Environmental Mapping and Analysis Program

Mission overview and applications

The EnMAP Satellite Mission

What is EnMAP?

Goals of the satellite mission

EnMAP (Environmental Mapping and Analysis Program) is a German Earth observation satellite, launched in April 2022, that uses imaging spectroscopy to diagnostically characterize the Earth's surface and record environmental changes.

Imaging spectroscopy or hyperspectral imaging is an innovativ remote sensing technology used to record image data in many narrow contiguous bands. The spectral range extends far beyond the visible light and include near and shortwave infrared wavelengths. Each individual pixel of the resulting hyperspectral image contains a continuous spectrum of the solar radiation, reflected by the surface and the atmosphere. These spectra include absorption features, which can be interpreted as "spectral fingerprints" of Earth surface materials. They may be exploited to characterize minerals in rocks and soils, analyze vegetation types and condiditions and identify substances in water (Fig. 1). EnMAP's hyperspectral measurements will provide valuable information to address key scientific questions for a range of applications such as agriculture and forestry, ecosystem compositions and dynamics, geology and soils, coastal and inland waters, and the cryosphere.

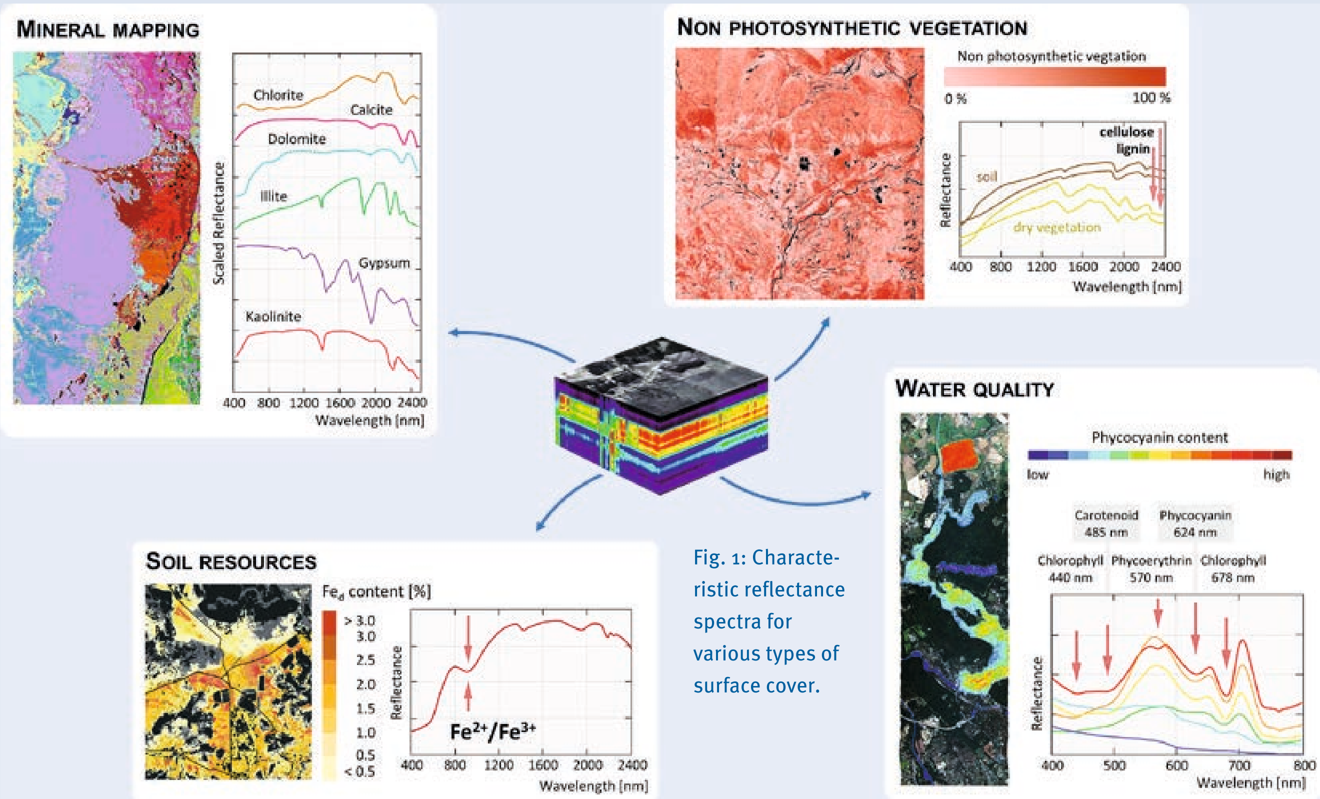


Fig. 1: Characteristic reflectance spectra for various types of surface cover.

Orbit characteristics

Orbit characteristics		
Orbit / Inclination	sun-synchronous / 97.96°	
Target revisit time	27 days (Viewing Zenith Angle ≤ 5°) / 4 days (Viewing Zenith Angle ≤ 30°)	
Equator crossing time	11:00 h ± 18 min (local time)	
Instrument characteristics	*VNIR (visible / near infrared)*	*SWIR (shortwave infrared)*
Spectral range	420 - 1000 nm	900 - 2450 nm
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	

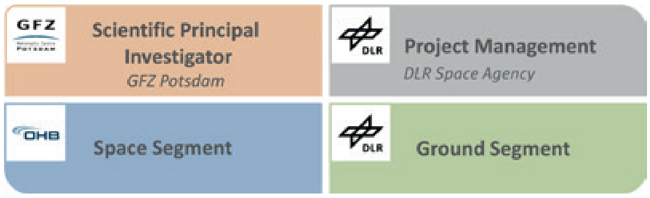


Fig. 2: Schematic overview of the project organization.

The satellite mission is managed by the German Space Agency, DLR Bonn, with funding from the Federal Ministry of Economic Affairs and Climate Action (BMWK). The German Centre for Geosciences (GFZ) in Potsdam is responsible for the scientific management of the mission, supported by a Science Advisory Group (EnSAG). OHB System AG in Bremen and Oberpfaffenhofen was responsible for developing the EnMAP instrument and building the associated satellite platform. The ground segment is operated by DLR. Specifically the satellite operation is managed by the German Space Operations Center and data processing and provision is done by the German Remote Sensing Data Center and the DLR Remote Sensing Technology Institute (Fig. 2).

Characteristics of the EnMAP mission

The core of the EnMAP satellite is the hyperspectral instrument that records the sunlight reflected from the Earth at wavelengths between 420 nm and 2450 nm in 246 adjacent spectral bands with a spatial resolution of 30 m. EnMAP's revisit time for any site on Earth except the pole regions is 27 days in nadir-view, or every four days with its across-track pointing capability (Fig. 3).

