Potential of EnMAP spaceborne hyperspectral data for the determination of surface soil properties and spatial mapping

Prof. Dr. Sabine Chabrillat and the soil group at GFZ remote sensing sectio

GFZ - Helmholtz Center Potsdam German Research Center for Geosciences,
Head hyperspectral remote sensing applications group, Potsdam
and
LUH- Leibniz University Hannover, Institute of soil science, Hannover,
Germany

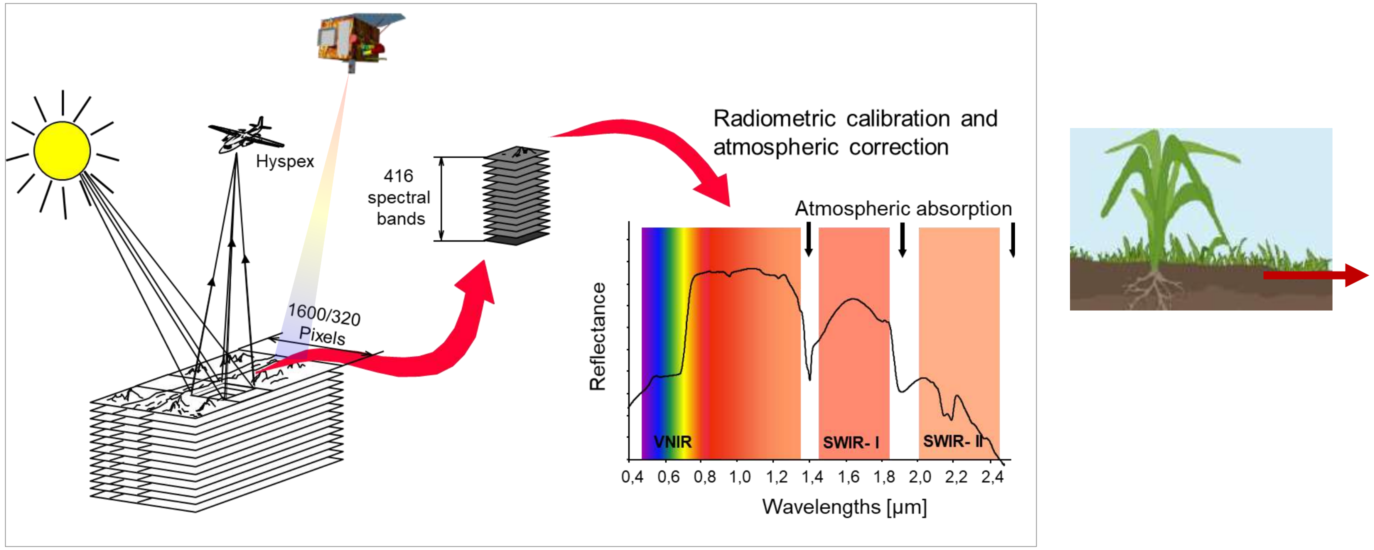
GFZ Helmholtz Centre Potsdam
Leibniz Universität Hannover

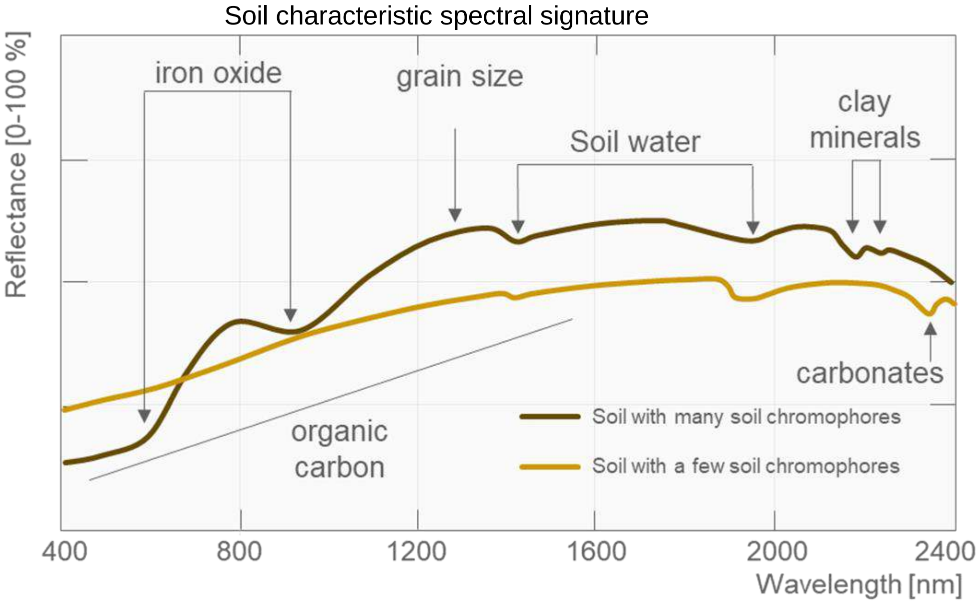
ESA Symposium on Earth Observation for Soil Protection and Restoration

HELMHOLTZ

Soil spectroscopy (Dry chemistry) from space

- Advanced optical remote sensing sensors that allow to acquire >100 narrow contiguous spectral channels (multispectral ~<10-15 spectral bands)
- Access to soil reflectance spectroscopy at remote sensing scale

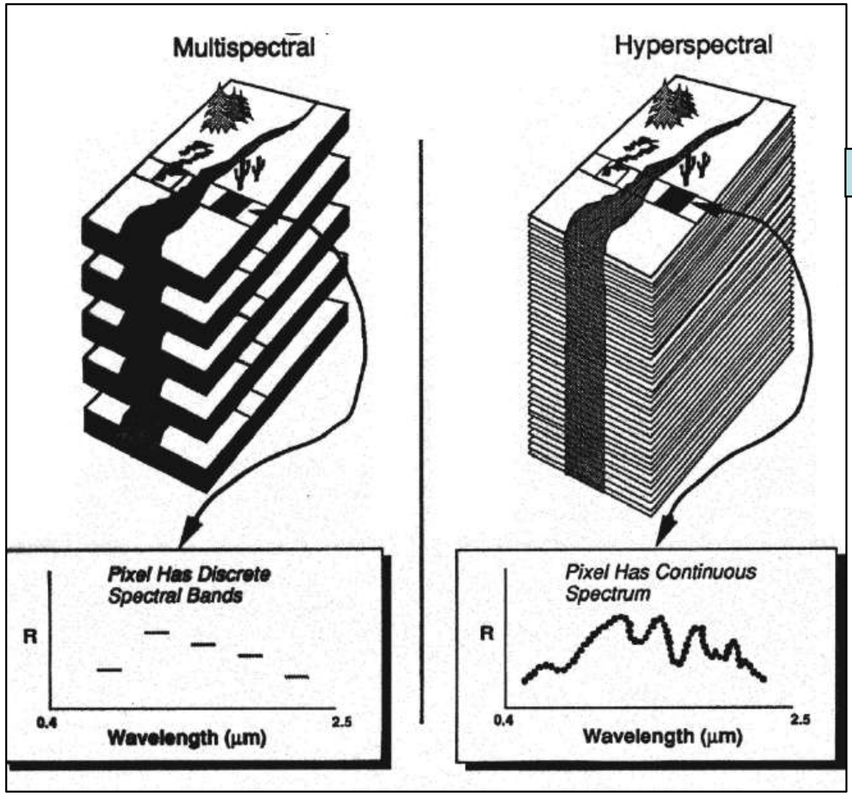




- Potential to identify constituents in Earth surface and provide **quantitative information on key biophysical and geochemical parameters (soil composition, state and type of vegetation, percent soil/vegetation surface material cover, topsoil water content, and more)**

Hyperspectral (spectroscopy) vs Multispectral (Landsat/S-2)

- Direct detection of soil constituents
- Direct detection of bare dry soil pixels, topsoil moisture, residues cover (NPV), vegetation cover (PV) based on the spectroscopy signal



