your personal data are inaccurate or incomplete.
Where applicable, you have the right to erase your personal data, to restrict the processing or the sharing of your personal data, to object to the processing or the sharing of your personal data, and the right to data portability.

You can exercise your rights by sending a written request to the contact identified in section 7.

7. Contact information

In case you have any questions about the collection or processing of your personal data, legal issues, or if you want to exercise your rights of access, rectification, erasure, restriction, data portability, or objection, you can send an email in your local language or in English (with a copy of an ID document if you want to exercise your rights) to INRAE (Pierre RENAULT, pierre.renault@inrae.fr).

8. Amendments

Acta and organisation identified in section 5b reserve the right to amend this notice partly or fully, or simply to update its content, e.g., because of changes in applicable law.
You will be informed by e-mail of such changes as soon as they are introduced.

9. Consent

You are free to accept or refuse to take part in this workshop and to the collection and processing of your data as part of the workshop, as described in section 2. If you accept to take part, you have the right to decline to answer any questions, or to withdraw from the workshop at any moment without providing a reason for it.

Regardless your involvement in the workshop, you are free to accept or refuse the collection and processing of your personal data beyond the scope of the [survey/interview/workshop] as described in section 2. If you accept you are free to exercise your rights to object to the processing or sharing of your personal data at any time, as well as all your other rights as described in section 6.

Regardless your involvement in Prepsoil activities, you are free to accept or refuse that your data may be shared with consortia of other projects related to the European Soil Deal for Europe, as described in section 4. If you accept, you are free to withdraw your authorisation at any time and to exercise your rights as described in section 6.

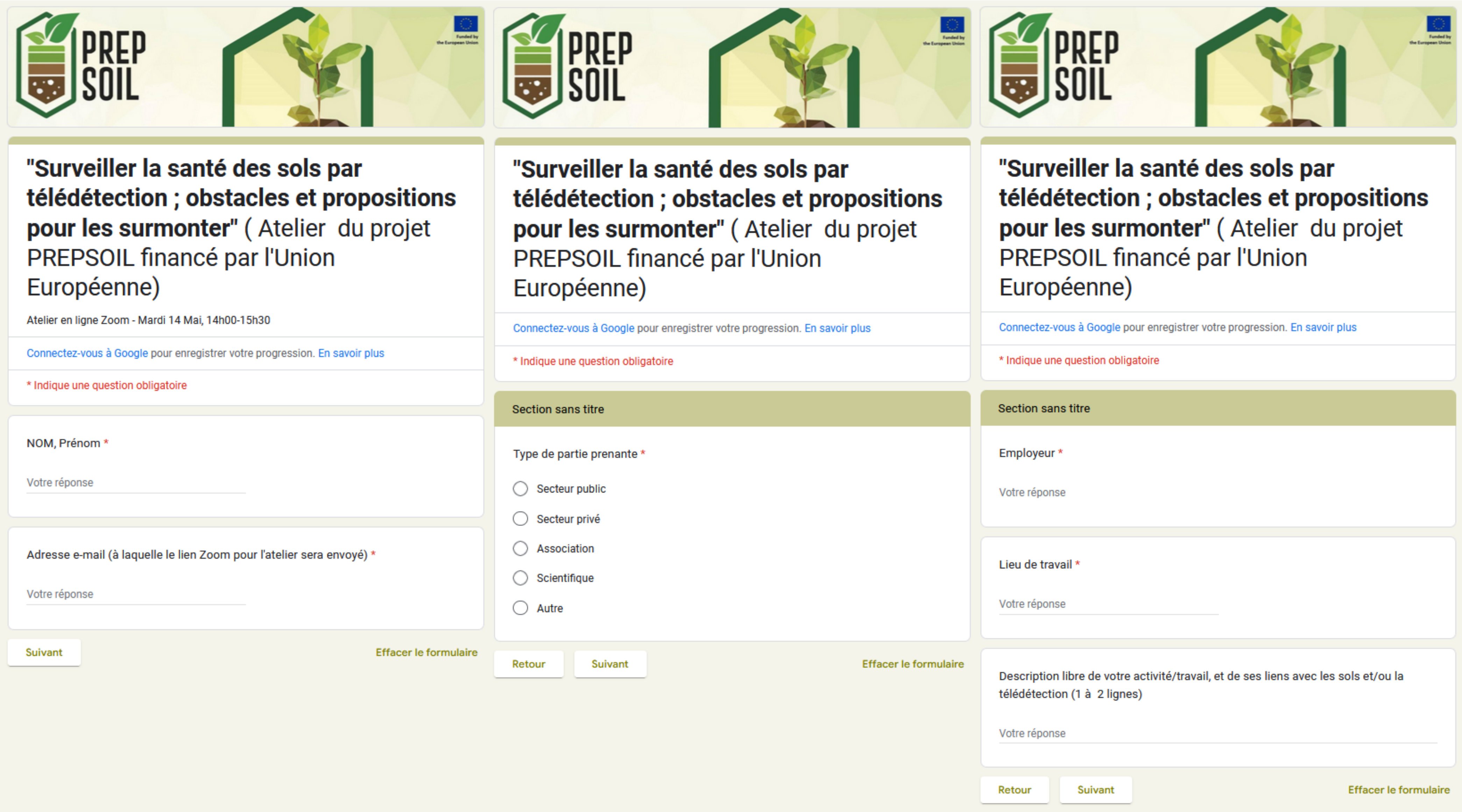
☐ **I give my informed consent to take part in this workshop and agree to the collection and processing of my data, as part of this workshop, as described in this document.**

☐ **I give my informed consent to the collection and processing of my data, beyond the scope of this workshop, for the purpose of involving me as a stakeholder in other activities of Prepsoil, as described in this document.**

☐ **I give my informed consent to my data being shared with consortia of other projects related to the European Soil Deal for Europe Mission, provided that it is only used to involve relevant stakeholders in these projects and that no commercial use is made of my personal data.**

Name and surname of stakeholder
Place, date and signature of stakeholder

- Example of online registration form (in French).



PREP SOIL

"Surveiller la santé des sols par télédétection ; obstacles et propositions pour les surmonter" (Atelier du projet PREPSOIL financé par l'Union Européenne)

Atelier en ligne Zoom - Mardi 14 Mai, 14h00-15h30

Connectez-vous à Google pour enregistrer votre progression. En savoir plus

* Indique une question obligatoire

NOM, Prénom *

Votre réponse

Adresse e-mail (à laquelle le lien Zoom pour l'atelier sera envoyé) *

Votre réponse

Suivant

Effacer le formulaire

PREP SOIL

"Surveiller la santé des sols par télédétection ; obstacles et propositions pour les surmonter" (Atelier du projet PREPSOIL financé par l'Union Européenne)

Connectez-vous à Google pour enregistrer votre progression. En savoir plus

* Indique une question obligatoire

Section sans titre

Type de partie prenante *

- Secteur public
- Secteur privé
- Association
- Scientifique
- Autre

Retour

Suivant

Effacer le formulaire

PREP SOIL

"Surveiller la santé des sols par télédétection ; obstacles et propositions pour les surmonter" (Atelier du projet PREPSOIL financé par l'Union Européenne)

Connectez-vous à Google pour enregistrer votre progression. En savoir plus

* Indique une question obligatoire

Section sans titre

Employeur *

Votre réponse

Lieu de travail *

Votre réponse

Description libre de votre activité/travail, et de ses liens avec les sols et/ou la télédétection (1 à 2 lignes)

Votre réponse

Retour

Suivant

Effacer le formulaire

"Surveiller la santé des sols par télédétection ; obstacles et propositions pour les surmonter" (Atelier du projet PREPSOIL financé par l'Union Européenne)

Connectez-vous à Google pour enregistrer votre progression. En savoir plus

Si vous souhaitez préparer une diapositive plus personnelle (à renvoyer aux modérateurs avant l'atelier), téléchargez le modèle de diapositive

(Votre diapositive complétée sera à renvoyer à pierre.renault@inrae.fr avant le 10 mai 2024)

Retour Suivant Effacer le formulaire

Adresse e-mail (à laquelle le lien Zoom pour l'atelier sera envoyé) *

Votre réponse

Suivant Effacer le formulaire

"Surveiller la santé des sols par télédétection ; obstacles et propositions pour les surmonter" (Atelier du projet PREPSOIL financé par l'Union Européenne)

Connectez-vous à Google pour enregistrer votre progression. En savoir plus

* Indique une question obligatoire

Consentement éclairé

Téléchargez le formulaire de consentement éclairé (en anglais)**, puis acceptez les conditions suivantes (requises pour valider l'inscription, à l'exception de celles marquées comme facultatives) : *
** : pour information, vos données personnelles ne seront utilisées que pour le traitement des données. Les résultats seront anonymisés pour les rapports publics.