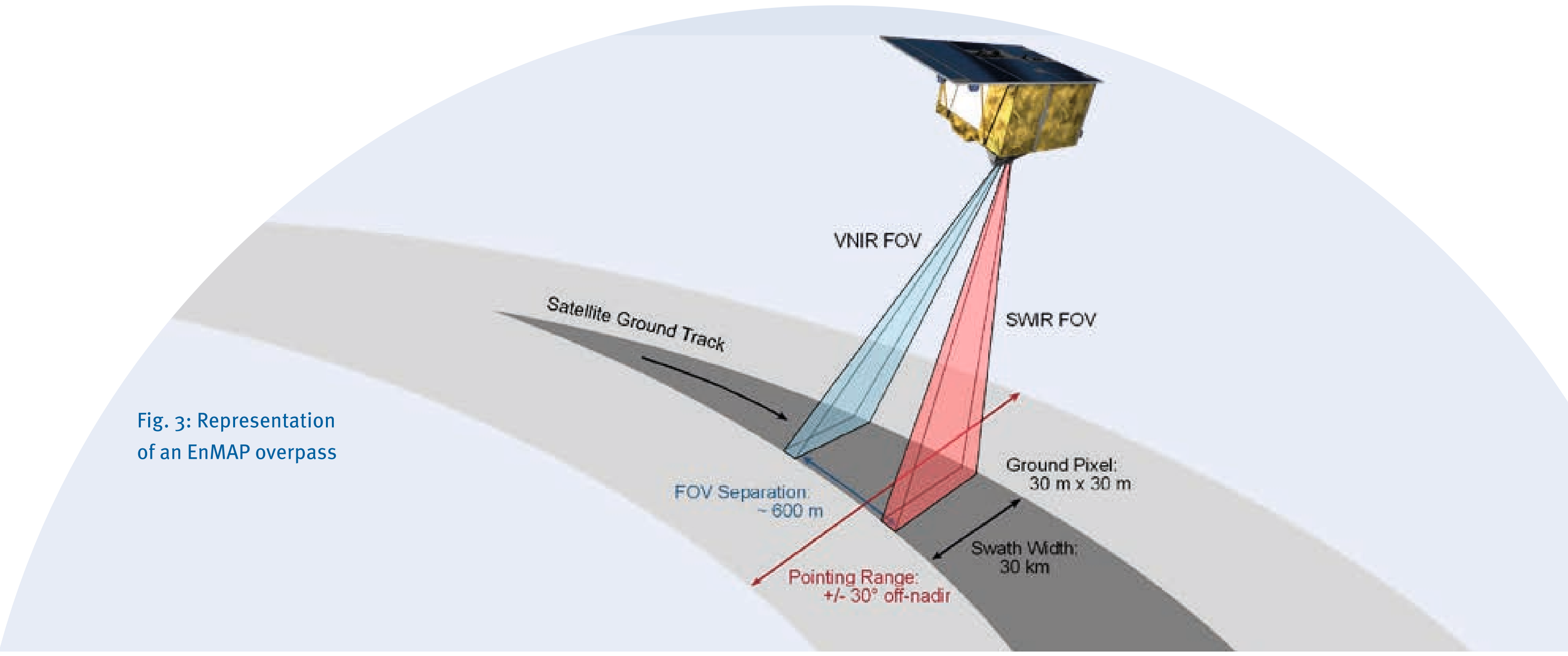


Fig. 3: Representation of an EnMAP overpass

Scientific preparation and support of the EnMAP mission

A special feature of the EnMAP mission is the intensive scientific preparation, which includes the development of hyperspectral data analysis software, an online teaching platform for hyperspectral remote sensing and the implementation of workshops and training courses. The goal is to enable the user community to effectively use the data to address a wide range of scientific questions and derive thematic information products. For example, processing algorithms are freely available in the EnMAP-Box, a software package developed specifically for processing hyperspectral data. Before EnMAP was launched, algorithms were developed and tested on images from airborne platforms. In the online teaching platform HYPERedu, teaching materials and courses are offered to students and teachers as well as professionals in science, government authorities and companies. In addition, summer schools and workshops are organized for training and networking for the user community (Fig. 4). In line with EnMAP‘s open data policy, not only the EnMAP satellite data but also the open source software, data from airborne campaigns and online training materials are provided free of charge.

Fig. 4: Impressions from past EnMAP schools with networking activities (top right), field measurements exercises (top left) and group picture taken during a demonstration of the airborne imaging spectrometer AVIS-3, which was employed in EnMAP preparatory flight campaigns (bottom).

Why do we need EnMAP?

Changes in our environment pose global challenges

Humankind is confronted with fundamental challenges in the 21st century. The most pressing include a sustainable and global management of land use, the adaption to climate change, combating progressive environmental destruction, and the responsible use of natural resources. These complex and interrelated aspects have to be monitored, quantified and understood in order to cope with the growing pressures on society and the environment.

Imaging spectroscopy can improve our understanding of the risks and consequences of environmental change. This technology is valuable for quantifying and modeling a wide range of surface processes. The growing availability of high-quality hyperspectral images contributes significantly to the knowledge of complex processes and feedback mechanisms of the Earth System. EnMAP's ability to record the Earth's surface at regular intervals and at high spatial and spectral resolution provides new possibilities to study the condition of ecosystems. These include the characteristics and composition of vegetation, soil and water as well as the ability to predict future changes. EnMAP contributes significantly to addressing environmental problems leading to improved concepts for the long-term management of land and other natural resources.

EnMAP a milestone in imaging spectroscopy

The development and use of imaging spectrometers for remote sensing has increased over the last three decades. Until recently, advanced imaging spectrometers have been used primarily on airborne platforms for scientific, experimental and commercial purposes. However, airborne instruments do have important disadvantages compared to instruments on satellites. They can record only a limited area on the ground and cannot provide regular or global scale measurements of surface processes. In addition, airborne data require a more elaborate correction, and repeated acquisitions of the same area are expensive (Fig. 5).

Current optical satellite instruments are predominantly multispectral that measure in individual, comparatively broad wavelength ranges and thus primarily provide qualitative information on the composition of the Earth's surface. Imaging spectrometers, however, enable diagnostic quantitative analysis of surface materials for a wide range of applications. In this context, the launch of the EnMAP satellite in 2022 represents a milestone in optical remote sensing technology and imaging spectroscopy that paves the way for an improved understanding of the processes taking place in our environment.

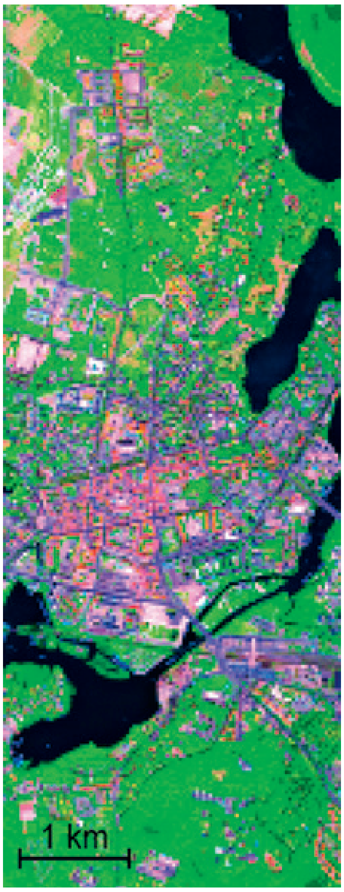


Fig. 5: Simulated EnMAP image of the city and surroundings of Potsdam, Germany, showing various urban, agricultural, managed forest and aquatic ecosystems. The simulation is based on airborne hyperspectral image data (HyMap). EnMAP will allow a more frequent coverage of larger areas than feasible in airborne campaigns.

What applications are possible with EnMAP?

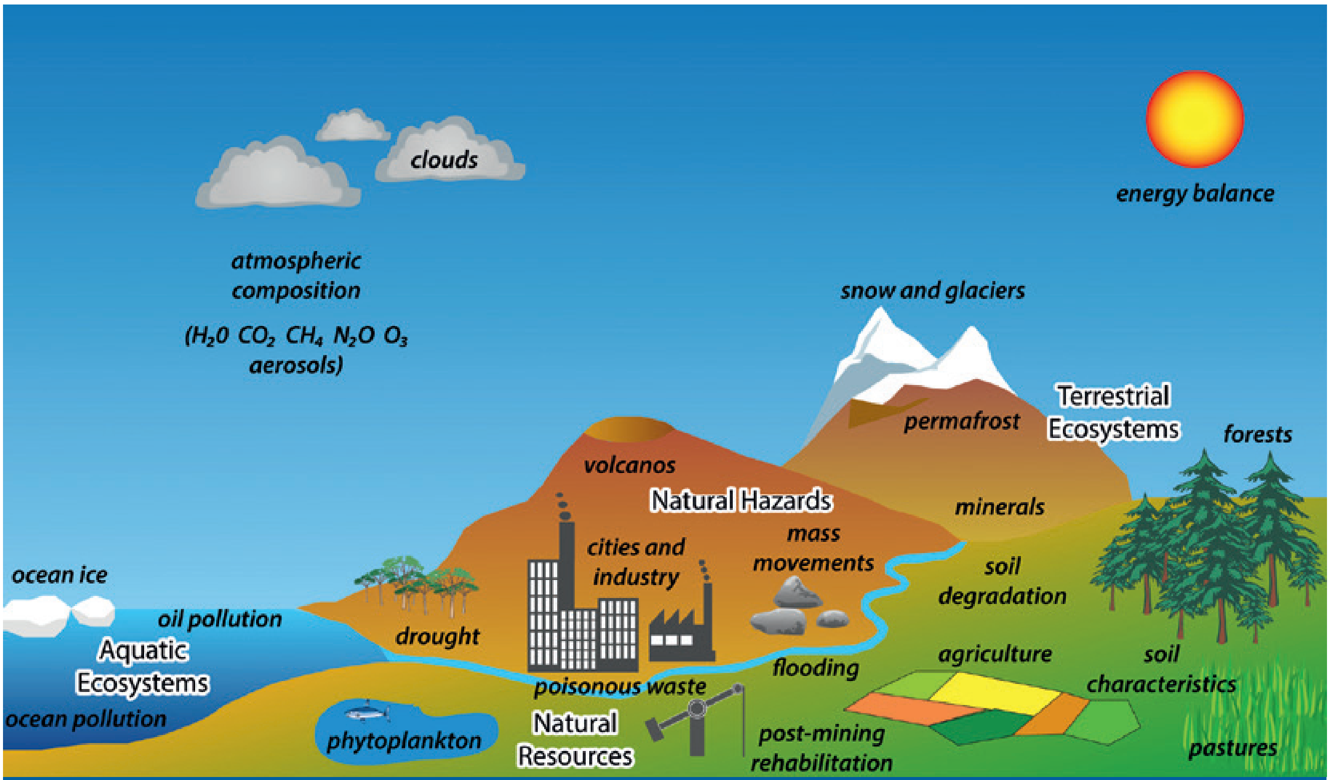


Fig. 6: Principal application fields for EnMAP.

New horizons in ecosystem research and in resource and disaster management

EnMAP's repeated observations and advanced spectral range and resolution will open up new horizons in ecosystem research, in resource exploration and in disaster management. It is expected that EnMAP will make significant contributions to the following scientific questions.

Climate Change Impact and Interventions

- How does climate change affect the functioning, composition and phenology of terrestrial and aquatic ecosystems?
- What interventions can effectively combat climate change and how can their implementation be monitored?

Land cover changes and surface processes

- What is the spatial distribution and extent of land degradation and land use/land cover change?
- What processes drive land degradation and how efficient are interventions?
- How does land degradation and land use/land cover change impact food security and environmental sustainability?

Biodiversity and ecosystem processes

- How do ecosystems change in their composition, spatial distribution and health?
- To what extent does ecosystem change affect the loss of biodiversity and the migration of species?
- How successful are measures to achieve ecosystem stability and to combat biodiversity loss?