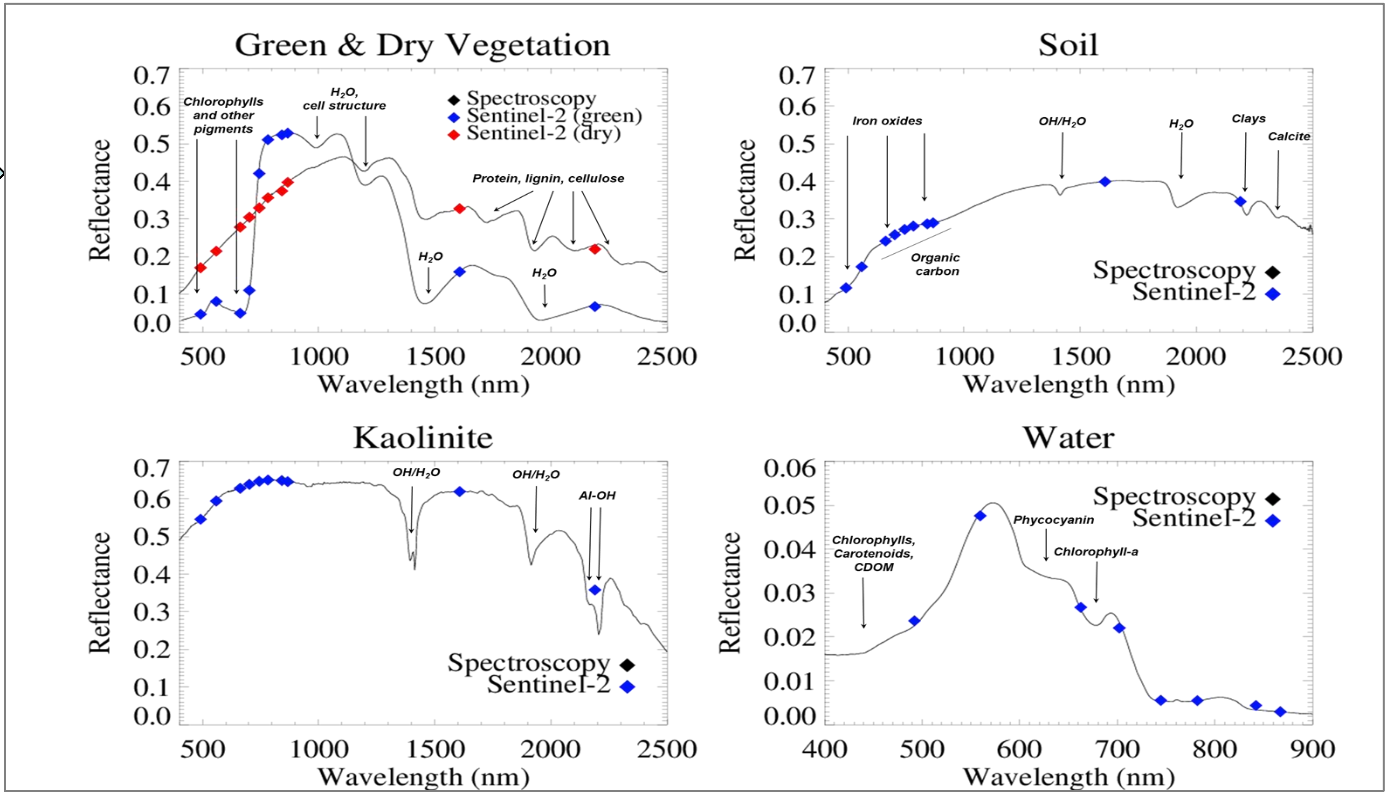


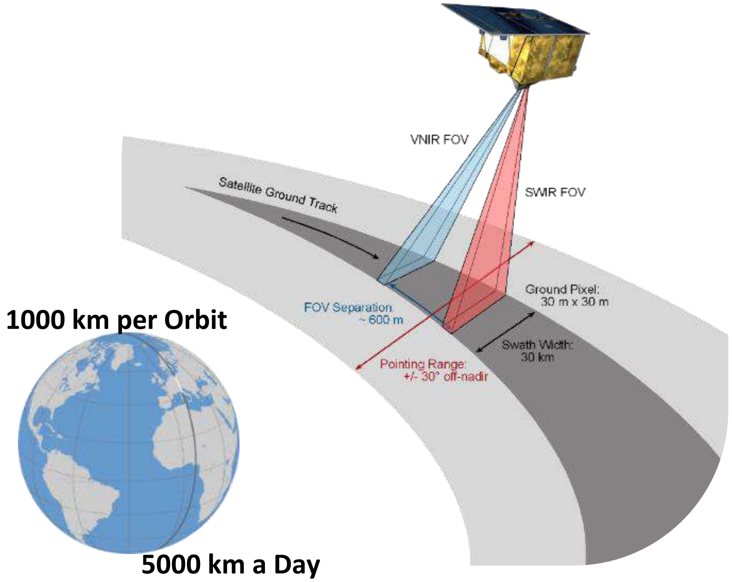
Fig. Courtesy L. Guanter (Rast & Painter, 2019, Surv Geophy)

EnMAP: A new sensor for monitoring Earth's environment

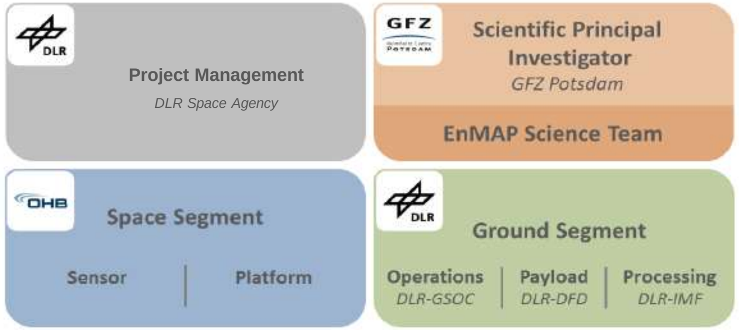
- **German hyperspectral spaceborne mission "Environmental Mapping and Analysis Program"**

- **Core parameters**: Global coverage, 30m pixel size, 225 spectral channels, revisit 27 days nadir, 4 days off-nadir pointing
  - Measurements of **key biophysical and geochemical parameters**
  - **Highly calibrated** imaging spectroscopy data
  - **Co-existence** with Sentinel-2 & Landsat-8
  - Data acquisition **on demand**

Orbit characteristics		
Orbit / Inclination	sun-synchronous / 97.96°	
Target revisit time	27 days (VZA ≤ 5°) / 4 days (VZA ≤ 30°)	
Equator crossing time	11:00 h ± 18 min (local time)	
Instrument characteristics	*VNIR*	*SWIR*
Spectral range	420 - 1000 nm	900 - 2450 nm
Number of bands	91	134
Spectral sampling interval	6.5 nm	10 nm
Spectral bandwidth (FWHM)	8.1 ± 1.0 nm	12.5 ± 1.5 nm
Signal-to-noise ratio (SNR)	>400:1 @495 nm	>170:1 @2200 nm
Spectral calibration accuracy	0.5 nm	1 nm
Ground sampling distance	30 m (at nadir; sea level)	
Swath width	30 km (field-of-view = 2.63° across track)	
Acquisition length	1000 km/orbit - 5000 km/day	