- [ ] J'ai lu le formulaire de consentement éclairé
- [ ] Je donne mon accord pour participer à cet atelier et j'accepte la collecte et le traitement de mes données, dans le cadre de cet atelier, comme décrit dans ce document
- [ ] J'accepte que certains moments de l'atelier soient enregistrés pour réduire la prise de notes et faciliter la synthèse du travail. Je sais que je peux éteindre ma caméra et/ou effacer mon nom lors de l'utilisation de Zoom.
- [ ] Facultatif : Je donne mon consentement éclairé à la collecte et au traitement de mes données pour m'impliquer en tant que partie prenante dans d'autres activités du projet PREPSOIL telles que décrites dans ce document et au-delà de cet atelier
- [ ] Facultatif : Je donne mon consentement éclairé au partage de mes données avec des consortiums d'autres projets liés à la mission européenne "Un pacte pour des sols sains en Europe", à condition qu'elles ne soient utilisées que pour impliquer les parties prenantes concernées dans ces projets et qu'aucune utilisation commerciale ne soit faite de mes données personnelles

Retour Envoyer Effacer le formulaire

Figure

Annexe V:

Workshops “Earth observation for soil health monitoring; obstacles and proposal in overcoming them”

(Results and discussion)

French workshop (led by Pierre Renault, INRAE)

The INRAE people involved in PREPSOIL would like to thank the people from the *"Chambre Régionale d'Agriculture de la région Grand-Est"* and the *"Réseau Mixte Technologique (RMT) Sols & Territoires"* (Strasbourg, France) as well as the INRAE Info&Sols research unit (Orléans, France) who helped them by moderating certain subgroups or acting as secretaries.

- *Factual summary of the workshop progress*

The "French workshop" took place on May 14, 2024, from 2pm to 3:30pm. It was preceded by a meeting with sub-group moderators and secretaries (1:15pm-1:55pm) and followed by a mini-debriefing from 3:30pm to 4pm. Registration was launched on 8 April 2024, *via* various distribution channels: the *"Association Française d'Etude des Sol"* (AFES), the *"Réseau National d'Expertise Scientifique et Technique sur les Sols"* (RNEST), the "*RMT Sols et Territoires*", and the *"Groupement d'Intérêt Scientifique Sol"* (GIS Sol). It was also posted on Linkedin. Subsequently, 2 NGOs (FNE and UICN) were contacted directly to increase the number of participants from the NGO sector. We had to inform three people who had not given their consent to at least the first 2 conditions of the informed consent form that they could not take part in this workshop unless they re-registered by accepting these conditions, which one of the 3 did. In practice, 43 people logged on to Zoom at the start of the session. There were 32 and 30 respectively at the start and end of the sub-workshops. This number dropped from 29 to 19 between the beginning and end of the feedback period (**Figure A4.1**).

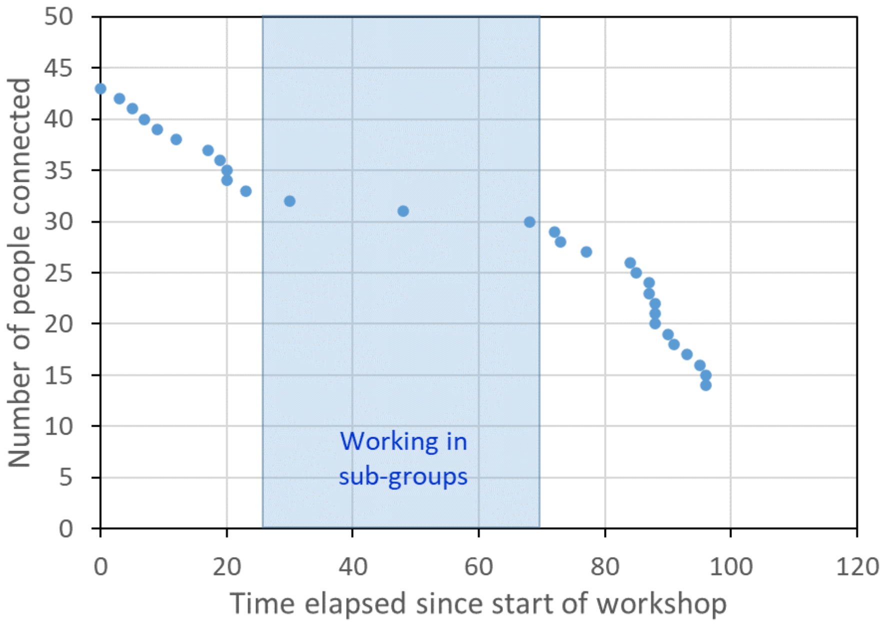


Figure A4.1: Evolution of the number of people connected to Zoom after the start of the workshop (the period between 30 and 70 minutes corresponds to the sub-workshop period).

Zoom was used as a videoconferencing tool. Iit enabled participants to be sent automatically to 4 virtual meeting rooms (for scientists, public-sector people, private-sector people, and a mix of people representing NGO and "other people",

respectively), and then, after working in sub-groups, to return automatically to the virtual room common to the whole group. Klaxoon was used as a whiteboard for each of the sub-groups. The whiteboards were recopied as they stood after the workshop, but given the load of some of the boards (particularly that of the scientists' group) and to ensure legible feedback, it was much more efficient to select all the Post-It notes in each of the 4 boxes of the SWOT analysis, copy them and paste their content into a Word file by simply pressing Ctrl-C then Ctrl-V.
A total of 9 moderators and secretaries, either scientists or those very close to the scientific sphere, were divided between the 4 groups (with 2 moderators and 1 secretary for the scientists' group). This enabled each group to have a reasonable size so that everyone could participate actively, with 9, 8, 8 and 7 participants in each of the 4 sub-groups at the start of the sub-group working period.

- *SWOT (Strength-Weakness-Opportunities-Threats) analysis in relation with the objectives of this workshop*

As the Post-It were written in telegraphic style, sometimes with abbreviations, we are reporting this part of the workshop in the local language (French), using colours to distinguish the contributions of the 4 sub-groups: black for scientists, blue for people working in the public sector, green for people working in the private sector, and red for people representing non-governmental organisations or falling into none of the four previous categories. It should be noted that there has sometimes been confusion between strengths and opportunities on the one hand, and between weaknesses and threats on the other. These confusions have no bearing on the objectives of the workshop.

Strengths:

- Augmentation de la puissance de calcul
- Données télédétection disponibles et produits propres sur étagère issues de la télédétection *via* Théia, Dynamis, Copernicus…
- Couplage avec la modélisation
- Etat => Chgts
- Groupe d'experts en cartographie des sols par modélisation statistique rattaché au Centre d'Expertise Scientifique « Sols et Végétation » du pôle de données et de service Théia
- Outils de Cartographie numérique des sols opérationnels
- Existence du Réseau Télédétection INRAE qui fédère des experts en télédétection et des utilisateurs de données de télédétection
- Capitalisation des données Sol dans une base nationale (DoneSol)
- Résolutions XY, t+ Spectr
- Programmes de cartographie des sols en cours à différentes échelles sur le territoire + réseau de surveillance des sols en France
- Masse information Lenteur « nettoyage »
- Traitement temporel de l'observation
- Projet de formation francophone en télédétection et cartographie des sols par modélisation statistique en cours de montage par le Groupe d'Experts Théia
- Aéroporté (gamma)
- La menace érosion : s'appuie sur une certaine maturité des équipes européennes quant au couplage /modèle/ données OT et MNT/et validation in situ ainsi que la spatialisation du diagnostic porté.
- Possibilité d'approche par Drone
- Soutien politique SML

- Etat d'avancement des différentes utilisations
- Existence du Réseau Télédétection INRAE qui fédère des experts en télédétection et des utilisateurs de données de télédétection
- L'humidité des sols des pistes intéressantes par Sentinel 1 et 2 à approfondir
- Quels autres proxys envisageables, validés, déployables ? avec la chaine adéquate d'expertise et/ou d'interprètes ?
- Menace artificialisation/urbanisation : une certaine maturité des modèles et des proxys à détecter, le jeu «multidate pluri-annuel optique + radar bande X récent » peut être assez parlant.