Water availability and quality

- What areas are affected by water scarcity and poor water quality?
- How do climate change and human activities reinforce water scarcity and water quality problems?

Natural resources

- How can natural resources, such as mineral deposits, soils, energy sources and ground water sources, be explored and managed in a sustainable way?
- What impact does industry, mining and agriculture have on natural resources?
- What is the degree and extent of environmental damage from natural resource extraction and to what extent is the damage being restored?

Hazard and risk assessment

- What regions are most vulnerable to natural and man-made hazards?
- In the case of a natural or man-made disaster, what areas are most affected?

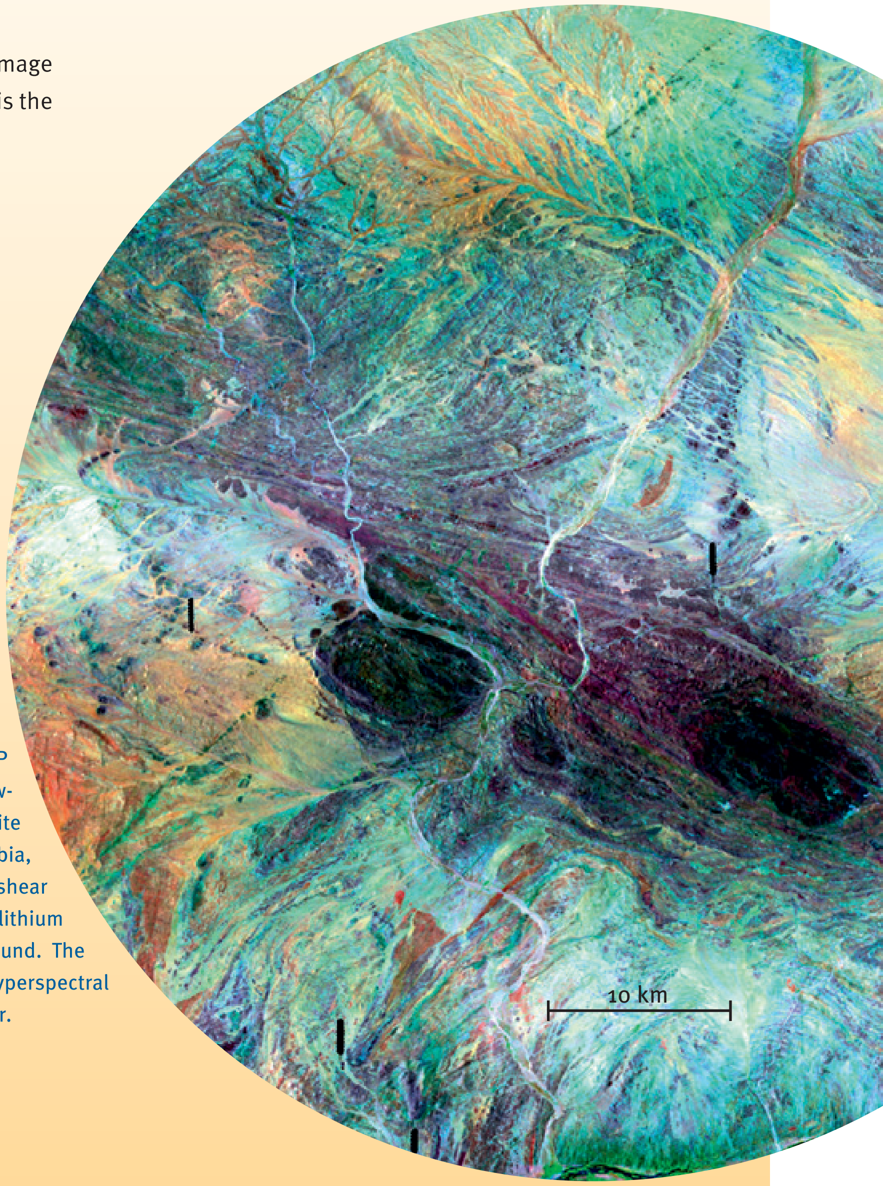


Fig. 7: Section of a simulated EnMAP image (false color composite) showing a section of the Poffadder Tantalite Valley Shear Zone, South Namibia, where the Hom River crosses the shear zone (at image center) and where lithium and rare earth elements can be found. The simulation is based on an airborne hyperspectral image mosaic from the HyMap sensor.

EnMAP as a valued agricultural engineer

On the path to sustainable agriculture

Agricultural production, as a source of food and biomass, is of great importance considering the continuous growth of the world population. Recent projections by the United Nations suggest more than 11 billion people will depend on the supply of agricultural goods by 2100. This growth in demand has been met by marginal increases in agricultural areas over the past centuries. Approximately 1.5 billion ha of continental land meet the climatic, topographic and soil-forming criteria that enable arable farming, far below what will be necessary to meet growing demand. Instead of increasing the amount of arable land, a promising solution is to increase agricultural production to optimize farming practices through improved management. Improving cultivation, fertilization, crop-protection and irrigation strategies can increase production while simultaneously reducing resource requirements. This gain in efficiency, often referred to as precision agriculture, is increasingly applied in the agricultural sector. In precision agriculture, land is managed on a small, site-specifi scale. The development of site-specific management strategies relies on current, spatial information on the growth status of the plants. Remote Sensing is the only method capable of providing spatial information on crop status in a comprehensive and nondestructive way.

Agricultural information systems are designed by combining remote sensing information with computational modeling.They support farmers in management decisions by providing continuous, spatial information. Management strategies may be adapted in a timely and area-specific manner preventing or reducing crop failures, through early detection of nutrient deficiency, water stress or pest infestation. A major challenge of precision agriculture is the retrieval of the desired information from remote sensing data. Multispectral Earth observation sensors are used to retrieve structural measurements, e.g., photosynthetically active leaf area. The results that have been obtained by these conventional sensors are limited due to their comparatively coarse spectral sampling.

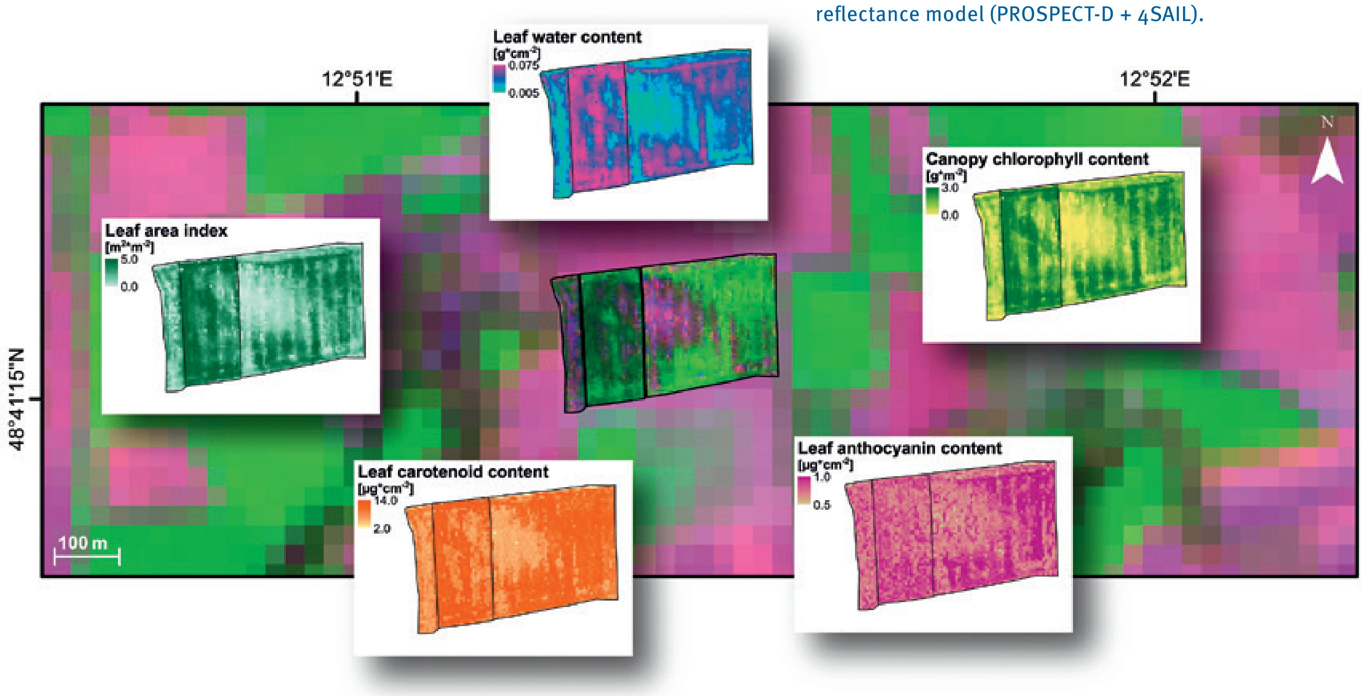


Fig. 8: Result of the spatial determination of various agriculturally relevant variables for a cropped field in the area near Neusling, Southern Germany, based on simulated EnMAP-Data. The estimations were achieved by inverting a canopy reflectance model (PROSPECT-D + 4SAIL).

