CSQ-41 Summary

Question	Knowledge Advancement Objectives	Geophysical Observables	Measurement Specifications	Tools & Models	Policies / Benefits
How does soil status control Earth system cycles and influence surface-air exchange processes?	A) Quantify surface soil hydraulic and thermal properties	Common soil attributes in soil spectral libraries (SSLs): mechanical composition (clay, silt, and sand content), organic matter, carbonate, iron oxides, hygroscopic moisture, and specific surface area); Soil dielectric properties (TIR emissivity; MW emissivity – dielectric constants) & SM from passive microwave observations (SMOS and SMAP) and follow-on high resolution mission, and SAR sensors	Soil and vegetation reflectance spectra at high resolution (10 – 100m), diurnal scale LST (100m) SM & VWC: kilometer scale (e.g. 1 - 10 km) at daily to diurnal time steps - a future higher resolution L-band space mission is highly desirable;	Spectroscopy; Multispectral/hyperspectral TIR SM & VWC: Retrievals algorithms (0th order RT models); Combination with SAR and scatterometer data; in-situ data for validation from e.g. International Soil Moisture Network (ISMN) GNSS and bistatic retrievals; use of auxiliary data by means of machine learning;	CC mitigation and adaptation policy; Climate finance; Green deal; Water and food security; Agriculture transition; EC Soil Deal mission: Farm to Fork Strategy, and EU Biodiversity Strategy for 2030; Climate Adaptation Strategy; New EU Forest Strategy; Long-term Vision for Rural Areas; Organic Action Plan; Common Agricultural Policy; EU's twin green and digital transition.

		VWC from coarse scale microwave observations (ASCAT, SMOS and SMAP) via vegetation optical depth; brightness temperature (e.g. SMOS and SMAP, and multi-frequencies in the upcoming CIMR), backscattering coefficient in C- (SAR and ASCAT) and L-band (e.g. ROSE-L); GNSS Groundwater: observations from mass change missions (GRACE and GRACE-FO); A new mission with much improved resolution in space and time will further advance the observations of terrestrial water storage.	10 ~100 km at weekly to monthly steps for groundwater;	Groundwater: change detection using time series of observation data; retrievals algorithms	
	B) Soil moisture profile as control of photosynthesis rates in vegetation canopies	Evaporation (and transpiration): observation of evaporation needs to cover the whole spectrum from	Evaporation: hm ~km at diurnal (half hourly) steps for **water potential** as well as full spectrum observation (incl. fluorescence)	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical,	

		optical to thermal range and the retrievals need to consider the involved essential physical and biochemical processes (coupling water, energy, and carbon cycles). Transfer of water through the soil, roots, stem and leaves can be quantified by measuring and simulating **water potential** and link the change of water potential to external forcings of radiation, precipitation and meteorology, the growth of above and below ground plant biomass, and the extraction of water by the growing roots. The direct observables are soil moisture, vegetation water content and near surface atmospheric water content.		TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	

	C) Quantify impacts of surface soil moisture and that of rooting depth soil moisture on surface-air exchanges	Quantify simultaneously SM, SIF, surface radiation fluxes (shortwave and longwave), sensible and latent heat fluxes	Sensible heat and latent heat fluxes (Evaporation): hm ~km at diurnal (half hourly) steps for **water potential** as well as full spectrum observation (incl. fluorescence), LST	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical, TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	
	D) Quantify the contribution of latent heat flux from bare soil and canopy to total surface-air exchanges, as well as that of groundwater level	Quantify simultaneously SM, SIF, surface radiation fluxes (shortwave and longwave), sensible and latent heat fluxes, together with TWS	Sensible heat and latent heat fluxes (Evaporation): km at monthly and seasonal steps: spectrum observation (incl. fluorescence), LST, TWS from GRACE and GRACE-FO and follow-on missions	Opt/TIR based retrieval algorithms; ESM/DTE based retrievals with data assimilation of optical, TIR and MW observations; Validation with in-situ measurements by Eddy covariance methods (e.g. Fluxnet)	

Narrative:

Recent floods and droughts in Europe have shown how the effects of climate change can be acerbated by unhealthy, i.e., compacted, sealed, eroded, and carbon-poor soils. It has been assessed 60-70% of soils in Europe are in an unhealthy condition. In the book “Collapse: How Societies Choose to Fail or Succeed”, authored by the “Pulitzer Prize” and “Wolf Prize in Agriculture” winner Jared Mason Diamond, soil problems (erosion, salinization, and soil fertility losses), water management problems, deforestation and habitat destruction are deemed the top environmental problems contributed to the collapse of past societies, and are the environmental problems facing humankind today.

Healthy soils are therefore not only essential for all life-sustaining processes on our planet, but also necessary for the successful implementation of EU’s Green Deal, providing ecosystem services, which include: Nutrient cycling, and producing safe and nutritious food; Storing and purifying water, regulating flows and recharging aquifers, as such providing a ‘buffer zone’ to reduce the impact of droughts and floods, contributing to climate adaptation; Sequestrating carbon from the atmosphere and reducing emission of GHG from soils, thus contributing to climate mitigation; Preserving biodiversity and supporting the quality of landscapes.