- Faible prix à large échelle
- Besoins liés aux opérations de compensation agricole, naturelle, ou forestière
- Permet d'identifier les hétérogénéités de sols
- Sciences participatives ?
- Besoin de suivi plus précis du puits de carbone du sol (levier décarbonation plan climat)
- Suivi temporel précis des changements dans les sols
- Accès à l'information rapide, facile et environnemental
- Permet d'avoir une meilleure approche dans le cadre du ZAN afin de renforcer la préservation des sols les moins dégradés et artificialiser les sols les plus dégradés
- Surveillance à grande échelle des sols, ce qui permet de couvrir des zones vastes et souvent inaccessibles

- Existence d'outils opérationnels de commande et visualisation d'analyses compatibles avec ces technos
- Fournisseurs de données de référence pour calibrer les OT (analyses au champ, géolocalisées)
- Vue globale (couverture territoriale large) et possibilité de voir l'évolution dans le temps
- Personnel (doctorant et post doctorant) dédié spécifiquement sur ces questions de surveillance des sols par télédétection

- Expérience sur sols et climats variés
- Difficulté de quantifier certains indicateurs essentiels à la santé des sols et à la résilience des cultures par télédétection (ex. capacité de rétention en eau) (partagé « Faiblesses »).
- Diachronie utile ; suivi des évolutions
- Assurer la crédibilité d'une évaluation de la santé des sols par télédétection auprès des utilisateurs (partagé « Faiblesses »)
- Création de réseau d'utilisateurs au niveau européen (partagé « Opportunités »)

Weakness:

- Dégradation des sols par les pratiques humaines souvent conditionnées à des intérêts financiers (machinisme agricole, phyto...)
- Manque de données d'acquisition de terrain sur les sols pour calibrer et valider les modèles. Densité trop faible.
- La menace contamination : piste : envisager la détection de déchets enterrés par double signature : thermique-radar, si la résolution le permet
- Densité insuffisante des données de terrain pour caler/spatialiser et/ou valider un indicateur
- Masse critique insuffisante des experts formés en observation de la Terre : quelle taille réelle ? Quels liens construits ou à construire vers les utilisateurs aval ?
- La spécialisation de la discipline, la connaître, son utilisation et l'interprétation
- L'hyperspectral : quelle biodiversité du sol peut-on réellement atteindre ???
- Classes/minorités sous-représentées Manque donnée calibr/valid
- La compréhension du compartiment sol demande des compétences multiples longues à acquérir

- Incertitudes, fiabilité des résultats
- Echelle non adéquate pour étudier les croûtes biologiques ?
- Sol couvert
- Extrapolation abusive- surajustement
- Surface sol only
- Le support spatial de terrain (données sol ponctuelles) est-il compatible avec le support des données de télédétection (maille raster) ?
- IA « aveugle »
- Nomenclature de l'occupation du sol : peut-être encore trop sommaire pour atteindre certains indicateurs : progrès à faire sur cultures intermédiaires (donc accès à une revisite adaptée) et aussi sur la typologie des couverts permanents comme landes, pelouses, vignes, vergers …
- Echelles de résolution très grandes par rapport aux besoins du terrain
- L'occupation du sol est le principal proxy utilisé, voire le seul, pour aborder les menaces sur les sols ou les services écosystémiques assurés.
- La menace contamination : globalement OT peu satisfaisante car cette menace est très complexe et rarement repérable par des modifications d'états de surface . Recommandations : Tenter de segmenter par cibles de pollutions possibles : ie pour mieux cibler les points de contrôle au sol, détection des zones irriguées dans une région d'utilisation autorisée d'eaux usées
- La menace diminution de la matière organique : indépendamment de l'espoir encore à prouver d'un observable corrélé directement au taux de C, la calibration et les valeurs seuils devraient dépendre d'un pré-zonage régional (strate) guidant ou contraignant la spatialisation de cette calibration
- Objectifs trop larges : quoi surveiller : la menace ? l'impact constaté de la menace ? le service écosystémique assuré ? le changement dans la continuité du service écosytémique ? ou seulement le changement d'occupation du sol à interpréter ensuite en indicateurs d'état voire de dégradation ??
- -aéroporté : l'apport de la gammamétrie est encore trop méconnu, alors qu'il est très significatif sur les textures de surface ou l'apport d'engrais par exemple.
- Faiblesse des formations pour une appropriation des possibles par la chaine d'utilisateurs aval : sans formation et esprit critique, danger de voir la diffusion de produits encapsulés presque « magiques » , mais avec enjeux et impacts économiques à la clé
- Clarifier entre « outil de surveillance » et « outil de ciblage de rémunérations des efforts » de qualité des sols, dont celui du stockage de carbone.

- Mauvaise connaissance de ma précision des corrections d'images
- Disponibilité des données
- Peu de compétences en interne à la métropole pour la télédétection
- les modèles de télédétection sont empiriques, aucune fiabilité sur de larges échelles pour du suivis
- Manque de formation des agents, manque de temps pour la prise en main de nouveaux outils
- Echelle d'observation : rôle des plates formes régionales d'information géographique à préciser
- Influence des conditions atmosphériques: amélioration des prétraitements du signal spectral
- Utilisation des images radar plus compliquée
- Interopérabilité des données
- Résolution spatiale limitée parfois
- Modèle de prédiction par type de sol. revoir la possibilité d'identifier des nouveaux indices spectraux qui ne dépendent pas de la nature du sol
- Nécessité d'une expertise spécialisée pour extraire des informations significatives

- Difficile d'utiliser ces données en milieu non agricole (partagé « Menaces »)

- Méconnaissance des produits existants, vocabulaire complexe...
- Validation et étalonnage pour les propriétés de sols en particulier
- Difficulté à comprendre les questions de résolution, incertitude liée aux indicateurs obtenus
- Taille des jeux de données nécessaires ...
- Compréhension de la qualité de données et confiance dans les valeurs produites pour l'utilisateur final
- Manque de compétence interne sur l'utilisation de la télédétection

- Manque de formation (bases de données)
- Complexité informatique des accès aux données
- Difficulté de quantifier certains indicateurs essentiels à la santé des sols et à la résilience des cultures par télédétection (ex. capacité de rétention en eau) (partagé « Forces »)
- Besoin d'accompagnement pour la prise en mains des produits dérivés par les utilisateurs
- Difficulté à retrouver la donnée
- Comment choisir la bonne donnée adaptée à ma problématique ? (Le bon service ? (Théia ...))
- Assurer la crédibilité d'une évaluation de la santé des sols par télédétection auprès des utilisateurs (partagé « Forces »)
- Coût des données et des outils ? et des formations ?
- Besoin d'une bonne maitrise du « machine learning »
- Comment combiner les données de télédétection à d'autres données ? (RPG ...) ?
- Niveau de confiance faible pour certains indicateurs. La télédétection souvent utilisée comme dernier recours de vérification
- Confusion effet de surface / cause de profondeur (quand on connait mal les sols) (partagé « Menaces »)

Opportunities:

- la montée en puissance du sujet, Effondrement de la fertilité, de la biodiv, question de la réserve utile et du stockage de l'eau à la parcelle...
- Vers un Open access total ?
- Ouverture des bases de données privées, publiques + Mise en commun !
- Puissance calcul
- Couverture nationale MNT lidar de l'IGN
- Développement de l'utilisation des drones
- GPS Tracteurs et opérations culturales
- Satellite Biodiversity (2028) : y a-t-il des campagnes aéroportées préalables de simulation susceptibles d'offrir des jeux tests ?
- Augmentation progressive des surfaces couvertes en données aéroportées
- Nouveaux capteurs : CO3D, TRISHNA
- Plus de recul temporel pour voir des évolutions
- Lancement de nouveaux satellites (Biodiversity, Fresh…)
- Satellite MERLIN (2028) : envisager de participer aux tests des signatures d'émission de méthane en lien avec la réduction/ disparition des permafrosts ??

- Incidences du ZAN : montée en compétences indispensable des ingénieries territoriales / lien territoire - ESR à renforcer
- Harmonisation des méthodes de mesure et des outils utilisés au laboratoire et sur le terrain pour améliorer la qualité de prédiction et la comparaison inter-laboratoires/ pays

- gratuité des données
- Surveillance continue et à long terme
- Evaluation de l'aptitude des terres à différentes utilisations, comme l'agriculture, la foresterie ou l'aménagement urbain
- Intégration de différentes sources de données
- Données lidar

- Avec les indices de végétation on a des relations de la qualité du sol avec le rendement des cultures
- Grandes cultures avec spécificités
- Intérêt fort du secteur (coop et négoce) sur la valorisation de la télédétection
- Des centres d'experts qui peuvent aider (CES Théia)
- Offre d'imagerie en amélioration (offres plus nombreuses, de meilleure qualité, certaines gratuites)
- Appréciation de l'hétérogénéité intra-parcellaire

- Création de réseau d'utilisateurs au niveau européen (partagé « Forces »)
- La gamma-spectrométrie comme moyen potentiel très novateur
- Mise en commun des outils et des bonnes pratiques
- Généricité, possibilité de remonter dans le temps
- Sources des données diversifiées (capteurs multiples, résolutions variées...)
- Offre de données OT très vaste

Threats:

- Risques d'évènements extrêmes liés au changement climatique
- Variabilité inter-annuelles
- Erosions plus fréquentes => Actualiser cartes propriétés
- Données télédétection à la demande propre longue à obtenir.
- Opacité des procédures ; Technocratie absolue
- Accès aux données
- Des choix politiques qui seraient calés sur une satisfaction des professions plus que sur les enjeux globaux
- Non diffusion gamma par intérêt stratégique commercial (U, Li..)
- Incompatibilité législatif sur les sols (propriété privée) et diffusion de données sensibles (pollution, dégradation des terres…) => risque de conflit juridique
- Crainte flicage/mesures contraignantes
- Masse critique d'experts sur les sols
- Risque de flicage des agriculteurs et des pays entrainant des contraintes financières
- Risque d'une surveillance à une échelle si fine qu'elle soit perçue comme trop coercitive
- L'hyperspectral présentera des limitations majeures : nébulosité gênant l'acquisition aux dates clés, volume des données, outils complexes d'extraction de l'information pertinente (à bord ou au segment sol), couverture régionale pas toujours compatible avec la fauchée envisagée : le tout pour quelle biodiversité du sol ???