Narrow absorption features may not be adequately resolved by multispectral data, which limits the number of variables that can be determined and can lead to large uncertainties. The use of hyperspectral imagery can reduce these challenges. The suitability of physical-based methods to obtain agriculturally relevant information from hyperspectral satellite data is being investigated at LMU Munich as part of the scientific preparation of the EnMAP mission. Hyperspectral data are acquired with airborne sensors and converted by computer software into images. Reflectance models are used to simulate the spectra of agricultural crops as a function of plant characteristics. These reflectance models can also be inverted (i.e., reversed) to retrieve important surface information about the target crops (e.g., see Fig 8).

EnMAP provides high-quality time series of hyperspectral data that meet the criteria for physically-based, transferable variable retrievals.

EnMAP will be used to create improved spatio-temporal information products to support site-specific management decision making (see Fig. 9). EnMAP paves the way for global hyperspectral data coverage and more efficient agriculture to ensure ecologically and economically sustainable use of bioproductive land.

EnMAP and Agriculture

With EnMAP, a special information products used for decision-making for site-specific crop production can be derived.

Implementing precision methods into farming strategies can lead to more ecologically and economically sustainable use of bioproductive land.

Compared to conventional multispectral Earth observation systems, hyperspectral imaging systems such as EnMAP guarantee (1) a greater variety of observable variables, (2) higher accuracy of the information products by avoiding misinterpretations, and (3) global transferability of variable estimation techniques, which are independent from in-situ calibration data.

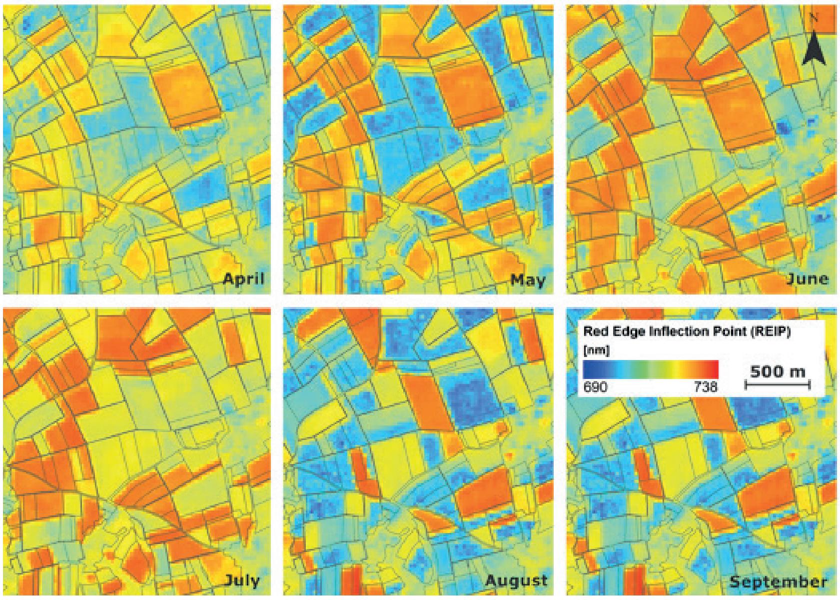


Fig. 9: Simulated EnMAP time series of a growing season for an agricultural cultivation area in the vicinity of Neusling, Southern Germany. The temporal evolution of the Red Edge Inflection Point (REIP) is shown, which can be an indicator of nutrient under- or oversupply.

EnMAP as an expert forest observer

Monitoring forest ecosystems at a time of climate change

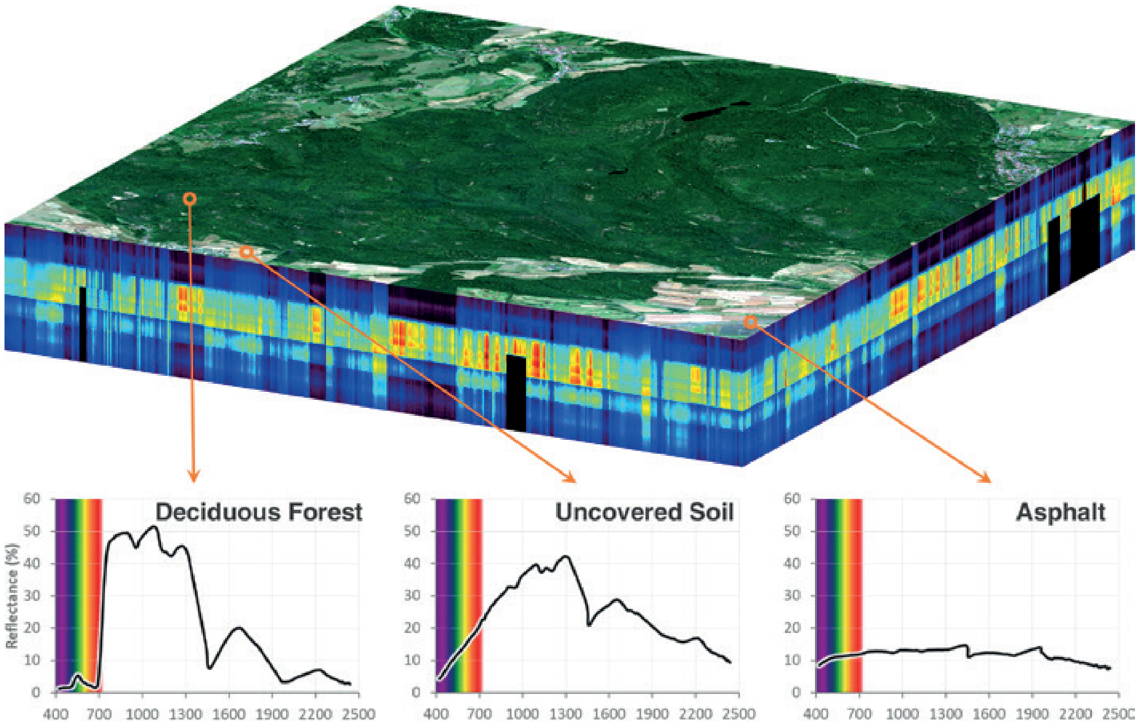


Fig. 10: Hyperspectral cube for a forest segment; each pixel contains a detailed reflectance spectrum.

Forest ecosystems cover a significant proportion of the Earth surface and offer many key ecosystem services. Forests are the most prominent terrestrial carbon dioxide sink, containing the highest volumes of biomass globally. They provide essential productive and protective functions in addition to supplying timber for human use. Their role in preserving biodiversity and climate mitigation cannot be overstated. However, forests and forest ecosystems are increasingly threatened by global warming, a rapidly growing population and ever expanding economic activities. Destruction of forests, conversion of forests to agriculture acreage, legal and illegal wood harvesting and recurring forest fires are only a few of the many threats to forest landscapes and ecosystems.

The study of forests must consider both the protection and preservation of forest ecosystems and the economic interests of commercial forest management. The demands for data that form the basis of decision making in an ever more complex world are constantly increasing. The information required to balance economic and ecological interests in sustainable forest management can not be retrieved without remote sensing technology. EnMAP makes a significant contribution to these requirements. It is capable of a regular monitoring of a representative, global network of selected forest locations. The mission has a key role in developing and optimizing methodologies for mapping tree species and age. It is able to assess forest structures and forest resources in discrete land segments. The specific properties of hyperspectral sensors (Fig. 10) are very effective for recording physiological variables, for example water and pigment content for the early identification of stress (Fig. 11). Regular monitoring of physiological variables opens new possibilities to derive vitality indicators via model calculations of plant production and forest growth. Estimates based on remote sensing data contribute to improving forest management concepts in anticipation of future climate conditions at regional scales.

The University of Trier is focusing on EnMAP's potential for forest research. One example is the development of model-based and advanced empirical methodologies for recording eco-physiological state variables. Powerful algorithms are being developed in parallel with the integration of atmospheric radiative transfer models with geometric-optical reflectance models for stands of trees.

The collection of time series across the growing season is central to the observation of dynamic forest ecosystems which are sensitive to phenological cycles, stress factors, and site differences. The regular revisit time of EnMAP compared to aircraft flights, will provide novel data at a regional scale.