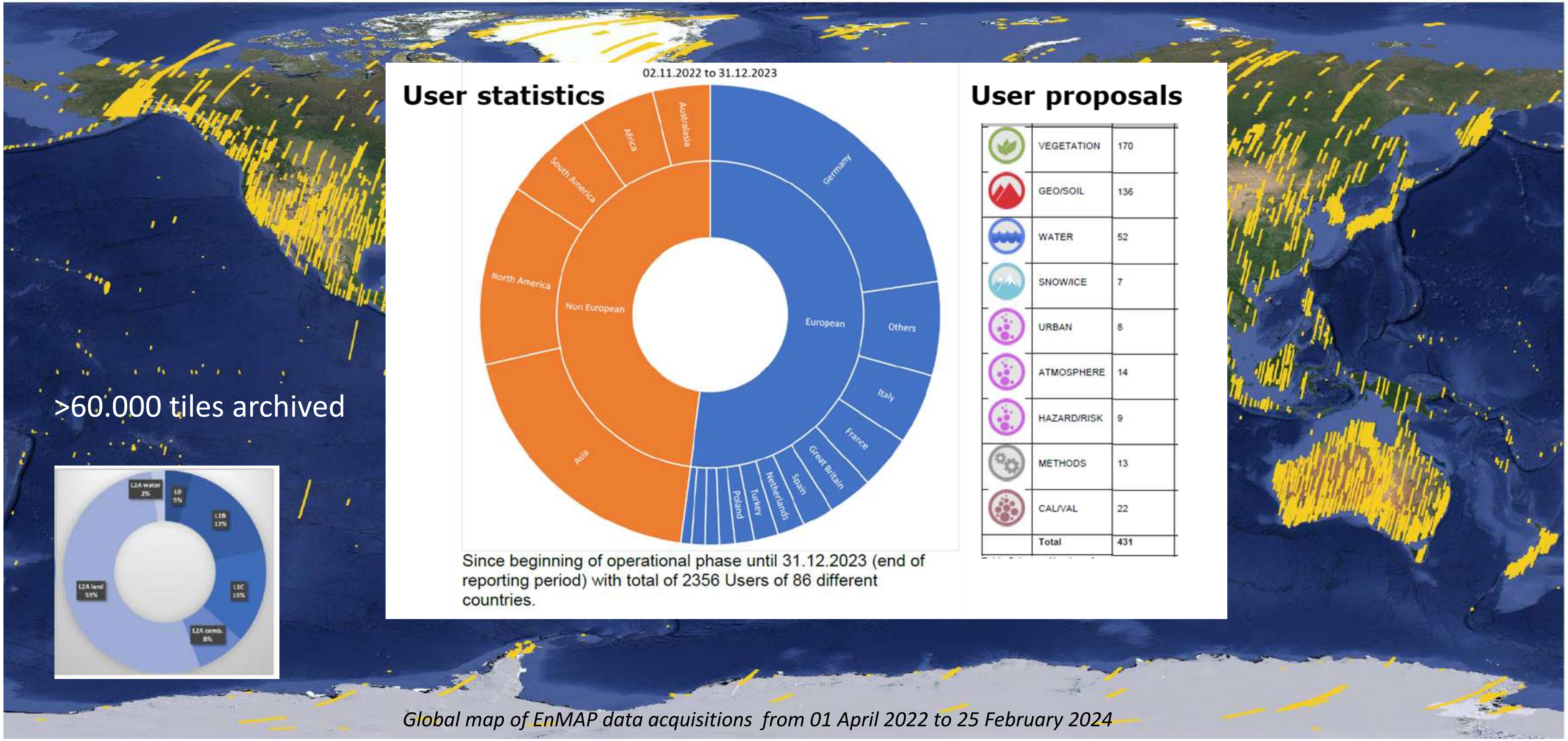


Mission consortium



- DLR Space Agency in Bonn is responsible for the overall project management
- Core funding from the German Federal Ministry of Economic Affairs and Climate Actions (BMWK)
- GFZ science PI: Extensive Scientific Exploitation preparation program, scientific mission support, user perspectives

EnMAP mission status



Since beginning of operational phase until 31.12.2023 (end of reporting period) with total of 2356 Users of 86 different countries.

User proposals

	VEGETATION	170
	GEO/SOIL	136
	WATER	52
	SNOW/ICE	7
	URBAN	8
	ATMOSPHERE	14
	HAZARD/RISK	9
	METHODS	13
	CAL/VAL	22
	Total	431

Global map of EnMAP data acquisitions from 01 April 2022 to 25 February 2024

Monitoring of soil properties: EnMAP science program

- Main research objectives
  - Demonstration of the potential of hyperspectral imagery for the delivery of soil products from airborne to spaceborne scale
  - Operational retrieval of soil properties: Develop processing chains and algorithms for the scientific exploitation of EnMAP data (L3 soil products)

- Challenges and gaps: Advances in soil properties mapping
  - Account for the disturbing factors (partial vegetation cover, soil moisture, ..)
  - Use of large-scale Soil Spectral Libraries (SSL) to develop robust multivariate calibration models
  - Contribute to the development of harmonized Soil Spectral Libraries for calibration/validation

Surveys in Geophysics (2019) 40:361–399
https://doi.org/10.1007/s10712-019-09524-0

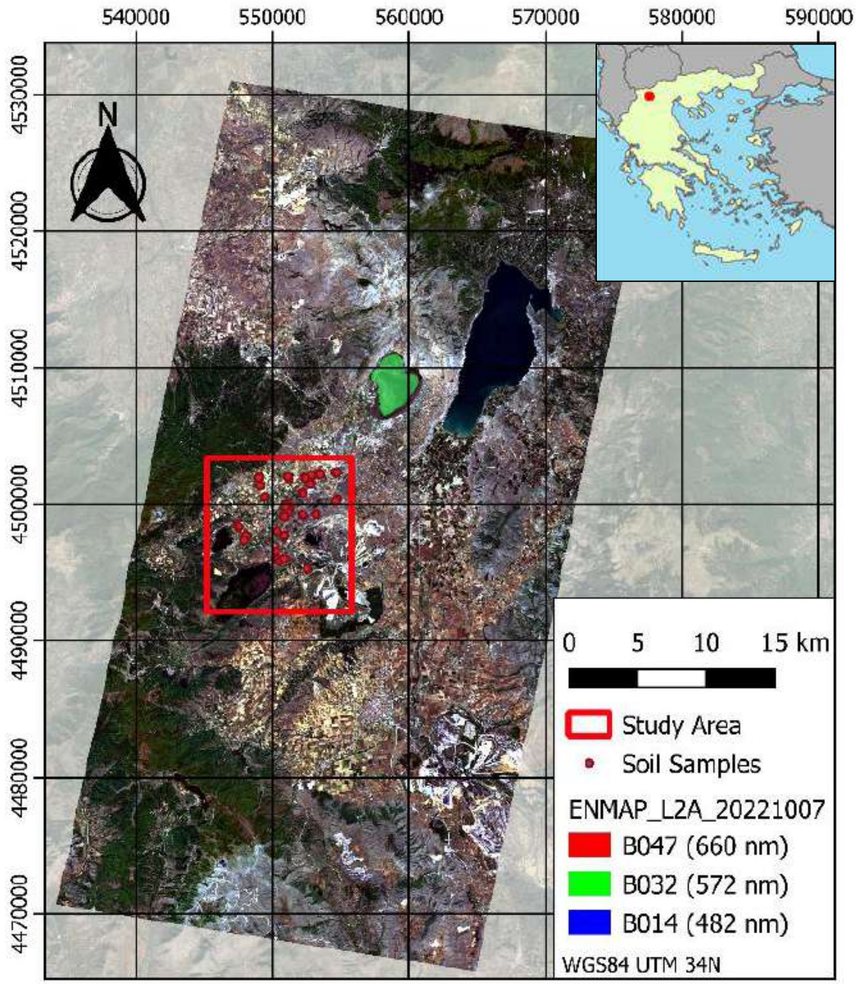
Imaging Spectroscopy for Soil Mapping and Monitoring

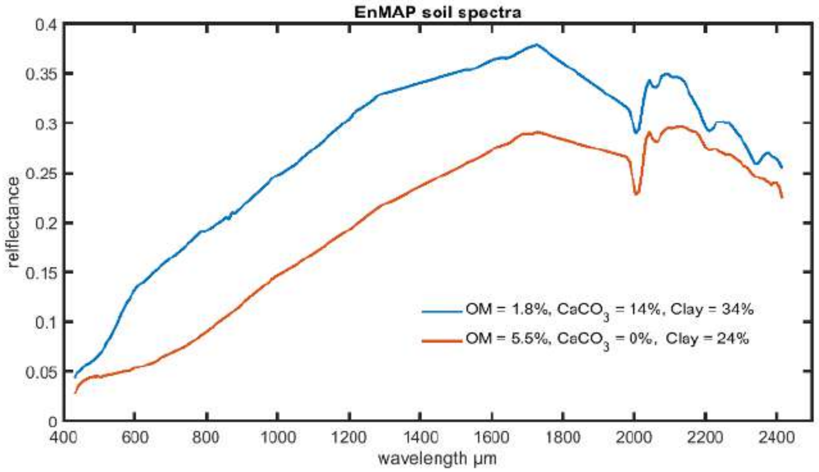
S. Chabrillat[1] · E. Ben-Dor[2] · J. Cierniewski[3] · C. Gomez[4] · T. Schmid[5] · B. van Wesemael[6]