- Difficile d'utiliser ces données en milieu non agricole (partagé « Faiblesses »)
- Niveau de précision de la télédétection, lien avec le parcellaire, et l'usage du sol, imprécisions liées à l'automatisation
- Absence de "big picture" pour comprendre qui fait quoi sur la télédétection et dans quelle mesure la donnée est accessible/gratuite (bcp de démarchage commercial)

- Données de rugosité, d'humidité, de quantité de résidus et de végétations qui floutent trop l'information pour du suivis
- Des préoccupations en matière de confidentialité et de sécurité, notamment en ce qui concerne la collecte et le stockage des données
- Évolution des politiques et des réglementations relatives à l'utilisation des données
- Accessibilité des données et des outils pour les exploiter (extraction, format, incertitudes,..)
- Peu de satellites hyperspectraux, possédant une large gamme spectrale avec un temps de revisite nécessaire (pour l'analyse des sols nu, au moment des semis par exemple)
- Coût des données
- Hétérogénéité des méthodes : cf. définition de l'artificialisation

- Manque de données pour les Sols fortement argileux soumis aux contraintes tropicales
- Peu de données pour les horizons en profondeurs (sol en 3D)
- Concurrence avec les analyses de sol / risque d'oubli de s'appuyer sur des observation de terrain pour la validation
- Compilation de données à créer: l'évolution de la couverture foliaire vs carbone organique du sol/érosion ?
- Confidentialité, difficulté d'accès à certaines données selon les pays
- Éloignement de la métropole (des préoccupations différentes pour les territoires d'outre mer qui sont un peu 'orphelins' en qtt de données dispo
- Instabilité géopolitique --> incidence sur constellations satellites

- Confusion effet de surface / cause de profondeur (quand on connait mal les sols)
- Ne pas se laisser impressionner par la technique et la beauté des images résultantes
- Croire que l'IA appliquée aux données d'OT va tout solutionner
- Résolution spatiale (quantification indicateurs au niveau de la parcelle et distinction entre parcelles)
- Une résolution qui n'est pas toujours adaptée
- Manques d'accès à l'hyperspectral pour la chimie des sols
- Compatibilité et continuité entre anciens capteurs et nouveaux (progrès continue vs obsolescence)

  - *Main conclusions*

The SWOT analysis summarised above was intended to meet the workshop's two objectives, namely to:
- Identify the bottlenecks (scientific, technological, technical, skills, etc.) to greater use of satellite EO, as well as CLMS and/or Galileo/EGNOS products, for soil monitoring;
- Propose measures to reduce/minimise these difficulties.

The proposals could not be ranked according to their supposed impact on bottlenecks, and according to how easy - or even expensive - they are to implement, because of the limited discussion time in the sub-groups.

The analyses carried out in the various sub-groups mainly distinguished the scientists' sub-group from the other sub-groups, even though some scientific remarks may have emerged simultaneously in different sub-groups, perhaps in part because the moderators and secretaries of each of the sub-groups were making their own contributions to the discussions.

For scientists in particular, the inaccessibility of data on soil properties at depth using direct remote sensing is an obstacle to the wider use of remote sensing.
They suggest three types of solution to overcome this problem in the short or medium term (long-term solution was not envisaged, e.g. with P-band wavelength sensors at the resolution of interest):

- Better couple *in situ* data and available covariates (accessible imagery proxies) with the operational models of interest for each type of potential threat;
- Encourage the widespread use of airborne gamma-ray spectrometry, which provides an integrated 60 cm parametrization of soil texture and certain other signatures such as fertilizer applications. Other European countries are also very interested in gamma-ray spectrometry, notably Denmark (all people working on peat are very interested in gamma-ray spectrometry because it enables easy detection of whether there is at least 50 cm of peat or not);
- Use process-based model inversion, e.g., using vegetation proxies such as NDVI or others to try and infer soil water holding capacity.

For French scientists, another bottleneck to wider use of remote sensing data is that of scale: for a given soil process or property, what resolution and coverage are appropriate?

- Basically, what grain of information should we have on the soil in relation to the resolution and remote sensing support available? We have to use rather punctual soil information (mainly from soil pits, 1 m^2) to calibrate or validate remote sensing models the resolution of which is ranging 100 m^2 - 1 km^2? This is not trivial;
- The geographical “laws” (or drivers) of distribution change with scale. On which overall coverage do we calibrate relationships? Soil carbon, for example, has completely different controlling factors depending on the scale envisaged (global, continental or regional): the main driving variables change (e.g. at world scale climate is the main controlling factor, followed by land use; at small national scale land-use and soil texture are dominant, at field scale, soil texture, and soil and crops management practices are dominant), therefore relevant models change with scale, and the variables are more and more uneasy to capture as detailed maps are required).

Scientists propose two types of approach to deal with this problem in the case of soil carbon:

- The first one is to use imagery to delimit areas that will enable the *ad-hoc* model to be applied upstream to spatialise a carbon estimate that is representative of these areas, with a sampling of areas that is well representative of this zoning and well designed in both geographical and feature spaces;
- The second one would be to increase the harvesting of *in situ* soil data from a variety of laboratories, or even to encourage public policy to impose procedures for the transfer of analyses, for example when fields are transferred from one farmer or owner to another, so as to accumulate field soil data. This solution is not linked to the technology available, but as field-scale analyses often come from a composite sample gathered on a rather large area (say 1 ha to 50 ha), it allows to have a soil support integrating the within and inter pixels variability on a consistent area. Note that a database of such soil agronomic analyses already exists in France, gathering several millions of analyses since 1990. But the collection of results is a voluntary process from the labs. There is no constraining obligation.This approach would allow to better match soil observations with the resolution of the sensors available, depending on the scale at which we are working.

Although scientists are aware of this, it is mainly people in the public sector or the private sector and people representing NGOs who report a problem with access to EO data and services (CLMS, Galileo/EGNOS). People of the public sectors mention (i) a lack of knowledge and skills to know what can be done with remote sensing, and (ii) a general lack of visibility of what is available, where the data can be accessed, and sometimes the price of the data, which can hamper accessibility. People in the private sector mention that end-users' lack of knowledge and skills in relation to existing products, but also in relation to what they can do with the products supplied. People representing NGOs or who do not fall into any of the other categories (i.e. Scientists, people of the public sector, people of the private sector) also mentioned difficulties in accessing services and data (with a labyrinthine character due in part to the plethora of data on offer, which is not easy to find one's way around) and the need for expertise that is not necessarily shared within the associative sector, particularly when it comes to coupling remote sensing with other environmental covariates, which can yield very interesting results.

To tackle these problems, they expressed (i) the need to raise awareness among product users, to support these users and to train them in the use of available tools, (ii) the need for exchanges between scientists and local authorities (currently considered insufficient or even non-existent), but also between field workers and database users, and (iii) the need for a collaborative web space to facilitate interaction between stakeholders, e.g. a universal web portal or an adapted website. And scientists also not that there is a major need to train users of remote sensing data so that they understand what types of media they can exploit and, consequently, to communicate on how to identify the limits to the use of PROXYS derived from remote sensing.

Another important bottleneck is the lack of standardisation. People of the public sector mentioned the lack of harmonisation (in concrete terms the heterogeneity of methods and products, with satellite products whose definitions are sometimes not in agreement with those of users). People in the private sector noted that advice based on EO data varies with the producers of that advice and the treatment chains they apply: for example, cloud cover limits the data that can be collected over vast territories, leading some operators to mobilize the data in spite of everything, correcting them but without really informing the user of what has been done.