It is with the above context, European Commission launched ‘A Soil Deal for Europe’ which aims to pioneer, showcase and accelerate the transition to healthy soils at the level in line with Green Deal commitments and targets by 2030, via establishing a robust, harmonised soil monitoring framework (EU Soil Observatory), as well as 100 living labs and lighthouses within territorial settings. This mission is also essential for the success of the 2030 EU Soil Strategy, EU Nature Restoration Targets, and Circular Economy Action Plan. There are also political “buy-in” from across the European Commission to the Soil Deal mission: Farm to Fork Strategy, and EU Biodiversity Strategy for 2030; Climate Adaptation Strategy; New EU Forest Strategy; Long-term Vision for Rural Areas; Organic Action Plan; Common Agricultural Policy; EU’s twin green and digital transition.

With the foregoing, it is clear that the concept of ‘soil health’ is gaining momentum, and the Soil Deal mission will give visibility to soils as a crucial, yet widely ‘unrecognised’ societal asset and public good.

In 2019, ESA organized the World Soil User Consultation Meeting, with the aim to discuss the necessary steps to develop a soil monitoring system utilizing space-based EO data with in-situ data and modeling (http://worldsoils2019.esa.int/index.php). There are operational passive and active remote sensing platforms that can be applied to observe soil properties (e.g., soil organic content, clay, particle size, soil roughness, soil moisture, and many other soil attributes): from the passive optical (e.g., both multi-spectral and hyperspectral), thermal and microwave systems to the active SAR and LiDAR systems (Ben-Dor et al. 2018, CRC). Although optical remote sensing techniques for soil monitoring are available, their applications to retrieve soil properties are constrained by the mixed coverage of bare soil and vegetation, as well as the need to refine models capable of resolving the signal from such mixed pixels, since the factors affecting soil reflectance include: (high/low) vegetation, soil cover and crust, soil moisture, and atmosphere’s gases and aerosols.

Despite the above mentioned challenges, soil spectroscopy has been profoundly developed for estimating soil properties, since its cost-effective nature and its high reliability (Viscarra Rossel, et al. 2022). The new sensors of the Copernicus Programme, LSTM (6 VNIR + 5 TIR) and CHIME (spectral sampling interval <=10nm for the range 400-2500nm), are deemed particularly relevant for monitoring soil properties, thanks to their spectral coverage but also the growing availability of soil spectral library.

Terrestrial spectral libraries are important databases for the analysis of hyperspectral remote sensing information, since they provide the spectral features of a collection of soil material from different horizons with detailed metadata consisting of exact location, pedogenic characterization, and measurement protocol in both field and laboratory. The common soil attributes in SSLs are: mechanical composition (clay, silt, and sand content), organic matter, carbonate, iron oxides, hygroscopic moisture, and specific surface area (as in the LUCAS SSL and global SSL). SSL is the basis for developing proxy models for soil property quantification, classification, mapping, and monitoring, and, therefore, directly linked to the development of remote sensing technology for soil monitoring.

Microwave remote sensing products of surface soil moisture (SSM) and root zone soil moisture (RZSM) (e.g., from radiometers and scatterometers) have long been used for drought monitoring and climate studies. Nevertheless, most of microwave SSM data are at regional scales (25km) and the 'root zone' is fixed as 1m globally by model inversion. While we know in reality, root growth is a dynamic process and, consequently, the depth of root water and nutrient uptakes vary over the growing season, affecting the water/carbon use efficiency, and therefore, the drought response of plants and ecosystems. There are now a plethora of SSM products at 1km generated with machine learning algorithms (Han et al., 2023). However, the physically consistent set of SSM and RZSM are still lacking at field and plot scales for tracking the soil water stress and its impacts on ecosystem functioning. Soil physical and thermal properties can also be retrieved by assimilating microwave observation signals into a land surface model (e.g. Zhao et al., 2023).

At the timescale of multiple years to decades, the averaged VWC measurements can be used to quantify ecological dynamics related to biomass and structure at biome, continent, and global scales. For example, the disturbance (e.g., fire, extreme drought) and land use dynamics can be informed by the sensitivity of VWC to aboveground biomass. Therefore, the remote sensing of VWC, SSM/RZSM, and SIF can be used to monitor the disturbance on soil properties at these large scales. At the scale of weeks to months, the interactions between SSM/RZSM, xylem hydraulic functions, and VWC come into play, and are useful to assess the risk of drought-induced mortality and flammability risk. At this level, the VWC, SSM/RZSM, and SIF data can be used to derive regional scale soil properties. While at diel timescales, VWC, SSM/RZSM, SIF measurements reflect the coordinated responses of root, xylem, and stomatal conductance to drying soil and air, and therefore, can be used to detect water stress before it is detectable through other leaf properties. As such, the diel monitoring of VWC, SSM/RZSM, and SIF hold promise as early warning signals for drought risks, and to derive Ψ_{soil} which dominates the soil hydrological process. Capabilities in simulating the various observed signal from both passive and active microwave sensors (e.g. Zhao, et al., 2022) will enable the use of such observation in land surface models and climate simulations.

An observation system as outlined above will provide measurements of soil reflectance, SIF, LST, SSM/RZSM, and VWC across different spatiotemporal scales. It will enable process-level understanding of drought responses of agriculture and nature ecosystems, and correspondingly the soil properties across different scales. Nevertheless, deriving process understanding from soil reflectance, SIF, LST, SSM/RZSM, and VWC observations will require the establishment of a Digital Twin of Soil-Plant system. This soil-plant digital twin will facilitate the assessment of evolution and health of plants and ecosystems and their interactions with soil properties, by optimally integrating multi-wavelength satellite (future) observations, in situ measurements, analytical- and physically-based models, data assimilation as well as machine learning algorithms.

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