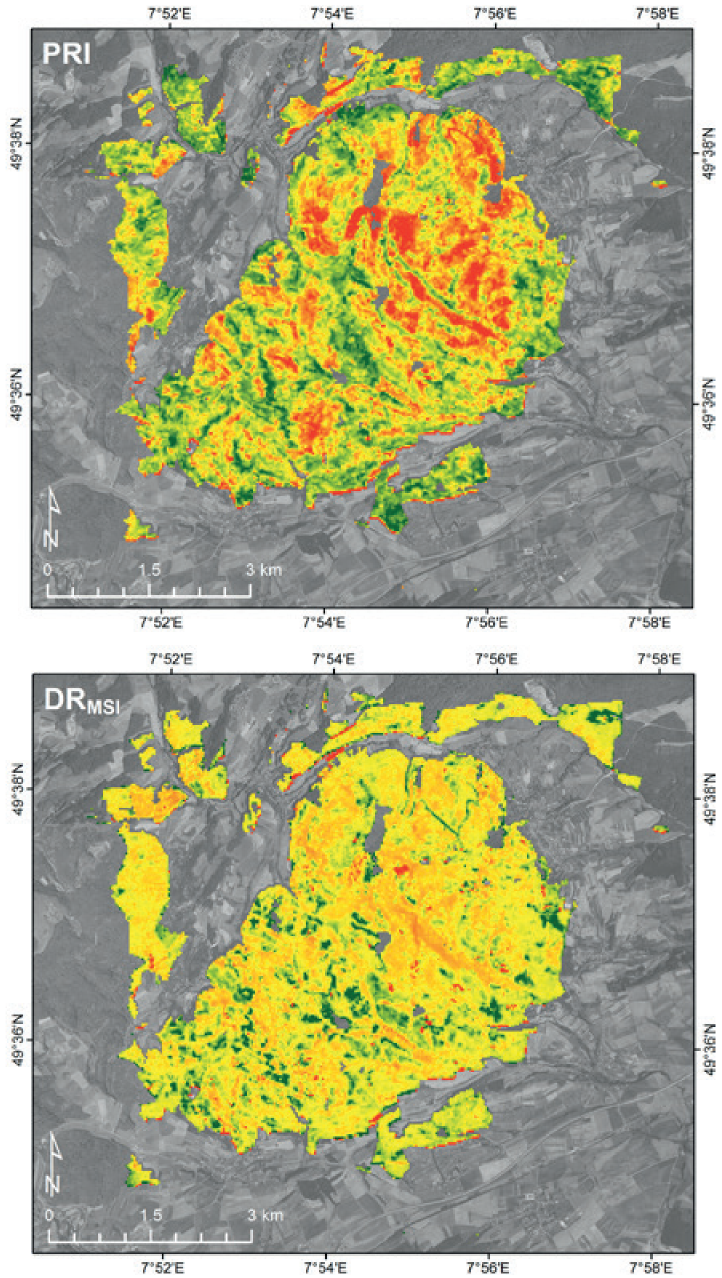


Fig. 11: Recording drought stress at Donnersberg, a forested area in Rhineland-Palatinate, Germany. At the top, the hyperspectral Photochemical Reflectance Index (PRI), calculated from simulated EnMAP data, shows early signs of drought stress, while the Moisture Stress Index Double Ratio (DRMSI) does not highlight drought-stressed areas yet.

EnMAP and forest ecosystems

Forest ecosystems provide fundamental ecosystem services investigated with EnMAP.

EnMAP will provide information on forest structure and resources critical for sustainable economic and ecological management of forest ecosystems.

The early identification of climate-related stress phenomena with EnMAP is important for developing appropriate forest management strategies.

EnMAP as an objective ecosystem analyst

Investigating gradual spatial and temporal changes in ecosystems

Fig. 12: Spectral field measurements validate the results of remote sensing image analysis.

Terrestrial ecosystems are rapidly changing as a result of climate change and human activities. Deforestation, extensive agriculture and urban sprawl are significantly impacting the condition, functioning and biodiversity of ecosystems. A better understanding of the interactions between human activities and the surrounding terrestrial systems and their ecosystem services is urgently needed. This can only be achieved through long-term regional monitoring.

Earth observation is a crucial tool for characterizing entire ecosystems and ongoing process changes. The concepts of Essential Biodiversity (EBVs) and Essential Climate Variables (ECVs) provide an appropriate framework to meet global standards for ecosystem monitoring. EnMAP data will contribute to the derivation of several EBVs and ECVs such as vegetation leaf area, biomass and species composition.

The regular regional sampling of hyperspectral data from EnMAP will improve interpretation of spectral signatures and their related physical processes. It will be possible to derive more detailed parameters on the type (e.g., species composition), structure (e.g., biomass) or condition (e.g., leaf nitrogen or water content) of vegetation with EnMAP data.

In addition, the regular, long-term monitoring of large areas with EnMAP will complement dense time series from multispectral sensors such as Landsat-8 OLI and Sentinel-2 MSI. This will enable assessments of gradual, continuous changes, such as the effectiveness of a protected area for preserving biomass or biodiversity, or the impact of drought on vegetation condition and recovery.

The focus of EnMAP research at Humboldt University Berlin is on the gradual spatial and temporal changes within individual ecosystems as well as the transitions between different types of ecosystems. The specific research topics are: (1) quantification of vegetation types and their fractional cover or biomass in different ecosystems, (2) assessment of the gradual succession of agricultural areas following abandonment, and (3) characterization of land use gradients in urban areas and direct surroundings.

Machine learning approaches have been adapted and enhanced for spectral analyses to better utilize the entire spectral information within hyperspectral data from modern, spaceborne imaging spectrometers such as EnMAP. Linking empirical and physical approaches and the generalization of empirical models to fully exploit the spatial and temporal resolution of the data is of particular importance.

The Castro Verde region in southern Portugal has been comprehensively monitored over the last 20 years (Fig. 12). The region is characterized by steppe grasslands which formed after the abandonment of degraded agricultural fields. Subsequent succession of natural vegetation has increasingly led to shrub encroachment (Fig. 13). Part of the study area is also within the Natura 2000 Special Protection Areas for Birds as there are steppe bird communities of national and inter-national importance. The conflicting ecosystem services, such as increasing carbon storage of encroaching shrubs and enhancing bird habitat and biodiversity, illustrates the complexity of such natural environments.

Hyperspectral imagery in this region is used to map gradual shrub encroachment over space and time. The quantification of different shrub types and steppe grasslands, as input for subsequent modeling of biotic processes is particularly challenging considering the various phenological stages of dryland vegetation. The performance and robustness of new machine learning techniques to describe subtle spectral differences between vegetation types have been tested. The developed approaches produce quantitative maps illustrating fractional shrub cover, i.e., information content which reaches far beyond conventional maps derived from discrete land cover classifications (Fig. 14). In particular the detection of low shrub fractions is of high relevance for decision making and early detection of ecosystem changes. The developed methods are freely available in the EnMAP-Box.

Fig. 13: Abandoned landscape with progressive shrub encroachment.

EnMAP and ecosystem changes

Research is lacking on transitional ecosystems and the gradual changes within them. Currently, it is challenging to comprehensively describe these changes in space and time.

EnMAP will offer basic and innovative analyses to improve the understanding of global change as well as the interactions between humans and their environment.

Characterizing and recording ecosystem services using a combination of qualitative and quantitative approaches is an important goal of the research within EnMAP.

Analyses of simulated EnMAP data reveal subtle processes that cause an ecosystem change.

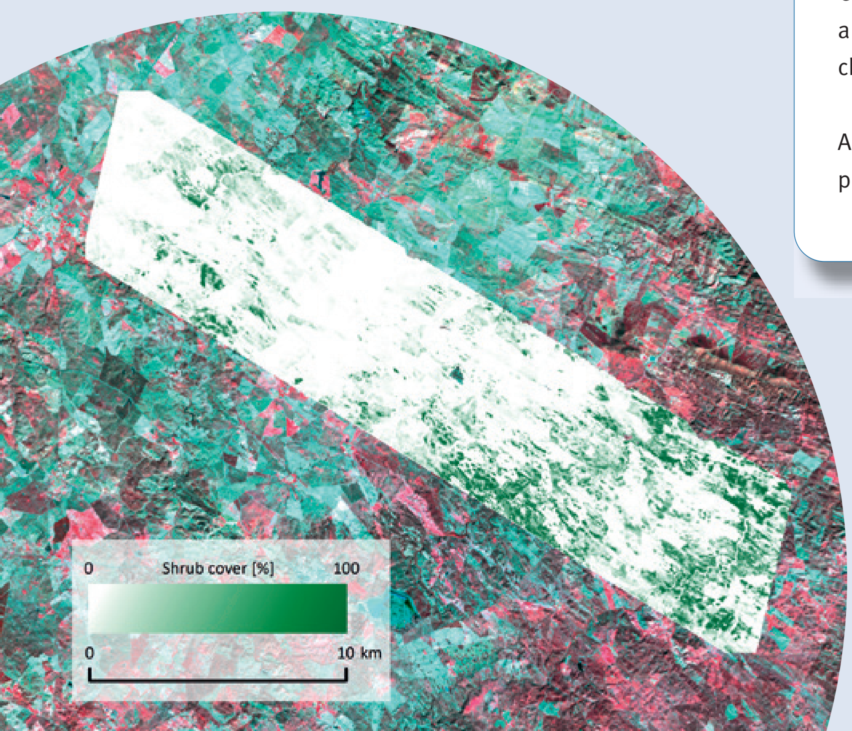


Fig. 14: Fraction map showing shrub cover in the Castro Verde region, Portugal, derived from a Support Vector Machine Analysis and simulated EnMAP data. False-color Landsat-5 composite shown in background.