To cope with these problems, they expressed the need for interoperability between the various products, the need standardized methods and procedures (e.g. what to do if there are a lot of clouds) which can guarantee a certain product quality, and requiring operators / data producers to provide a confidence interval to assess product quality. The need to identify and quantify uncertainties was also expressed by people representing NGOs.

Other items mentioned included (i) the regret that information on non-agricultural soils (forests, etc.) is not always accessible, and that it is sometimes only available at temporal and spatial resolutions that are sometimes not fine enough, due to the fact that these soils are rarely bare, (ii) the need to call on partners from different horizons, with different skills and different vocabularies to devise solutions that add value to EO data, and (iii) the risk of “deluding oneself” into thinking that remote sensing can solve everything, especially with artificial intelligence. Some wondered whether citizen science could be used as complementary information to remote sensing (as covariates). Others have high hopes for hyperspectral imaging.

Norwegian workshop (led by Tove Ortman, NIBIO)

- *Factual summary of the workshop progress*

As a part of the PREPSOIL Task 5.2 work to explore the potential and hinders towards using Earth Observation (EO) data in soil monitoring, an online workshop where held with Norwegian stakeholders the 22nd of April 2024. The workshop was arranged by NIBIO, and was an 1,5 hours long. The ambition was to invite a broad group of Norwegian stakeholders with an interest of using remote sensing and earth observations to discuss the potential for increased use of this in soil monitoring.
Invitations were sent out around a month before the workshop, to members of the PRESOIL soil hub, and to actors that are currently working with EO and soil monitoring in Norway, both researchers, representatives from policy makers, agricultural advisory service and farmer's organisations, and from private business specialised in e.g. drones. In order to reach broad, all participants were encouraged to forward the invitation to all contacts that they thought could be interested, thus using the snowball method. While signing up the participants where asked to accept the informed consent form, something which everyone did.
When inviting participants, it became evident that the interest for discussing EO in soil monitoring in Norway was mostly limited to researchers. In total 17 participants attended (see Appendix A, participant list), and only one of these were from outside academia, namely a representative from the Norwegian Agricultural Agency. A reflection from the NIBIO group that arranged the workshop is that at the moment, soil monitoring by remote sensing appears to be a subject that mostly is known among researchers in Norway. Even tough 17 are fewer than the recommended number for the workshops for PREPSOIL Task 5.2, the NIBIO arranging group believes that it is a representative number for the number of actors in Norway working with these issues. Norway is a relatively small country, and the work with EO in soil monitoring is still limited and mostly research focused. The interest from NGOs were very limited, and several of the invited stakeholders (from e.g. the Norwegian farmer's associations) expressed that they didn't know enough about this, and that more knowledge and research in Norway was needed before this was something that they felt that they could engage and see the potential in. Most companies working with technological solutions appeared to be closely linked to research institutions, and their perspectives can therefore be said to be represented by researchers.

When we became aware of the structure of the group of participants before the workshop, we decided to take it into account in the planning of the workshop. Since the participants had a high expertise in the subject, the introduction was shortened (especially the last part, were practical examples were given), and instead room were given for the research groups to present themselves and the work they were doing in relation to EO in soil monitoring. The adjusted agenda was:

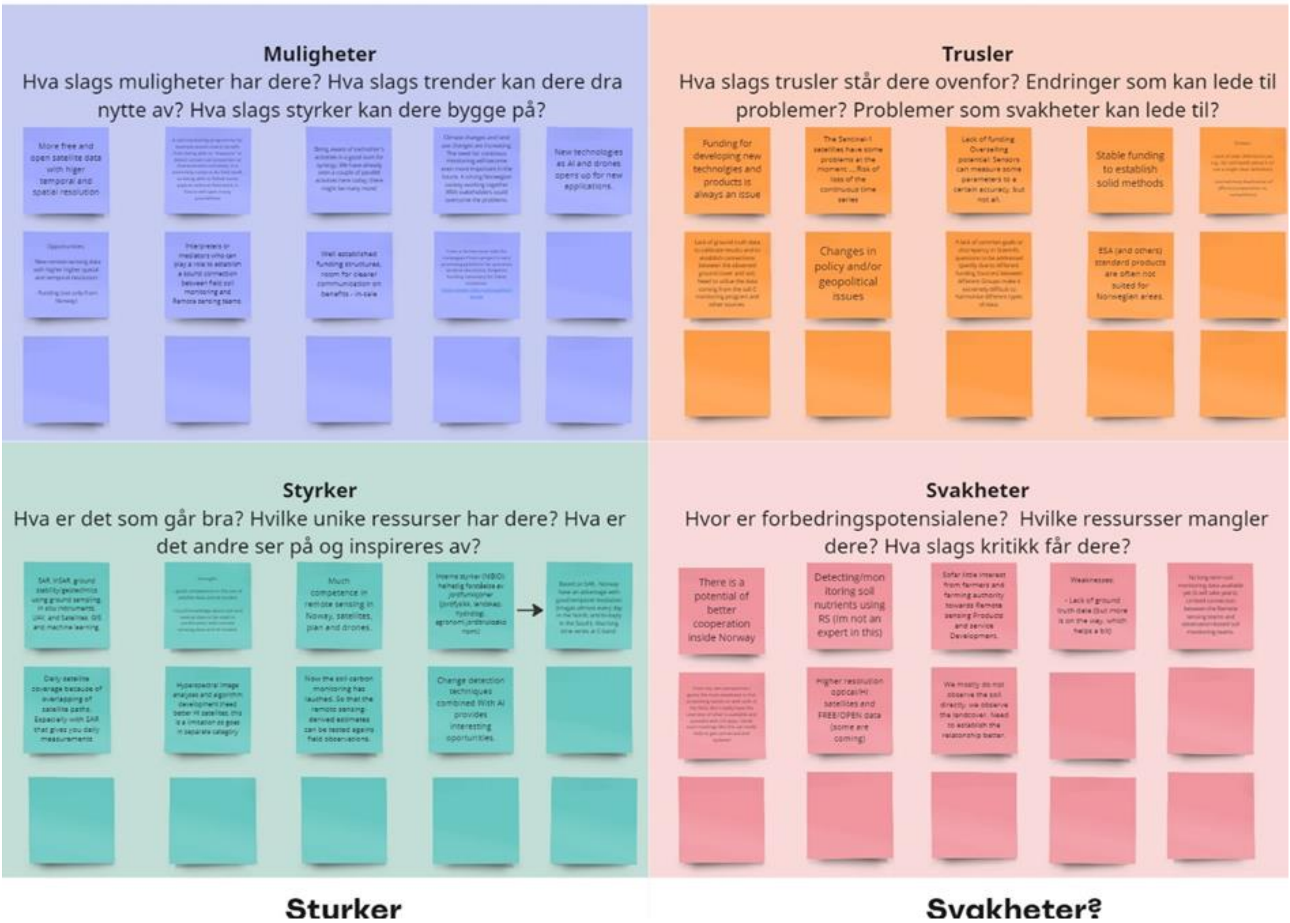
- **15 min introduction** by NIBIO researcher arranging the workshop about the state of soils and soil health, objectives for the workshop and a short overview of the use of EO in soil monitoring in Europe;
- **30 min presentation from Norwegian stakeholders** and discussion about the current status of EO in soil monitoring in Norway;
- **45 min SWOT analysis and group discussion** with all stakeholder sin one group.

7 researchers from 3 different institutes (NGI, NORCE and NIBIO) presented the work they and their groups were doing, and the representative from the Norwegian Agricultural Agency presented the perspective on this type of data from a

policy making perspective. After each presentation the group had the opportunity to ask questions and discuss.
Since all stakeholders could be regarded as one large group with similar interests, the decision was taken to conduct the SWOT analysis and discussions in one large group. Apart from the fact that we wanted for all stakeholders to be able to discuss together, we also counted on that many of the participants had a high degree of familiarity with online meetings and discussions. Even though the group was somewhat to large for the format, it worked well. We used a MIRO board (an online tool), which enabled the participants to write up their thoughts on post-its. We then went though and discussed one part of the SWOT, letting the participants present their thoughts. After completing the SWOT analysis, we concluded with a group discussion about possible ways forwards.

- *SWOT (Strength-Weakness-Opportunities-Threats) analysis in relation with the objectives of this workshop*

The workshop was conducted in a mixture of Norwegian and English, since there were some international researchers in the group who were most comfortable in English. Therefore, most participants wrote their notes in English. To help the participants, a few guiding questions were included in the SWOT analysis (see **Figure A4.2**), such as for Strengths: What works well? What unique resources do you have? What are others admiring and inspired of?



Picture A4.1: The original SWOT table that were produced during the workshop.

Table A4.1: The SWOT table filled in during the workshop (Items marked with an * have been translated from Norwegian).