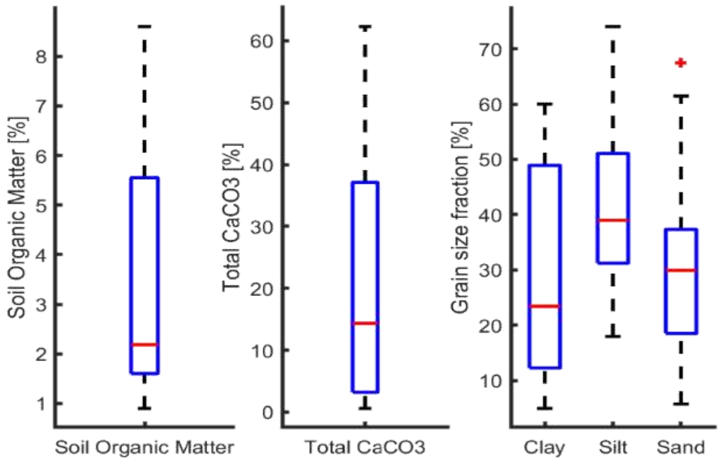
Received: 16 February 2018 / Accepted: 28 February 2019 / Published online: 20 March 2019

- Preparation/demonstration for current & upcoming spaceborne imaging spectroscopy missions (CHIME copernicus services: preparation for SOC CHIME products)

Selected Examples
Mapping soil properties from the Aminteio test site





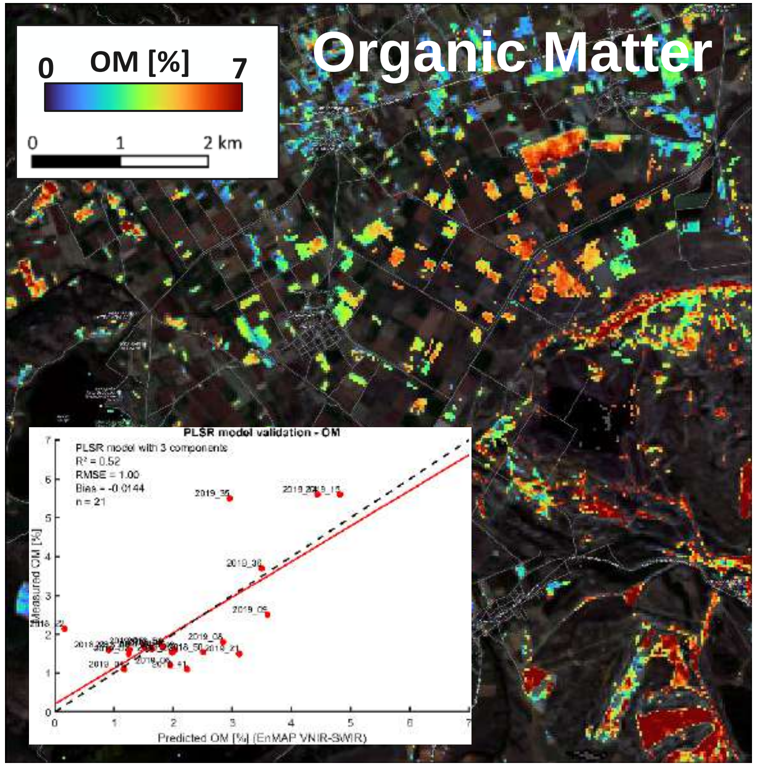


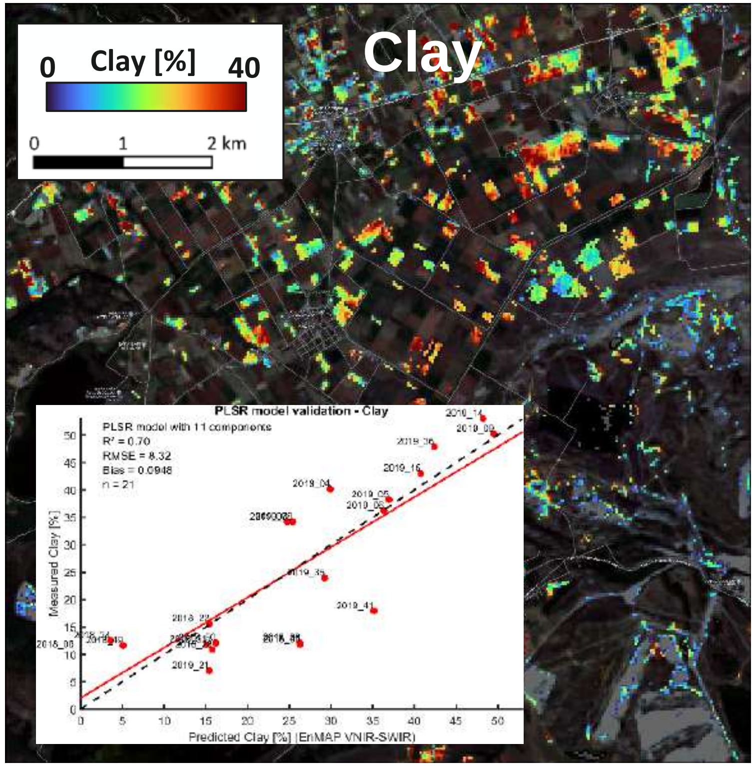
Soil variability
- Organic rich alluvial soils
- Calcite rich Regosols at piedmont
- Clay and iron-oxide rich Cambisols

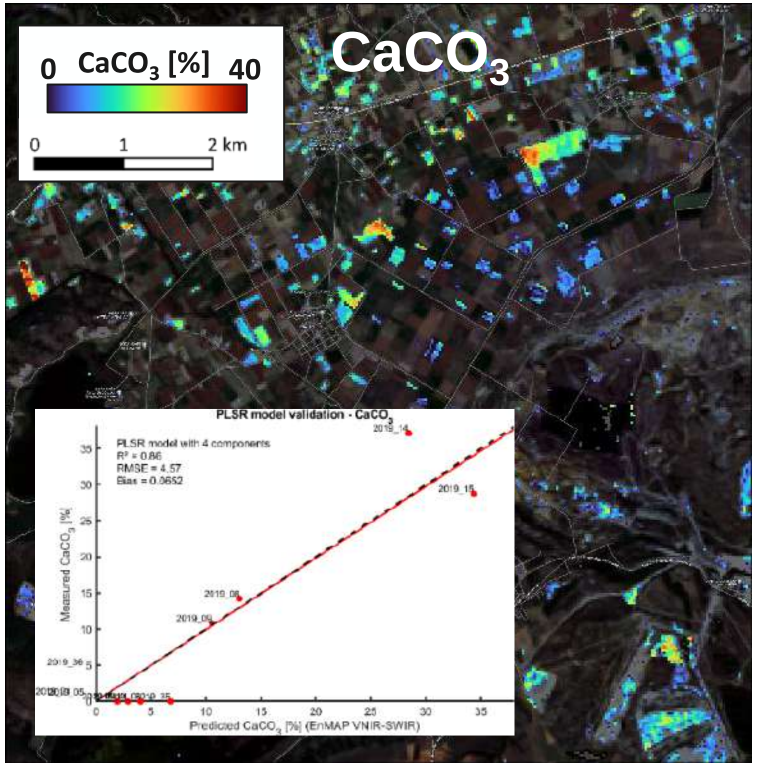
R. Milewski

Soil carbon, texture, and carbonate mapping

- EnMAP soil models (PLSR) calibrated on local datasets
- Soil organic carbon content, soil texture (clay%), and carbonates mapping
- High accuracy due to high data quality