EnMAP as a modern soil scientist

Worldwide analysis of soils and degradation processes

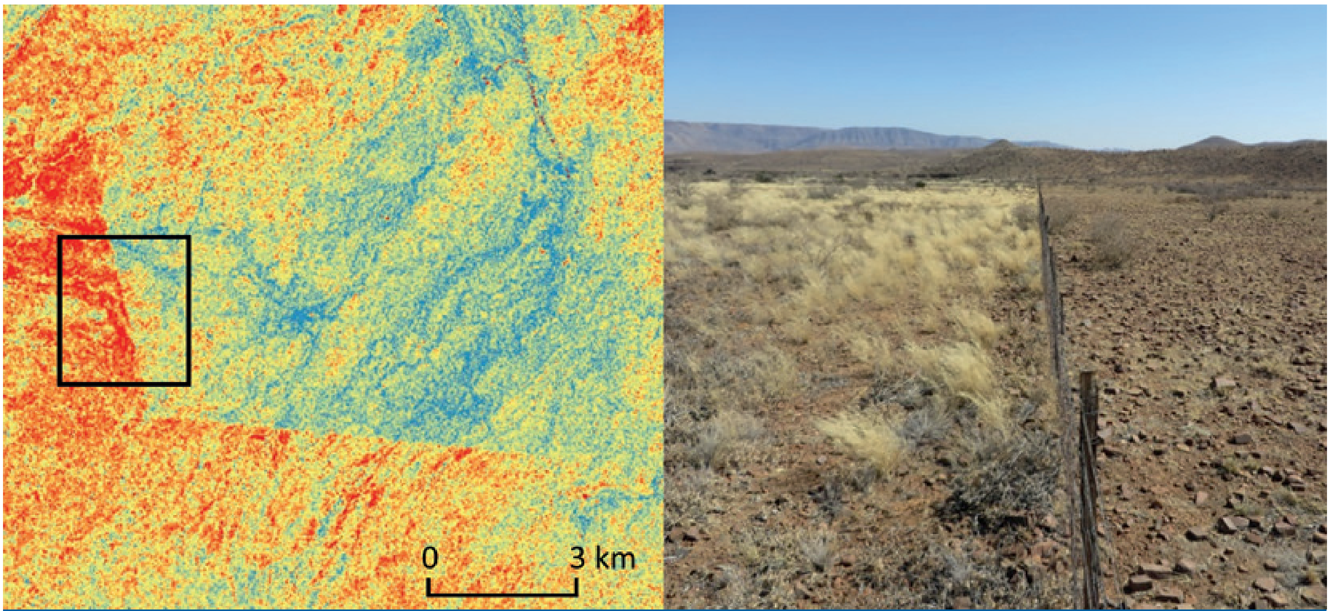


Fig. 15: Consequences of overgrazing (right side of fence) in Tsauchab Valley (Naukluft, Namibia) to be seen in change detection map based on satellite imagery (1984-2015) of 30 m resolution (left) and photo taken in October 2014 (right).

Soil is not a renewable resource when viewed on the time scale of a human being. It is worth protecting because of its crucial role in food production, water regulation, pollution filtering, and carbon storage. The ecosystem services provided by soil are threatened worldwide by climate change, natural hazards and human activities. The consequences are an increased soil loss due to wind and water erosion, or land-slides, as well as a reduced soil quality due to organic matter loss, contamination, salination and soil compaction. In 2006 the European Commission issued guidelines on the protection and preservation of Europe's soils. Its goals are sustainable soil use, preservation of soil quality and functions, as well as soil restoration.

Inappropriate land use such as deforestation and over-grazing leads to soil degradation worldwide (Fig. 15). The loss of vegetation cover, monoculture farming and inadequate irrigation systems lead to erosion and low soil quality (Fig. 16). This erosion can cause rivers and dams to become extremely silty influencing regional water quality. Soil degradation is especially problematic if it progresses at a slow pace and is only recognized at a late stage. Nearly 70% of the Earth's drylands are already showing signs of degradation. To control soil erosion, information on vulnerability and long-term processes is needed. The United Nation's Convention to Combat Desertification (UNCCD), signed by almost 200 states, highlights the need to monitor, analyze and assess soil degradation processes worldwide.

There is a global need for systematic, large area mapping of topsoil characteristics with high spatial resolution that goes beyond recording degradation processes. Soil maps are often based on data that has been collected for individual field locations only. Large area maps are needed for many applications, including agriculture, soil preservation strategies, and input for climate models.

EnMAP offers new opportunities to quantify key soil parameters for a global characterization of soil conditions and degradation indicators. Regular monitoring facilitates early identification of degradation, which enables timely implementation of suitable countermeasures to sustain soil quality and crop yields. Important parameters such as the ratio of vegetated to bare soil area, water and pigment content of plants, soil organic, clay, carbonates and salt content, and soil moisture can be measured from space with new precision thanks to EnMAP (Fig. 17). Especially in drylands, the vegetation cover consists

Fig. 16: Soil degradation and erosion on agricultural land in Camarena near Madrid, Spain.

EnMAP and soil

EnMAP will allow for a repeated, quantitative, diagnostic derivation of key soil parameters.

EnMAP will make an important contribution to the generation of soil maps worldwide.

Early stages of progressive soil degradation will be recognizable.

EnMAP will, therefore, facilitate the development of timely countermeasures.

not only of green plants but also a high proportion of dry biomass. This dry material is very important to prevent erosion and can be detected with EnMAP.

At GFZ methods to detect and characterize soil properties have been developed. These data are critical for erosion and soil degradation modeling. A set of algorithms to derive key soil and erosion parameters has already been developed (EnSoMAP, the EnMAP soil mapper). The studies are performed in different climate zones around the world at test sites in Germany, Europe, Asia, Australia and southern Africa.

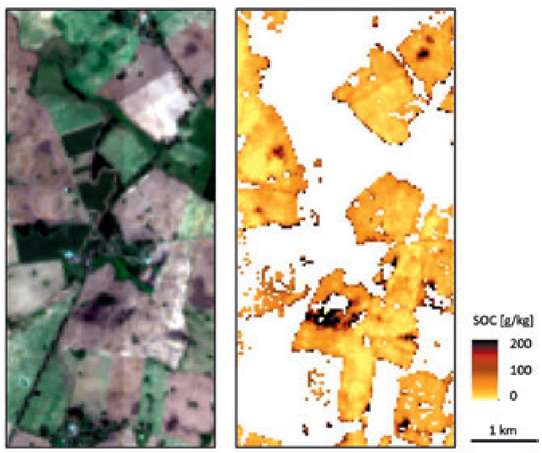


Fig. 17: Mapping of organic carbon content in topsoil with EnSoMAP and simulated EnMAP data in the Demmin study area in north-eastern Germany.

EnMAP as a skilled exploration geologist

Detection and sustainable use of geo-resources

Fig. 18: Nickel-Laterite-Mine near Agios Ioannis, Greece.

The current increase in global commodity prices, driven by population growth and consumption, has led to mining operations in regions previously deemed uneconomical. Ferrous and non-ferrous metals as well as energy resources (oil, gas and coal) are in high demand. However, much of society now demands environmentally friendly and sustainable extraction and use of resources. This challenges geo-scientist to develop new solutions in the mineral and hydrocarbon extraction sectors. A key focus is the minimization of land-use in mining operations (Fig. 18) for cost effective and environmentally friendly extraction. Remote sensing methods, particularly imaging spectroscopy, contribute to mineralogical and geological mapping during the full life cycle of a mine: from exploration to extraction and later closure and reclamation operations.

A unique feature of imaging spectroscopy is the identification of minerals in rocks and soils based on characteristic absorption features (termed "spectral fingerprints"), which are neither visible to the human eye, nor with previous spaceborne sensors (see Fig. 19 and 20). These absorption features are used to quantify surface materials. EnMAP records the spectral fingerprint of common geological materials in its more than two-hundred narrow spectral bands (Fig. 20). These include oxides and hydroxides, phyllo-sillicates, sulfates, carbonates as well as the economically important rare earth elements.

Minerals are identified by the position and form spectral fingerprints and the depth of these features is correlated with abundance. These physical relationships enable the development of new analysis techniques previously not possible using multispectral remote sensing (Fig. 20). Automatic algorithms characterize and quantify minerals and materials up to the sub-pixel scale using spectral reference libraries. EnMAP enables new and more detailed diagnostics of surface processes, which go well beyond simple classification of rocks and soils.

As part of the EnMAP scientific preparations, the GFZ developed new innovative expert systems (EnGeoMAP) for the automatic identification of minerals and soils. Simulated EnMAP images were used in the development process of EnGeoMAP to ensure reproducible and robust analysis results. New concepts and associated software have been developed to characterize mine-waste material and reclamation sites.

Fig. 19: Spectroscopic measurement of malachite (copper carbonate, green material) at the Haib River copper molybdenum deposit, Namibia.

EnMAP and geology

EnMAP enables a unique characterization of minerals and rocks via imaging spectroscopy.

EnMAP delivers a significant contribution to the mineralogical and geological mapping of mineral resource sites.

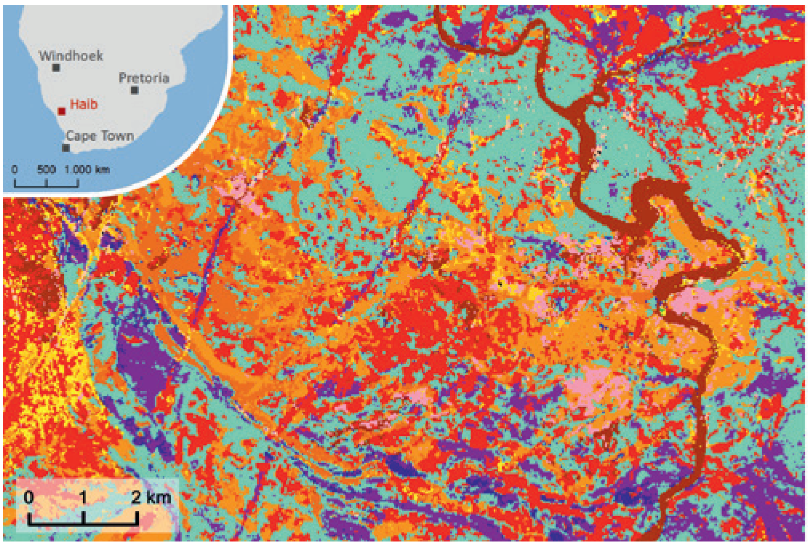
EnMAP enables an area wide spatio-temporal assessment of mining regions and their related mining activity, highlighting key areas for later reclamation operations.