Strengths	Weaknesses
- SAR, InSAR, ground stability/geotechnics using ground sampling, in situ instruments, UAV, and -- Satellites. GIS and machine learning. - Good competence in the use of satellite data and AI models - Good knowledge about soil and several data to be used in combination with remote sensing data and AI models - Internal strength at NIBIO research institute: holistic understanding of soil functions (soil physics, landscape, hydrology, agronomy, farm economics)* - Based on SAR, -Norway have an advantage with good temporal resolution (images almost every day in the North, and bi-daily in the South). Also long time series at C-band. - Much competence in remote sensing in Norway, satellites, plan and drones. - Daily satellite coverage because of overlapping of satellite paths. Especially with SAR that gives you daily measurements - Hyperspectral Image analyses and algorithm development (need better HI satellites, this is a limitation so goes in separate category - Now the soil carbon monitoring has launched. so that the remote sensing-derived estimates can be tested against field observations. - Change detection techniques combined with AI provides interesting opportunities.	- Detecting/monitoring soil nutrients using RS (I'm not an expert in this) - So far little interest from farmers and farming authority towards Remote sensing products and service development. - No long-term soil monitoring data available yet (it will take years). Limited connection between the remote sensing teams and observation-based soil monitoring teams. - There is a potential of better cooperation inside Norway - Higher resolution optical/HI satellites and FREE/OPEN data (some are coming) - We mostly do not observe the soil directly, we observe the landcover. Need to establish the relationship better. - From my own perspective I guess the main weakness is that us working hands on with soils in the field, don't really have the overview of what is available and possible with EO-data. I think such meetings like this can really help to get connected and updated
Opportunities	**Threats**
- A soil monitoring programme for example would clearly benefit from being able to "measure" or detect certain soil properties or characteristics remotely. It is extremely costly to do field work, so being able to follow some aspects without field work in future will open many possibilities - More free & open satellite data with higher temporal and spatial resolution - Being aware of each other's activities is a good start for synergy. We have already seen a couple of parallel activities here today; there might be many more! - Climate changes and land use changes are increasing. The need for continuous monitoring will become even more important in the future. A strong Norwegian society working together With stakeholders could overcome the problems. - New technologies as AI and drones opens up for new applications. - New remote sensing data with higher spatial and temporal resolution - Funding (not only from Norway) - Interpreters or mediators who can play a role to establish a sound connection between field soil monitoring and Remote sensing teams. - Well established funding structures, room for clearer communication on benefits - in-sale - From a farmer/user side the Norwegian Presis project is very promising (platform for precision land use decisions), long term funding necessary for these initiatives (https://www.nibio.no/prosjekter/presis)	- Funding for developing new technologies and products is always an issue - The Sentinel-1 satellites have some problems at the moment ....Risk of loss of the continuous time series - Lack of funding. Overselling potential: Sensors can measure some parameters to a certain accuracy, but not all - Stable funding to establish solid methods - Lack of clear definitions yet, e.g., for soil health (what it is? not a single clear definition) - (sometimes) duplication of efforts (cooperation vs. competition) - Lack of ground truth data to calibrate results and to establish connections between the observed ground cover and soil. Need to utilize the data coming from the soil C monitoring program and other sources. - Changes in policy and/or geopolitical issues - A lack of common goals or discrepancy in scientific questions to be addressed (partly due to different funding Sources) between different groups make it extremely difficult to harmonise different types of data. - ESA (and others) standard products are often not suited for Norwegian areas.

- *Main conclusions*

The main conclusions of the workshop is presented in **Table A4.1**. In the discussion of the different points, certain aspects were highlighted orally by the participants:

- When discussing strength, several participants pointed out that we have many competences at the different research institutions, ranging from remote sensing to agriculture, forest and soil expertise;
- With regard to weaknesses several participants pointed out the current low opportunities for funding for soil monitoring by Earth Observations in Norway. There seems to be low political interest nationally in funding Copernicus. *"The remote sensing community has to use time to convince authorities to support this"*, one researcher said. The policy maker representative from the Norwegian Agricultural Agency responded that there is a lack of knowledge from decision makers about the potential, and that meetings such as this workshop makes it clearer for them what the potential is. **Lack of knowledge and contact between researchers and policymakers were pointed out as a weakness – but it is not unmanageable**, was the conclusion from the policy maker representative. Several of the participants expressed an interest for more meetings across disciplines, and with policy makers to help developing the opportunities for using EO for soil monitoring in Norway;
- Another challenge pointed out as a weakness were collaborations between researchers: finding collaboration between experts in remote sensing and soil experts. A remote sensing specialist at NORCE pointed out that satellites may not be able to measure what farmers are interested in. We need to work on sensor and satellites together with those who use them, i.e. that the researcher collaborate with farmers and other end users. The researcher stated that *"If we don't start doing this at some point we'll never succeed"*;
- A technical field that the participants felt had potential for improvement in Norway is the competence in drones, "We must have more competence about using drones, because you cannot do everything with satellites", as one researcher from NORCE institute put it;
- Opportunities that were pointed out especially were the possibilities to make data collection more efficient. One researcher from NIBIO specialised in agricultural soils pointed out that the costs to send people out in the field to take measurements is huge. "If we can start to develop indicators remotely it would be a great advantage. Which ones are the more low hanging fruits? It would be good to identify". This statement was met with agreements, and interest from the remote sensing specialists, seeing potential in finding possible collaboration with the specialists in agricultural and forest soils;
- With regards to potential threats, the policy maker representative concluded that lack of cooperation between researchers is potentially a threat, making the available datasets less complete that they could be. If the time is spent on competition rather than cooperation, then we waste resources;
- In the final discussion (15min) several stakeholders concluded that the workshop had been very useful to get an overview of what others were working with, opening up for new collaborations. The participants agreed that the participant list and the power point presentation (including the presentations of the participants) should be shared among the group afterwards, so that it would be possible to find and contact each others. The research field seems to divided into separate groups in Norway, and the participants described that just this workshop become away of stakeholders go become aware of each other, which can enable a higher degree of collaboration in future. Another actual result of the workshop was the discussion between the researchers and representative from the Agricultural Agency. However, the participants expressed that they wished more stakeholder groups could have been present, for example farmers. Many participants hoped to be able to meet across disciplines at similar platforms in future,

and expressed an interest in becoming involved in transdisciplinary work related to soil monitoring, i.e. living lab initiatives.

Czech Republic workshop (led by Jaroslav Smejkal)

- *Factual summary of the workshop progress*

The workshop was organised by Lesprojekt on 17 May 2024 from 09 am to 2 pm in Rostěnice (Czech Republic) with 23 participants (6 scientists (5 of them from Lesprojekt), 13 people in the private sector (12 of them being private farmers), and 4 representatives of NGOs).

The workshop programme was as follows:

1. A preliminary presentation of the subject and the objective of the workshop (Where: meeting room, start at 09:00);
2. A presentation of the introductory PPT slide show (Where: meeting room);
   Transport by bus to the external workplace (duration: 30');
3. Working in two groups with close stakeholders, including:
   a. An introduction (Where: field);
   b. Initial brainstorming (Where: field (**Picture A4.2**));
   c. Discussion (fulfillment of the 4 boxes of the SWOT analysis) (Where: stable (**Pictures A4.3 & A4.4**));
      Transport by bus to the headquarters of the company (duration: 30');
   d. A final discussion aimed at meeting the two objectives of the workshop (Where: meeting room), i.e.:
      - Identify the bottlenecks (scientific, technological, technical, skills, etc.) to greater use of satellite Earth observations (EO) and CLMS and/or Galileo/EGNOS products for soil monitoring;
      - Propose measures to reduce/minimise these difficulties, ranking them (subjectively) successively (i) according to their supposed impact on bottlenecks, and (ii) according to how easy - or even costly - they are to implement;
4. A final time where the group tries to answer collectively to the 2 questions collectively, trying to limit itself to 3 cases (Where: meeting room);
5. Lunch from 13:00 to 14:00 (Where: corporate dining room);
6. The end of the workshop.

Picture A4.2: Introduction and initial brainstorming.

Picture A4.3: Group discussions - preparation of SWOT analysis

Picture A4.4: Group discussions – preparation of SWOT analysis

- *SWOT (Strength-Weakness-Opportunities-Threats) analysis in relation with the objectives of this workshop*

The SWOT analysis is summarised **Table A4.2**.