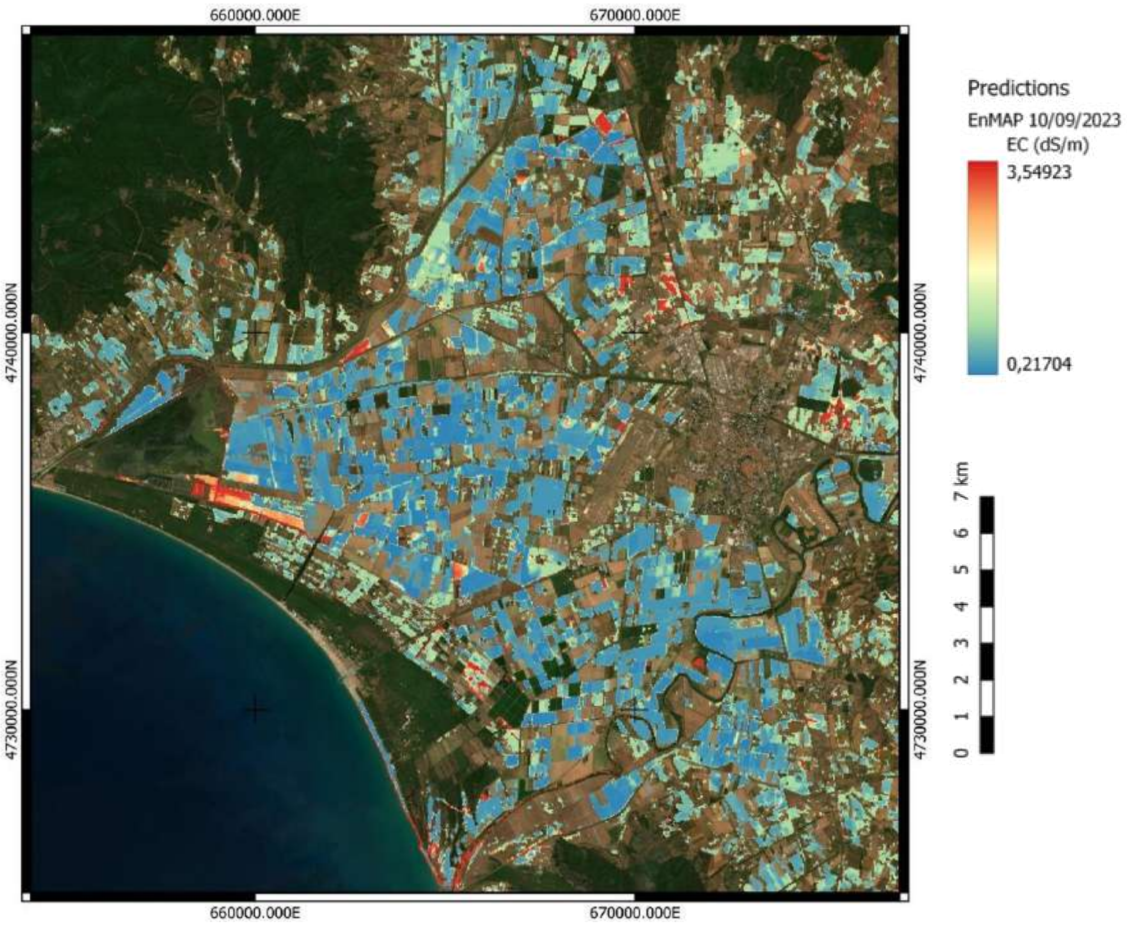
R. Milewski

Emerging salinity mapping

- Grossetto test site
- Emergent surface effluorescence after the summer
- Low EC values <10 dS/m
- Typical EO methods do not work (no abs feature, by start of salinity decrease in reflectance)
- EnMAP acquisition coincident to field acquisitions
- Use of RF model
- **Imaging spectroscopy can map appearance of salinity**

Soil salinity class	Electrical conductivity of the saturation extract, dS/m	Effect on crop plants
Non saline	0 - 2	Negligible salinity effects
Slightly saline	2 - 4	Yields of sensitive crops may be restricted
Moderately saline	4 - 8	Yields of many crops are restricted
Strongly saline	8 - 16	Only tolerant crops yield satisfactorily
Very strongly saline	> 16	Only a few very tolerant crops yield satisfactorily

Soil salinity classes and crop growth (FAO, 1988)

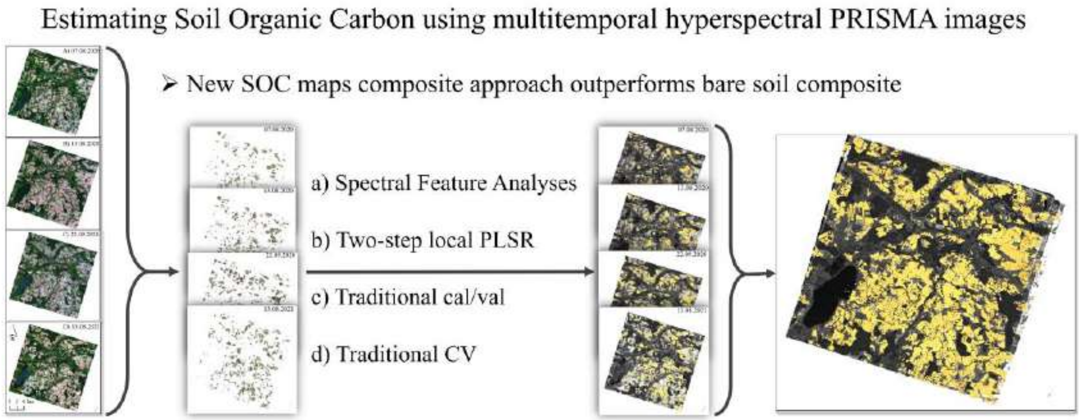


EnMAP image 10.09.2023

Slide G. Lazzeri@Univ. Florence

Soil carbon mapping - Hyperspectral temporal composites

- **Goal:** Create spatially more complete maps of soil organic carbon (SOC) using multitemporal hyperspectral images
- Demmin test site (NE Germany), high local variations in SOC content
- New and ancillary datasets (4 PRISMA images*, 183 local soil samples, LUCAS SSL)



→ Spatially more complete SOC maps
→ Using separate prediction models for each time-frame **improves accuracy**
→ **Path the way for CHIME/SBG!**

Date	Method	Validation type	RMSE	R2	RPD
Quatrotemp median spec	traditional PLSR	CV	7.75	0.60	1.58
	traditional GPR	cal/val	4.86	0.53	1.47
	two-step: local PLSR & PLSR	cal/val	4.93	0.52	1.45
	SOC1 with log(SOC)	CV	8.58	0.51	1.43
Quatrotemp median SOC	traditional PLSR	CV	5.55	0.79	2.21
	traditional x	cal/val	4.86	0.53	1.47
	two-step: local PLSR & x	cal/val	4.75	0.56	1.51
	Indices	CV	5.06	0.83	2.42

Approach using median SOC outperforms median spectra

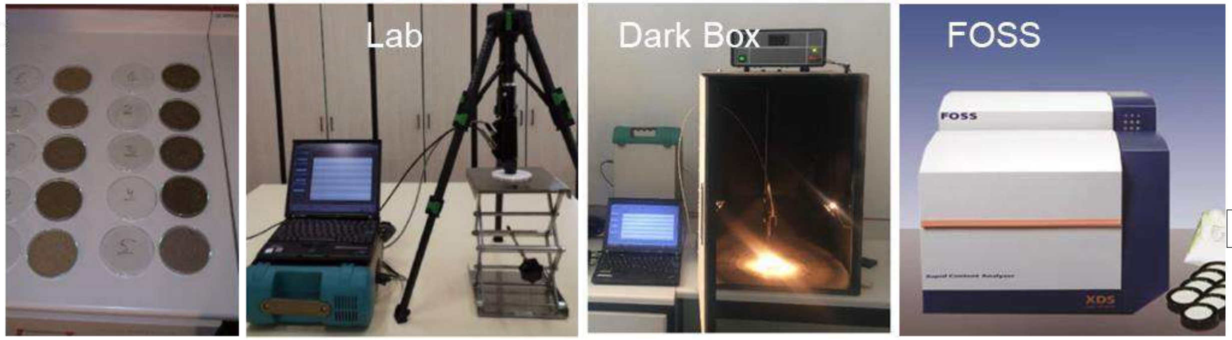
Ward et al., 2024, in review

* Thanks to Ettore Lopinto, Giovanni Rum and Marco Celesti for the provision of PRISMA imagery for HYPERSENSE sites

Impact of surface conditions

- From soil spectral libraries to satellite observation

Typical case in soil science: Soil spectral libraries



CZU GFZ UCL/Requasud

Photos@ GFZ, CIEMAT, CSIRO

Samples dried and sieved 2mm
Standardised stable illumination and lab conditions
Lab sensors eg. FOSS lab spectrometer (LUCAS)