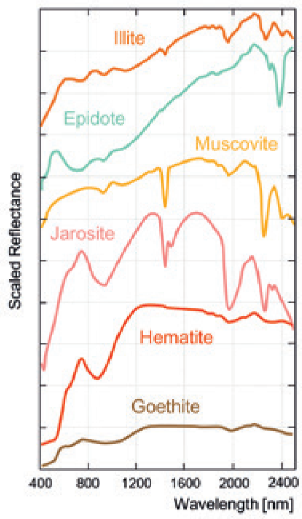
The impact on from mining and post-mining residues worldwide has a significant influence on the ecosystem funcioning and biodiversity. These impacts must be accounted for in modern mining operations (Fig. 18). Effective land management and low-impact mining is in the best economic interest of every mining company today. More effective material extraction reduces costs and increases revenue. A win-win situation for the economy and the environment is made possible by imaging spectroscopy in mining.

More precise identification and quantification methods developed in the EnMAP preparatory phase have enabled the development of new tools for environmental impact assessment. These include monitoring the spatiotemporal evolution of large mining and post-mining landscapes leading to better landscape management and more effective reclamation operations.

Selected mining regions in Namibia, South Africa and Greece are analyzed with local academic partner institutions to achieve these goals. Data was analyzed in the field (Fig. 19) and laboratory using spectrometers. The established multi-scale, wide-area and temporal approach to characterise mining activities is the basis for the future use of EnMAP data in the operational phase of the mission.

Fig. 20: Mineral map of the Haib River copper molybdenum deposit, Namibia, calculated from simulated EnMAP data using EnGeoMAP.





EnMAP as a versatile hydrologist ...

Detecting changes in the Wadden Sea

Fig. 21: Satellite image of the Wadden Sea with low spectral resolution (Landsat) in the background and a strip of high-spectral resolution airborne scanner data (AISA). This figure exemplifies the different spatial coverage of extensive landscapes like the Wadden Sea achievable with locally collected airborne data compared with region-wide satellite data such as EnMAP data.

The Wadden Sea is the largest tidal flats system in the world and is listed as a UNESCO World Heritage Site. The spatial extent, dynamic change triggered by currents and tides, and the relative inaccessibility of the area make remote sensing data an important tool for monitoring and assessing this sensitive and unique natural environment.

The distinct elements of the Wadden Sea are narrow channels, open tidal flats with sandy or muddy sediments, extensive mussel populations and resurgent seagrass beds (Fig. 21). High spectral resolution data improves the characterization of low-contrast mudflats, whose surfaces lack sharp borders and land use variations one experiences on dry land. As part of the EnMAP preparation phase, in-situ measurements were made in order to spectrally characterize different tideland surfaces.

To understand the potential of EnMAP laboratory analyses of sediments to calculate parameters like chlorophyll content in combination with a hyperspectral airborne campaign (AISA) (Fig. 22) were used to develop narrow-band indices and algorithms for surface classification. Calculating parameters like the intensity of microalgae colonization (the phytobenthos index) and chlorophyll content provide important information about the primary production of biomass in tidal flats.

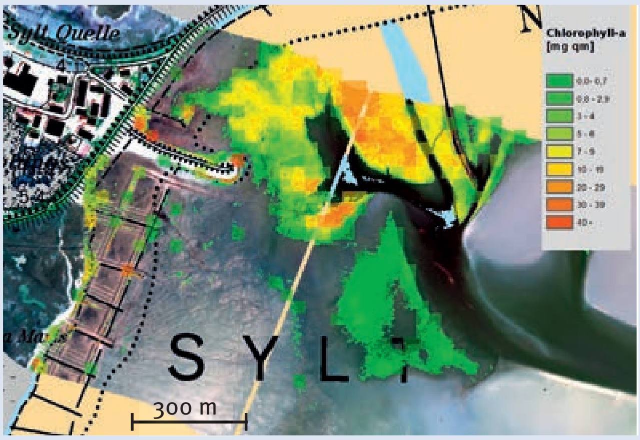


Fig. 22: Chlorophyll map derived from hyperspectral airborne image data (AISA). The coarser resolution of the future EnMAP data is indicated by the larger coloured semi-transparent pixels.

... and reliable coastal researcher

Studying remote Arctic coastal regions

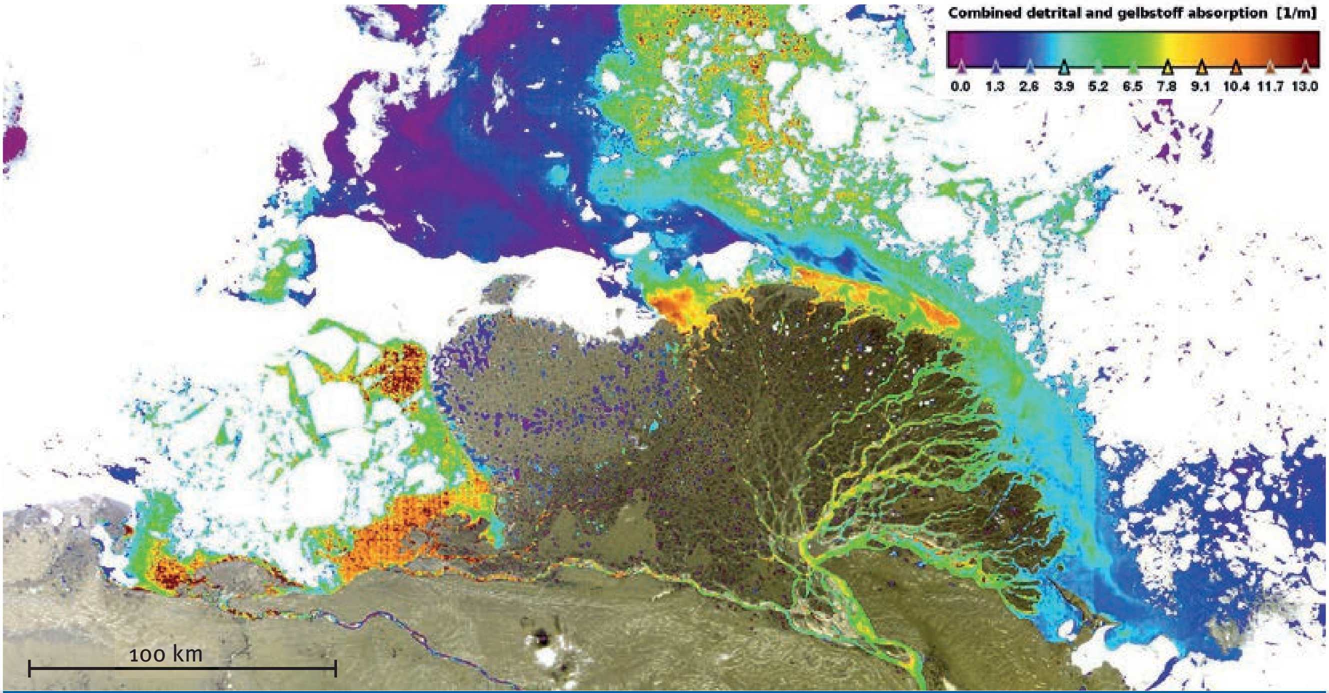


Fig. 23: Satellite image of the Lena delta, eastern Siberia, recorded on 04 July 2011 with the MERIS sensor. EnMAP will provide a much finer spectral and spatial detail.

The thawing of permafrost soils and the progressive melting of sea ice have received worldwide attention. Sea ice melt leads to an influx of substance-rich freshwater to coastal areas and serious erosion of unstable coasts, especially in eastern Siberia. Little is known about the state and distribution of permafrost soils and its decomposition in highly vulnerable coastal areas.

The satellite image in Fig. 23 shows an extremely high concentration of organic substances in the Lena delta of eastern Siberia. Their absorbance values translate to less than 0.5 m visibility depth for these waters. The Lena River transports large amounts of carbon into the Arctic Ocean, making it a large carbon source. The concentration of organic substances in coastal waters is high. Comparisons with in-situ measurements made on the same day show good correlation with deviations less than 10%. EnMAP will facilitate these investigations at significantly greater spatial and spectral resolution.

EnMAP and water bodies

The high spectral resolution of EnMAP provides comprehensive information on inland and coastal water quality, leading to a better understanding of local ecosystem processes.

The high spectral resolution can also identify suspended particles, dissolved organic matter, phytoplankton and dominant algae species.

EnMAP data improves regional and global understanding of the role of coastal and inland waters in the carbon cycle.