Table A4.2: SWOT (Strength-Weakness-Opportunity-Threat) analysis summary

	Useful	Harmful
Internal (which you can influence)	**Strength:** • High-quality hardware and software equipment for data processing. • Extensive network of experts proficient in working with EO data. • Free access to data from Sentinel satellites.	**Weakness:** • Insufficient expert knowledge for effectively utilizing EO data. • Prolonged time required to develop expertise and skills. • Cloud cover issues affecting the quality of Sentinel 2 data. • The need to integrate knowledge of EO with soil characteristics (physical and chemical properties).
External (beyond your control)	**Opportunity:** • Development of new sensors and satellites enhancing data quality and variety. • Availability of data over extended periods, facilitating temporal trend assessment. • Utilization of additional airborne sensors to complement satellite data. • Implementation of AI tools for improved data processing and analysis.	**Threat:** • Emergence of new standards and the introduction of paid commercial platforms. • Changing data and digital policies potentially restricting access. • Limited availability of data. • Challenges in processing large volumes of EO data. • Issues related to spatial resolution of the data.

- *Main conclusions*

The participants to this workshop identified bottlenecks to greater use of satellite EO. These bottlenecks include:

- Scientific bottlenecks, including the necessity of integrating knowledge from EO with soil characteristics (physics and chemistry), the insufficient expert knowledge for working with EO data, and the low experience with Sentinel 1 data processing;
- Technological bottlenecks, including Issues with spatial resolution of satellite data, cloud coverage affecting data quality, particularly Sentinel 2, and handling and processing large volumes of data;
- Technical bottlenecks, including the emergence of new standards and the prevalence of paid commercial platforms, the frequently changing protocols and standards, and the evolving data and digital policies;
- Skill bottlenecks as a prolonged time is required to develop expert knowledge and skills.

The participants to this workshop proposed masures to reduce/minimize these difficulties, **ranking them** (subjectively) **successively according to their supposed impact on the bottlenecks**:

1. Training and Education Programs:
   - Develop comprehensive training programs to build expertise in EO data processing and interpretation;
   - Conduct workshops and courses to enhance skills in Sentinel 1 and Sentinel 2 data handling;
2. Research and Development Initiatives:
   - Promote interdisciplinary research to integrate EO data with soil physical and chemical properties;
   - Support R&D for improving spatial resolution and cloud cover mitigation techniques;
3. Policy and Standards Advocacy:
   - Engage with policymakers to influence favorable data and digital policies;
   - Advocate for standardized protocols that are stable and adaptable to technological advancements;
4. Technological Solutions:
   - Invest in AI and machine learning tools to handle large data volumes efficiently;
   - Develop and implement technologies to improve data processing capabilities;
5. Collaboration and Networking:
   - Strengthen collaborations among experts and institutions to share knowledge and resources;
   - Create platforms for continuous exchange of best practices and innovations.

The workshop participants proposed an alternative ranking of measures to reduce/minimise these difficulties, by **ranking them** (subjectively) **according to their ease - or even cost - of implementation**:

1. Training and Education Programs:
   - Relatively low cost and high impact, with potential for partnerships with educational institutions and online platforms;
2. Collaboration and Networking:
   - Facilitates knowledge sharing with minimal financial investment, leveraging existing networks;
3. Policy and Standards Advocacy:
   - Moderate effort required to engage with stakeholders but can significantly influence the operational environment;
4. Research and Development Initiatives:
   - Higher cost due to the need for funding and resources, but essential for long-term advancements;

5. Technological Solutions:
    - Potentially high cost due to the development and deployment of new technologies, but critical for overcoming technical and technological bottlenecks.

Polish workshop (led by Artur Łopatka)

- *Factual summary of the workshop progress*

Workshop was organized as an online workshop by the team of The Institute of Soil Science and Plant Cultivation (IUNG) on 08 May 2024 from 10:30-12:00 in an online forum by using the Zoom platform. Registration for the workshop was conducted via a Google Forms application, during which participants were required to accept consent for the processing of personal data and the use of an image or optional recording of the event. Acceptance was necessary to participate in the workshop. The invitation to take part in the workshop was sent out almost two weeks in advance. Through the form, 62 persons registered, while 41 persons attended the workshop.

The invitation was addressed to individuals and institutions involved in remote sensing, spatial planning, regional planning, surveying and cartography, environmental protection, agriculture, forestry, urban planning, soil science, public administration units, commercial companies specializing in the use of remote sensing tools and software.

Among the participants who registered for and attended the meeting, those representing the scientific sector from research institutes and universities predominated. The webinar was also of interest to regional spatial planning offices (public administration). The figure below shows the percentage participation of the different participant groups in the workshop:

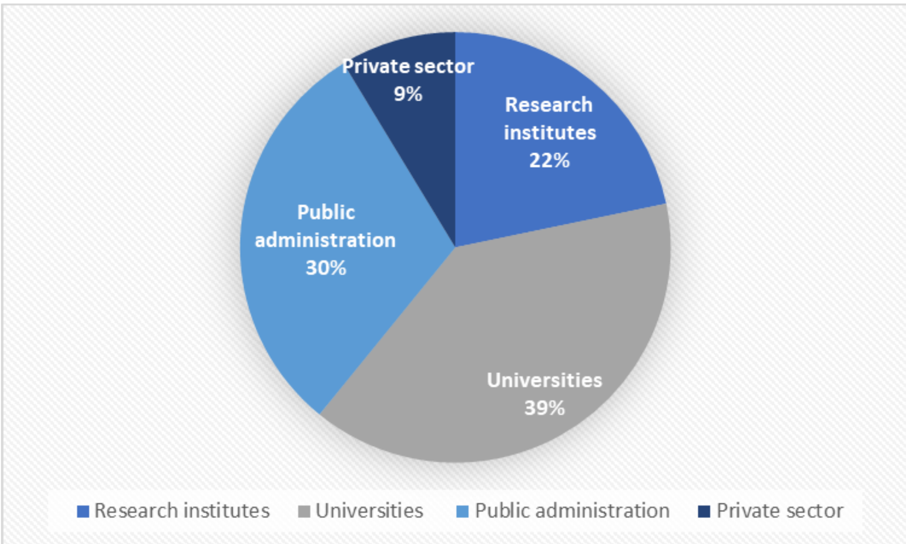
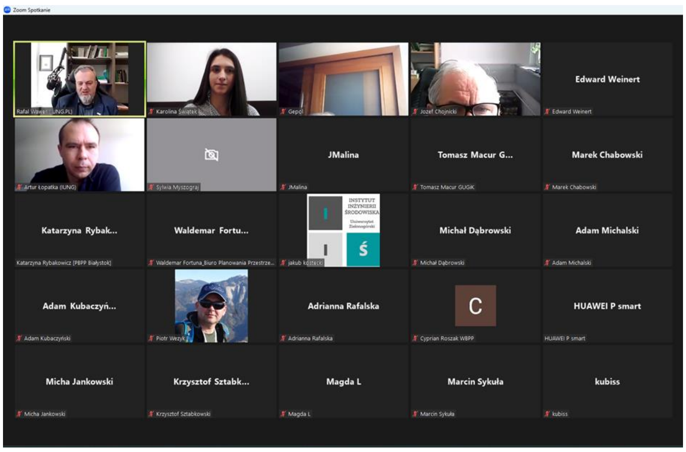


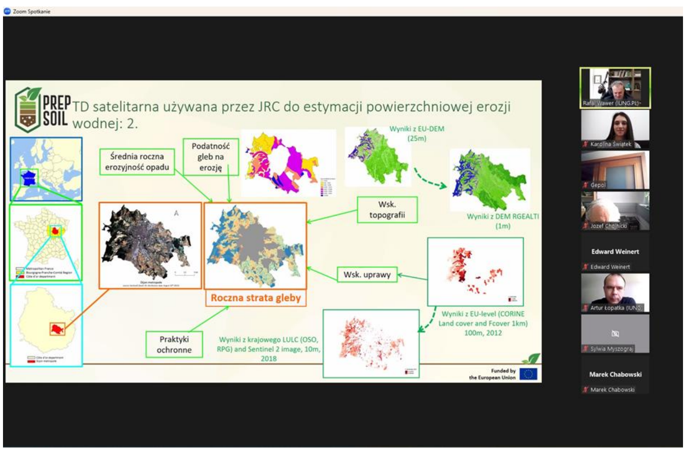
Figure A4.2: Distribution of registrants between researchers, academics, government employees and private sector employees.