Natural top-soil conditions & mixing in the FOV
Uncontrolled atm & illumination
EO sensors lower performance than lab

Goal

- Assessing the effects of applying laboratory spectral models to the EO scale taking into account the effect of mixed pixels in a realistic landscape
- Assessment of the impact of the disturbance effects on the SOC modelling

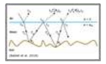
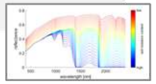
Impact of surface conditions

- Development of a Spatially Upscale Soil Spectral Library (SUSSL)
  - Simulation of “landscape-like” reflectance spectra based on LUCAS SSL + convolution to EO sensors + SOC modeling on the original and degraded soil spectral library

Disturbance effects	Mixing steps	Modelling principle
Early green crops	10, 20, 30	Virtual 3D soil / plant landscape scenarios modeling sampled by Monte-Carlo ray-tracing technique (HySimCaR, Kuester et al. 2014)
Crop dry residues	10, 20, 30	
Forest/Trees	10, 20, 30	Linear mixing with tree spectrum (*pinus ponderosa*) to simulate pixels at agricultural field borders and individual trees within crops
Soil roughness (microtopography)	10, 20, 30	Linear mixing with shadow reflectance using MODTRAN diffuse sky irradiance to simulate shaded soils
Soil moisture	very low, low, medium	Physically based simulation of soil moisture levels using the MARMIT 2.0 model (Bablet et al. 2018)





Generation of spatially upscaled SSL (SUSSL) databases at 1 nm spectral resolution

Baseline SOC model: CNN applied to LUCAS 2015 SSL (validation) samples

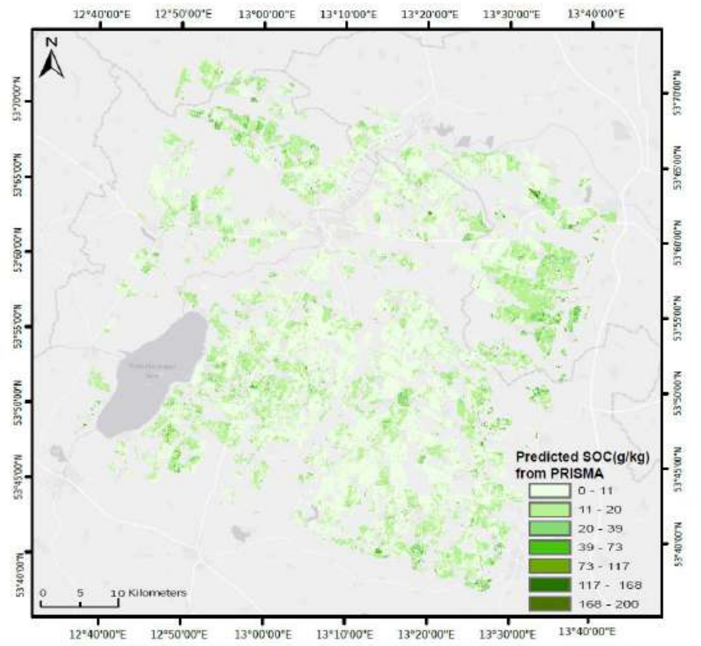
CHIME	Sentinel-2
R^2 : 0.75 RPD : 2.00 RMSE: 6.57	R^2 : 0.41 RPD : 1.30 RMSE: 10.16

- Results
  - The disturbance factors are an **essential factor of decrease** in the SOC prediction accuracy
  - After selection of bare soil pixels, a **high increase in the SOC modelling performance** is observed that brings the model errors close to the non-degraded SSL when applying strict thresholds
  - CHIME (hyperspectral) is **more performant** than Sentinel-2 (multispectral)

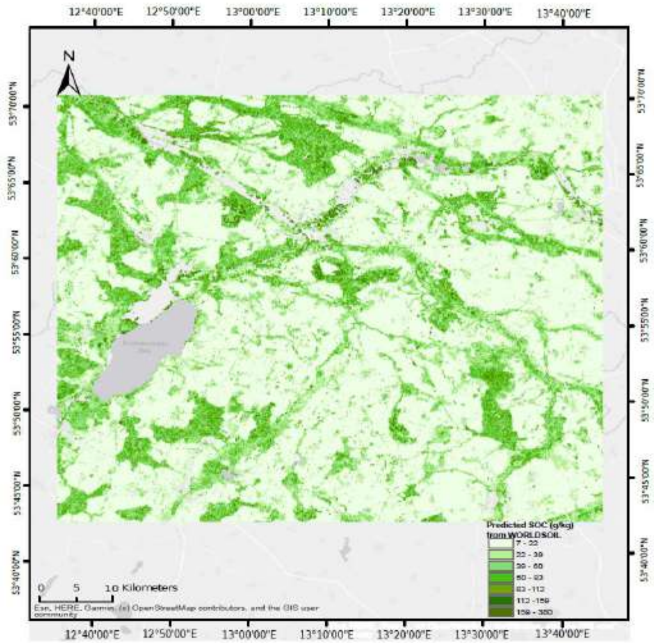
Validation of remote sensing soil maps: Validation concept and test Demmin site

- Development of the validation concept
- Trial (demonstration site) with local test site Demmin and local soil cal/val data set
  - Pixel-wise comparison with independent EO soil products
  - External soil data set: Sampling performed specific for validation of EO products