Table A4.3 shows the list of institutions that participated in the webinar and the number of participants from each institution:

Institution	number of persons
The Institute of Soil Science and Plant Cultivation (IUNG)	3
Nicolaus Copernicus University in Toruń	7
The Warsaw University of Life Sciences (SGGW)	2
Head Office of Geodesy and Cartography	2
Institute of Agrophysics Polish Academy of Sciences (IA PAS)	5
The Łukasiewicz Research Network – Institute of Aviation	4
University of Life Sciences in Lublin	4
Greater Poland Voivodeship Spatial Planning Office	2
University of Warmia and Mazury in Olsztyn, Department of Soil Science and Microbiology	4
University of Agriculture in Krakow	10
Wrocław University of Environmental and Life Sciences, Institute of Soil Science, Plant Nutrition and Environmental Protection	1
Pomeranian Regional Planning Office	1
PPHU GEPOL – private company	1
Warsaw University of Technology	2
Bydgoszcz University of Science and Technology	3
Podlaskie Office of Spatial Planning in Białystok	1
The Forest Research Institute	1
The Institute of Environmental Protection – National Research Institute (IEP-NRI)	1
Agri Solutions – private company	1
Office for Spatial Planning of the Łódzkie Region in Łódź	1
The Bureau for Forest Management and Geodesy State Enterprise (BULIGL)	1
University of Zielona Góra	3
City Council of Bydgoszcz	1

Table A4.3: list of institutions that participated in the webinar and the number of participants from each institution





Picture A4.5: Zoom screens of the workshop

The interactive application slido was used for the active session. By scanning a QR code or a link, participants were able to connect to a prepared session of questions, which were questions relating to the SWOT analysis. Below is one of the questions along with the answers received.

Picture A4.6: Example of the use of slido application

- *SWOT (Strength-Weakness-Opportunities-Threats) analysis in relation with the objectives of this workshop*

Strengths	Weaknesses
• Systematic analysis of large areas • Possibility of monitoring hard-to-reach areas • Possibility of large-area monitoring • Spatial variability • Diversity of the surveyed characteristics • No limited survey time • Data availability • Availability of point data • Speed and low price • Cost reduction • Ease of implementation • No borders	• Influence of atmospheric conditions • Accuracy limited by quality of input/survey data • High cost of dedicated software • Difficult to extrapolate data • Poor accessibility, specialised knowledge required

Opportunities	Barriers and Threats
• Precision agriculture • Ecosystem services • Spatial planning • Updating soil maps • Environmental monitoring • Agriculture, environmental protection • Soil mapping • Exploration of areas not yet covered by monitoring • Low-cost way to verify and implement measures • Possible use of technology in the Rural Development Programme	• Dynamic soil variability • Need for field reference • Over-reliance on technology • Risk of misinterpretation • High survey costs • Errors in interpretation • Lack of field surveys • Large area and long term cloud cover

- *Main conclusions*

Defined sector-specific constraints during the discussion:

The perceived limitations related to the use of remote sensing and remote sensing data in the scientific area in Poland:

Answers	Number	Share
Specialist knowledge required to interpret data.	5	100%
Sensitivity to variability in atmospheric conditions.	2	40%
Continuous need to improve remote sensing data analysis methods.	2	40%
Need for continuous updating of remote sensing technologies.	2	40%
Difficulties in interpreting combined data.	1	20%
No consistency and integration of data from different sources.	1	20%
Necessity of calibration and validation of data.	1	20%

What limitations do you identify in using remote sensing data and remote sensing in the area of skills

Answers	Number	Share
Need to be familiar with remote sensing data analysis tools and software.	2	40%
Required programming skills for effective data processing.	2	40%
Need for continuous improvement of remote sensing skills.	2	40%
Lack of appropriate skills to analyse remote sensing data.	2	40%
Required specialist knowledge to interpret data.	2	40%

Required skills to work with advanced remote sensing tools and technologies.	1	20%
Lack of skills to integrate data from different remote sensing sources.	1	20%
Lack of skills to deal with errors and inaccuracies in data.	1	20%

What limitations do you perceive related to the use of remote sensing data and remote sensing in the technical area?

Answers	Number	Share
Provide continuous support and maintenance of remote sensing infrastructure.	4	80%
The need to continuously update remote sensing technologies.	3	60%
Risk of data loss in case of systems failure.	2	40%
Difficulties with data calibration and validation.	2	40%
High data acquisition and processing costs.	2	40%
Limited ability to integrate data with other technologies.	1	20%
Frequent interference and interference in data.	1	20%

Restrictions on the use of remote sensing data and remote sensing in the technological field?

Answers	Number	Share
Need for continuous support and maintenance of remote sensing infrastructure.	3	60%
Need for continuous updating of remote sensing technologies.	3	60%
Need for continuous improvement of data analysis methods.	2	40%
Problems with calibration and validation of data.	2	40%
Need for specialist knowledge to interpret data.	2	40%
Limited ability to integrate data with other technologies.	1	20%
Difficulties in interpreting complex data.	1	20%

What steps do you think should be taken to reduce the difficulties involved in using remote sensing data?

- provide training to 'de-emphasise' this area
- Organise as many courses as possible in Poland. Ideally, they should not require the participant to pay, as this is often a problem if the potential participant is a student or a scientist who has not planned such a course, e.g. in the project budget. Courses should be about acquiring and interpreting satellite data. Preferably free data and free software. Later, when the subject matter has become widespread, commercial courses can be run on paid data and programmes.

Annexe VI:

Setting up a virtual discussion group on the PREPSOIL website: discussion of some of the main results of the workshops

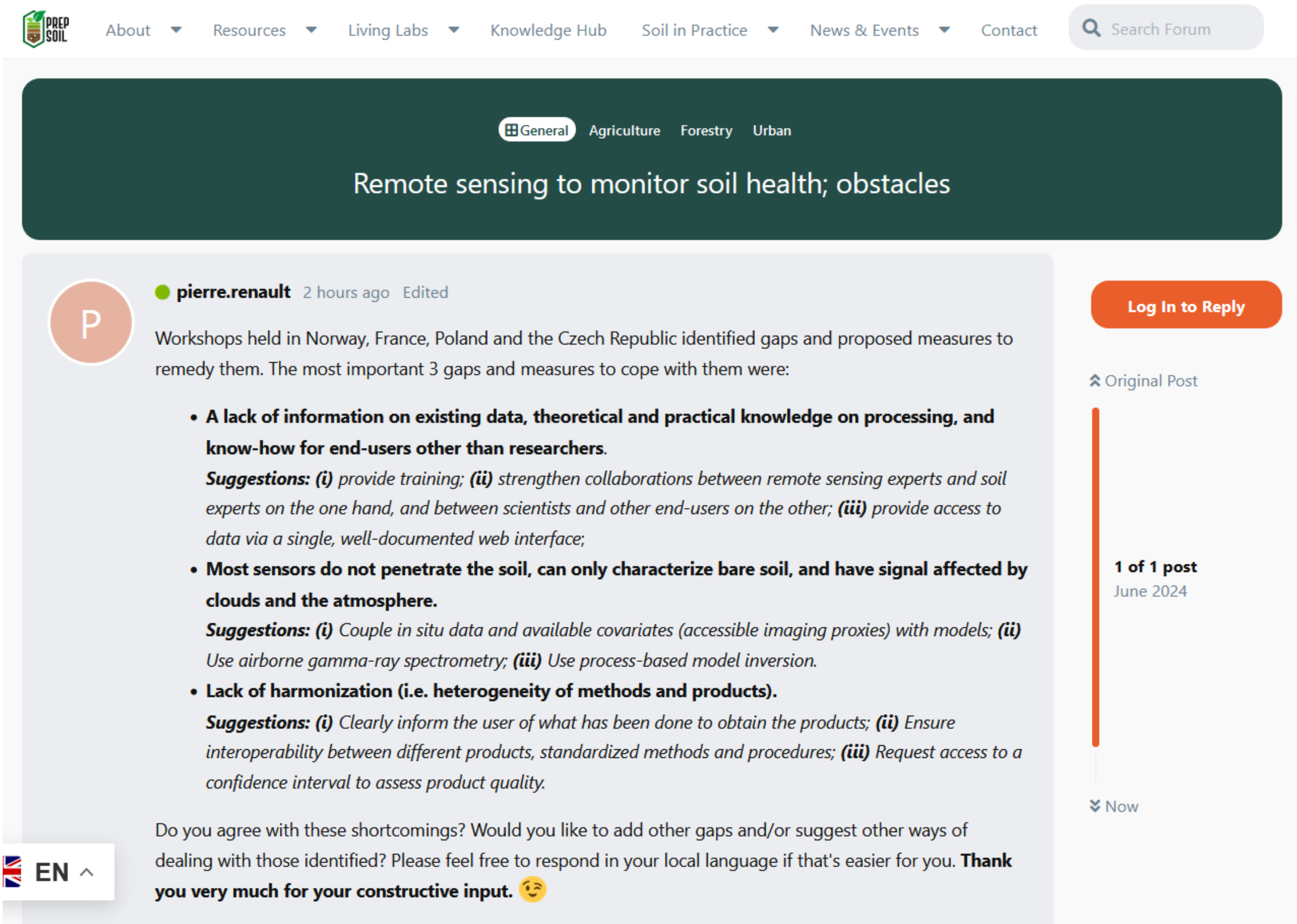


Figure A6-1: The initial Post to launch the Virtual discussion group