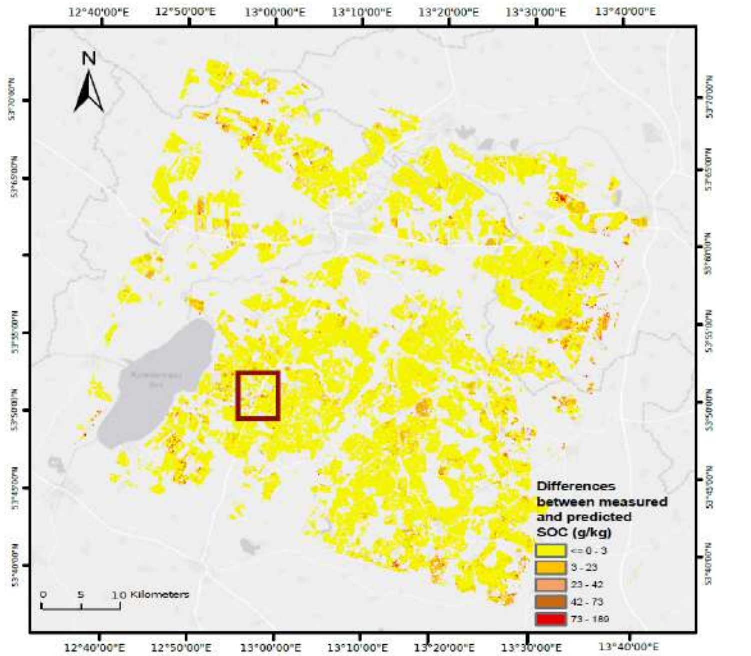
PRISMA prediction 30m resampled 50m



S2 Worldsoil prediction 50 m 2018-2020

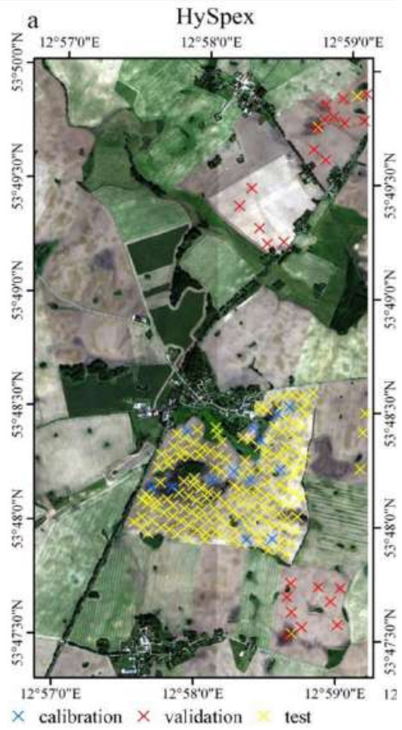


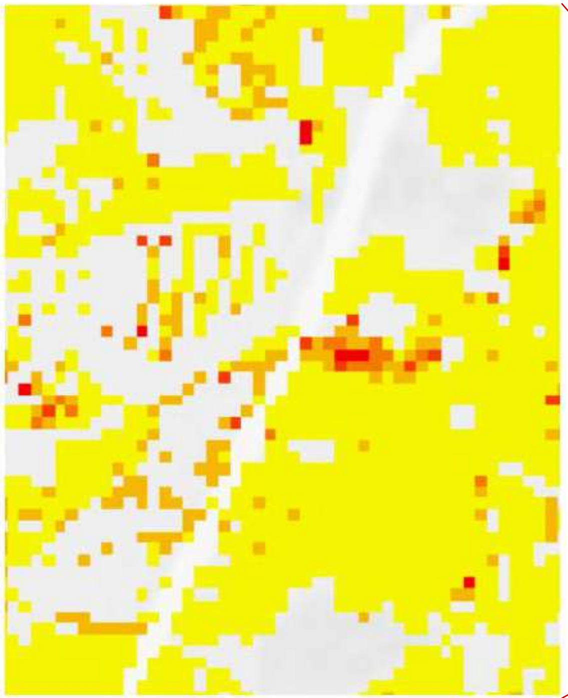
Difference map (in the bare soil areas)



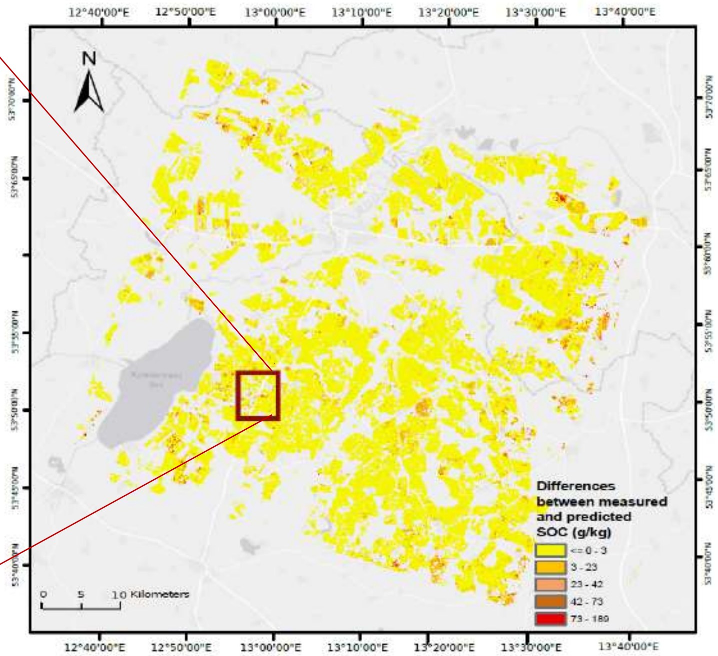
Validation of remote sensing soil maps: Validation concept and test Demmin site

- Development of the validation concept
- Trial (demonstration site) with local test site Demmin and local soil cal/val data set
  - **Pixel-wise comparison** with independent EO soil products
  - **External soil data set**: Sampling performed specifically for validation of EO products



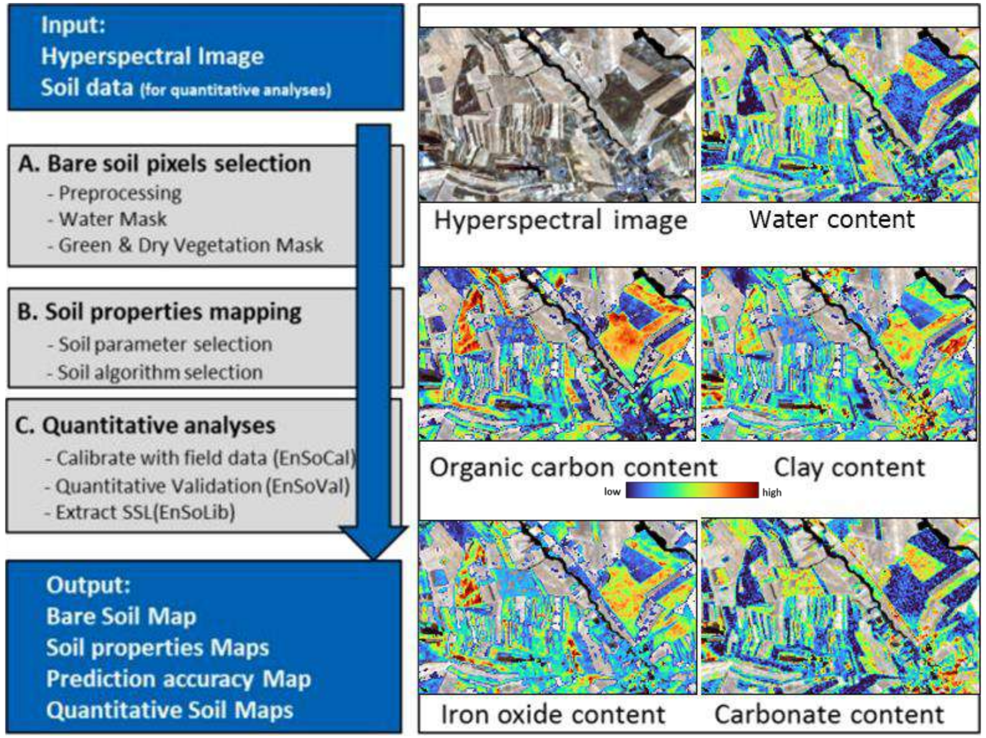


Difference map (in the bare soil areas) between PRISMA and S2 Worldsoil



Operational retrieval algorithms: HYSOMA/EnSoMAP
From EnMAP reflectance products L2A → Topsoil properties maps

- Development of HYSOMA/EnSoMAP 2.0 (EnMAP Soil Mapper) operational soil toolboxes for end-to-end processing chains with harmonized quality measures
  - Automatic selection of **bare dry pixels**
  - **Automatic generation of semi-quantitative soil maps** (Soil moisture content, organic carbon content, iron oxides, clays, carbonates, gypsum content) + quality layer map
  - **Fully quantitative soil mapping** using in-situ data for model calibration
- Implemented as QGIS tool within EnMAP-Box 3
- Further developments
  - Hysoma/EnSoMAP 3.0 toward PLSR/ML algorithms

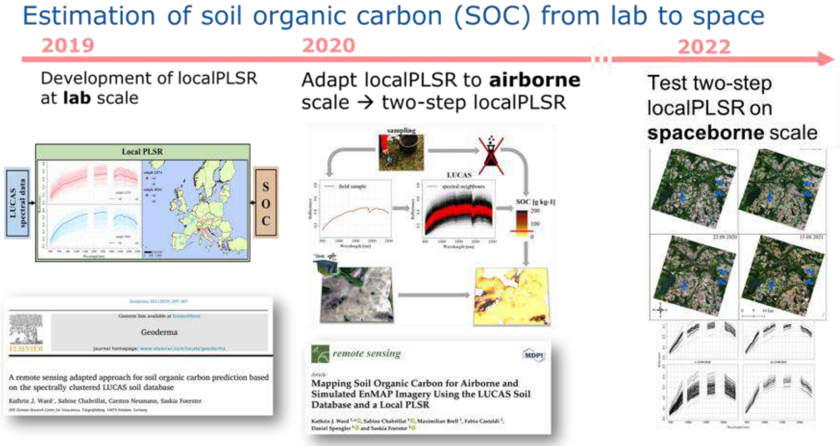


Example Camarena test site, Spain, EnMAP imagery 03.08.2022

Toolbox download:
www.enmap.org/enmapbox.html

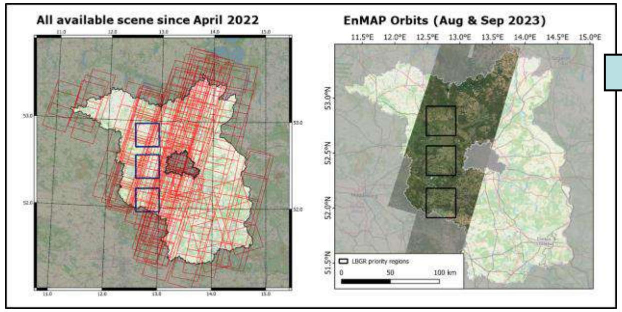
Retrieval algorithms: Regional modeling (local PLSR), ML workflow algorithms

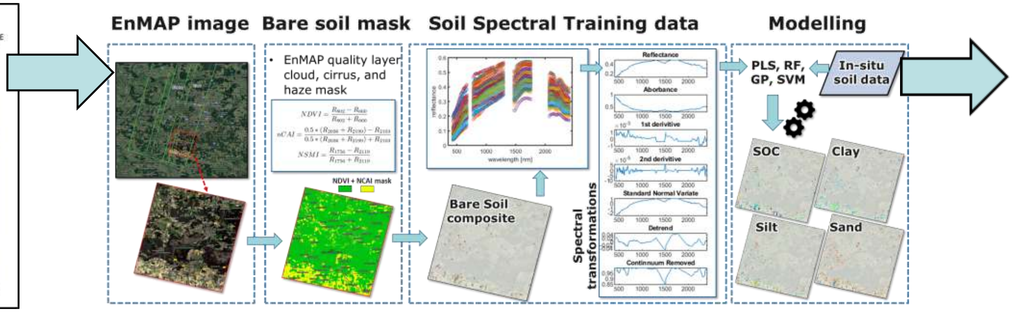
- Development of new methods (local PLSR) for soil spectral modeling using large soil databases (LUCAS) and spectral neighboring: Spectrally local/regional modeling

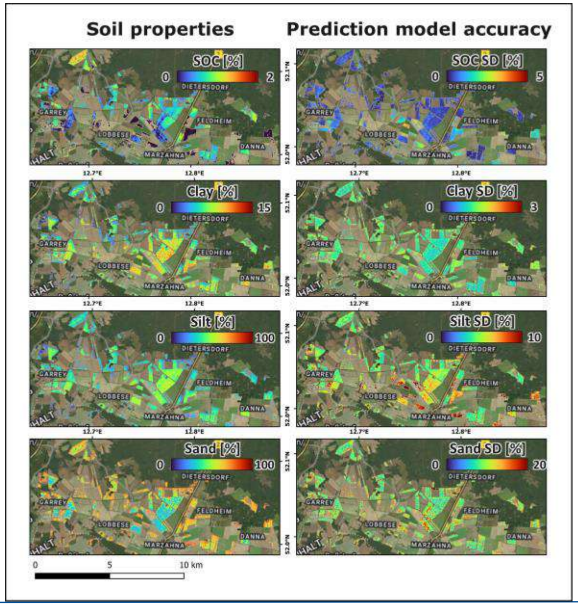


Ward et al., 2024, in review

- Development of an automatic workflow from the images to the soil maps to compute large areas soil maps with best pre-processing and best modeling performances

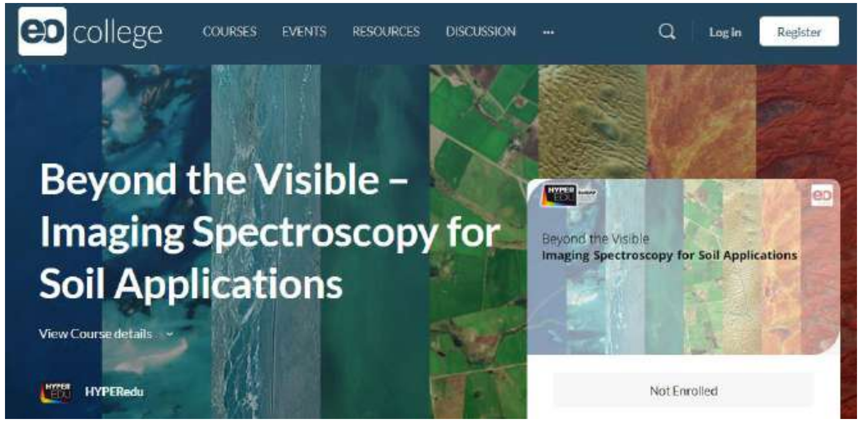


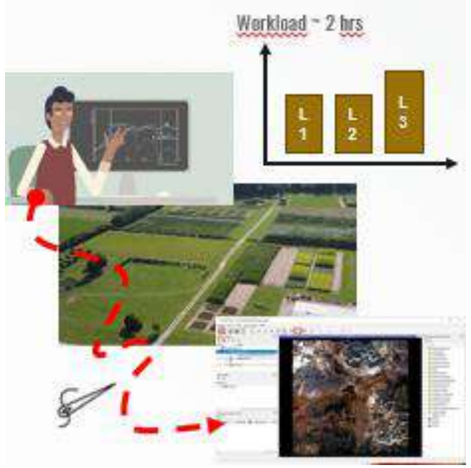


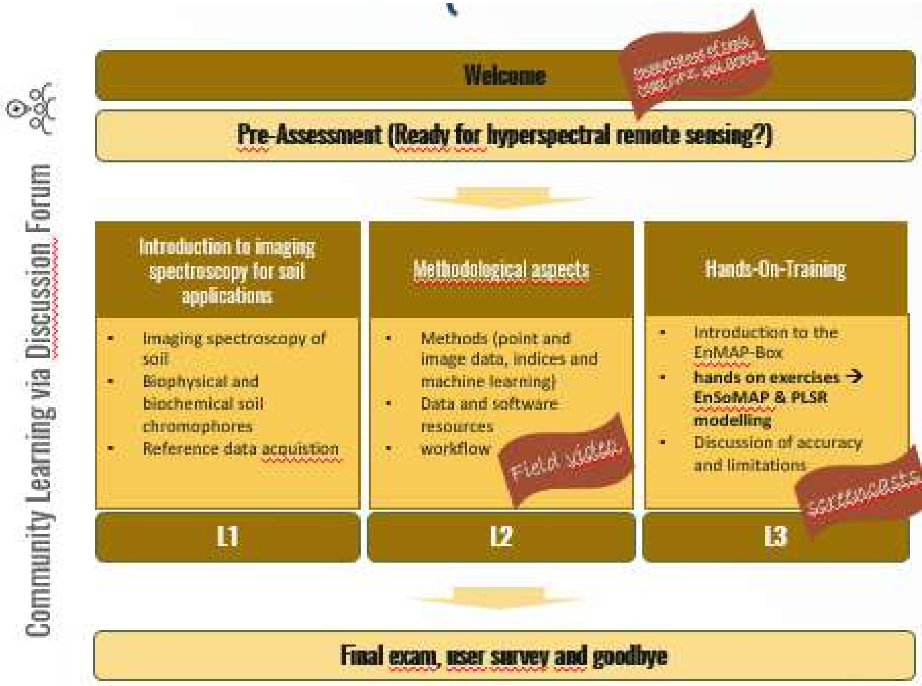


Milewski et al., 2024

Capacity building: HYPERedu the EnMAP education initiative
New mini-MOOC on soil







- Filming days at beginning of Mai 2023

- Texts, (interactive) graphics, quizzes
- **Field video and screencasts**
- Reference to other MOOCs
- **2 hands-on tutorials**
- Final assignment (certificate)
- Lots of resources
- Offline course document (PDF)

https://eo-college.org/courses/beyond-the-visible-imaging-spectroscopy-for-soil-applications/ → Course release March 2024

Summary

- EnMAP after ~1.5y in operational phase
  - >2,400 users, > 460 user proposals, the mission is a success
  - Data quality exceeds requirements
  - EnMAP contribution to science fields and Copernicus services: Spaceborne hyperspectral remote sensing holds large potential for soil mapping and monitoring
    - Focus on key parameters linked to soil health and soil erosion/degradation indicators
    - Support timely delivery of soil products and integration into soil mission

- Toward global soil mapping and monitoring: Capacity of new generation imaging spectroscopy satellite sensors
  - Major advances in methodologies and data availability were achieved
  - Nevertheless, challenges to be addressed before realizing full potential (E.g. corrections for surface disturbances, modeling accuracy, global soil databases for cal/val – soil+spectral data – , standard practices)

Thank you for your attention !

chabri@gfz-potsdam.de

ESA Symposium on Earth Observation for Soil Protection and Restoration