EnMAP as a farsighted urban planner

Monitoring the composition of urban areas

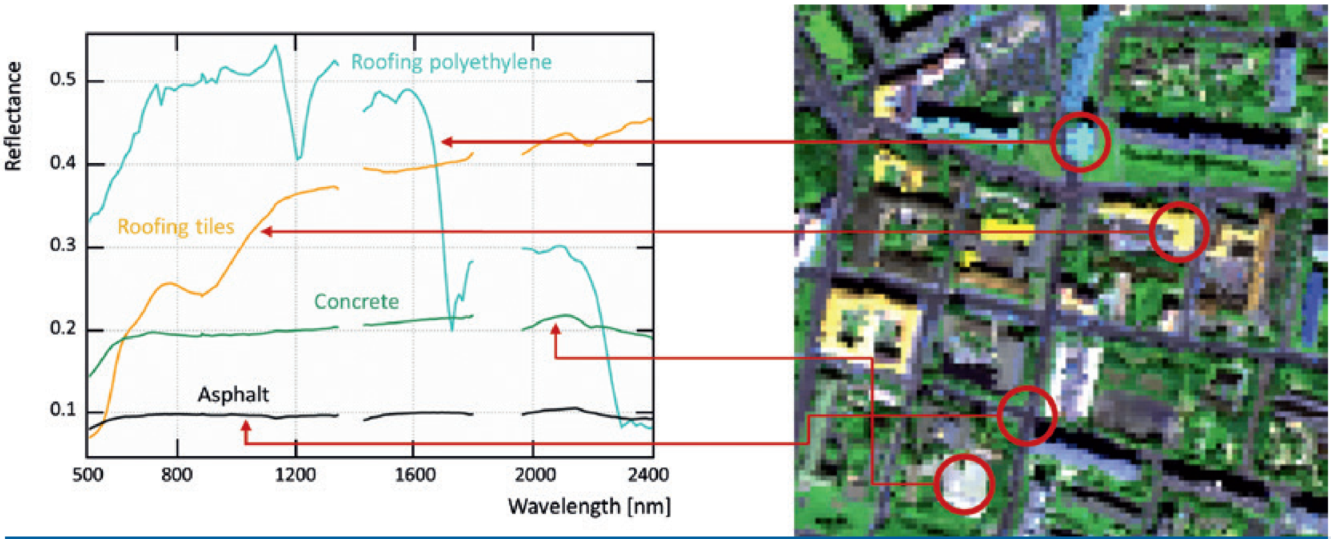


Fig. 24: Urban surface materials can be identified by their material-specific spectral reflectance signature.

Rapid conversion processes are taking place in urban population centers worldwide. Today, more than half of the global population lives in cities. This development has numerous negative consequences on the environment. Addressing these issues puts enormous demand on those attempting to manage urban regions. The most urgent problems include urban sprawl, high traffic density, and climate-induced vulnerabilities. The susceptibility of cities to natural hazards such as storms and flooding also poses special planning challenges.

These problems are especially pronounced in megacities. It is necessary to balance the needs of ecologically responsible, economically profitable and socially compatible development, while preserving the unique character of a city and its environment.

The key element for this kind of sustainable urban development is a thorough understanding of the evolution and interactions between natural, built-up and socio-economic environments. The central component for assembling this knowledge is an extensive database of up-to-date geo-information on the spatial and temporal development of built-up areas and the surrounding natural and cultural landscapes.

This is where EnMAP makes an important contribution. Continuous monitoring of the Earth's surface from space provides a unique overview of the spatial fabric and development of built up areas and cultural features. Because of EnMAP's high spectral information content, detailed qualitative and quantitative information on the nature and distribution of urban surfaces and their climatic effects can be derived.

Fig. 25: The ground resolution of the EnMAP sensor is 30 m.
This means that one EnMAP pixel contains information on several types of urban surface materials that can be quantified with spectral unmixing methods.

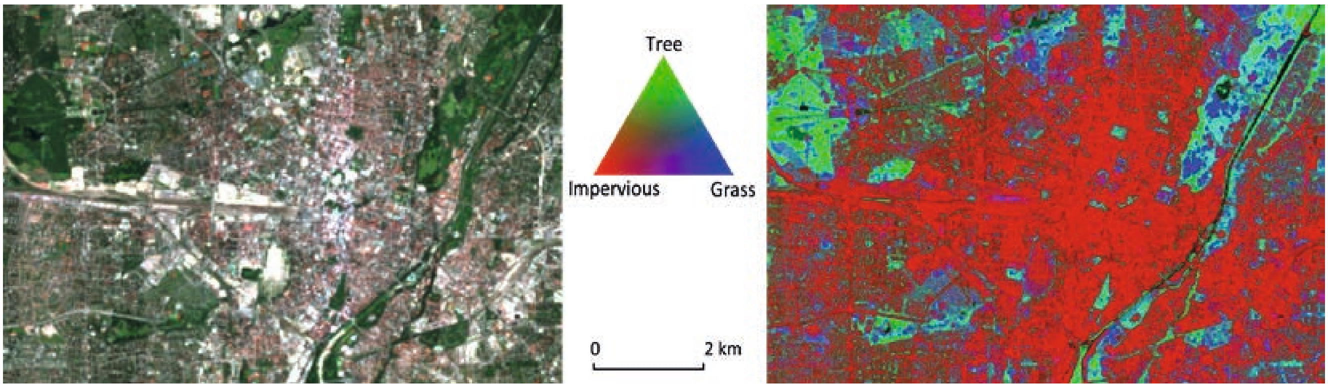


Fig. 26: Simulated EnMAP data of the city of Munich, Germany, shown as (left) true color image and (right) derived abundances of impervious surfaces (red), trees (green) and grass (blue).

Cities contain a wide range of natural and artificial surfaces with characteristics of varying relevance for city planners. Roofing materials are especially diverse, and knowing the material and distribution can provide information on urban structure. Additionally, environmentally problematic materials like asbestos or specific components like solar panels can be identified. Permeability of surfaces is also relevant to city planners. Impervious surfaces such as concrete and asphalt lead to run off of rainwater or environmentally harmful liquids into the sewer system. Partially impervious surfaces allow some of the rainwater to be absorbed by the ground mitigating the burden to city water supplies. Vegetated urban areas provide many benefits for the local climate and quality of life of the city's inhabitants. Urban surfaces can be identified and recorded with imaging spectrometers such as EnMAP. Studies with airborne hyperspectral sensors have shown that surface materials have unique spectral reflectance characteristics (Fig. 24).

In contrast, multispectral systems with their few channels are not suitable for detecting urban surfaces at the material level. The challenge in using EnMAP data for urban applications relates to the pixel size. Figure 25 shows that one EnMAP pixel contains spectral information for a number of different surfaces. Because of EnMAP's high spectral information content, the percentage of the individual surfaces can be determined with a procedure known as spectral unmixing.

The knowledge about urban surface materials at subpixel level makes it possible to derive planning-relevant indicators with high precision. The quantification of the imperviousness is one of the key elements when monitoring the development of urban areas, particularly megacities, which have rapidly expanded in recent years (Fig. 26).

EnMAP and urban areas

Knowledge gained with EnMAP about the nature, distribution and changes in surface materials, such as streets, roofing and vegetation, is important for planning and developing urban areas.

EnMAP data can quantify the degree of imperviousness and the percentage and quality of vegetation in urban conglomerates.

EnMAP provides basic spectral data important for the active planning of sustainable cities.

EnMAP as a chemical laboratory assistant in space

Observing areas affected by hazardous waste, pollutants and dusts

Fig. 27: Tailings from gold mining near Klerksdorp, South Africa

Anthropogenic pollution can be intentional or accidental in nature. It is produced by non-renewable resource exploitation, industrial processing, agriculture, urban development, transportation, and shipping, and impacts all aspects of society including the economy, health and well-being and the environment.

Diagnostic data to inform decision making is critical for anthropogenic hazard management whether for emergency response, routine monitoring or assessments of potential risks. Imaging spectroscopy can provide key quantitative diagnostic information and has a proven track record.

The best known use of imaging spectroscopy to monitor anthropogenic hazards is to determine the impacts of mineral mining activities. Minerals are valuable resources used in modern society and the demand for these commodities is increasing. However, the extraction and processing of minerals are associated with various economic, environmental and social issues (Fig. 27). Responsible exploration and mining is crucial to the continuity of current mineral resources operations and expected expansions. Over the last three decades, hyperspectral remote sensing has supported responsible resource extraction. This is because this technology is able to provide (1) crucial mineralogical information that improves resource characterization, thereby reducing the environmental footprint and more efficient and safer mining practices; and, (2) quantitative environmental information required for decision making and compliance with regulatory requirements. Figure 28 shows the use of imaging spectroscopy for monitoring acid mine drainage conditions.

In addition to mine waste monitoring, imaging spectroscopy has been successfully used to map other anthropogenic hazards including hazardous dust fallout and oil spills. Large amounts of dust fallout can be generated as a result of accidental spills or human misdemeanors. Imaging spectroscopy can remotely and rapidly detect and locate dust fallout and is an important tool for emergency responders clean-up crews. Such was the case during the World Trade Centre attack on 11 September 2001. Imaging spectroscopy was deployed diagnosing the composition and mapping the distributions of potentially hazardous dust to guide the clean-up process.

An oil spill, discharged accidentally or intentionally, can float on the surface of water bodies as a discrete mass and is carried by wind, currents, and tides. Oils spills can have detrimental impacts on humans, flora and fauna, as well as natural and built up environments. Marine transportation can also be disrupted causing widespread economic impacts. The largest oil spill in U.S. history occurred on April 20, 2010, when an

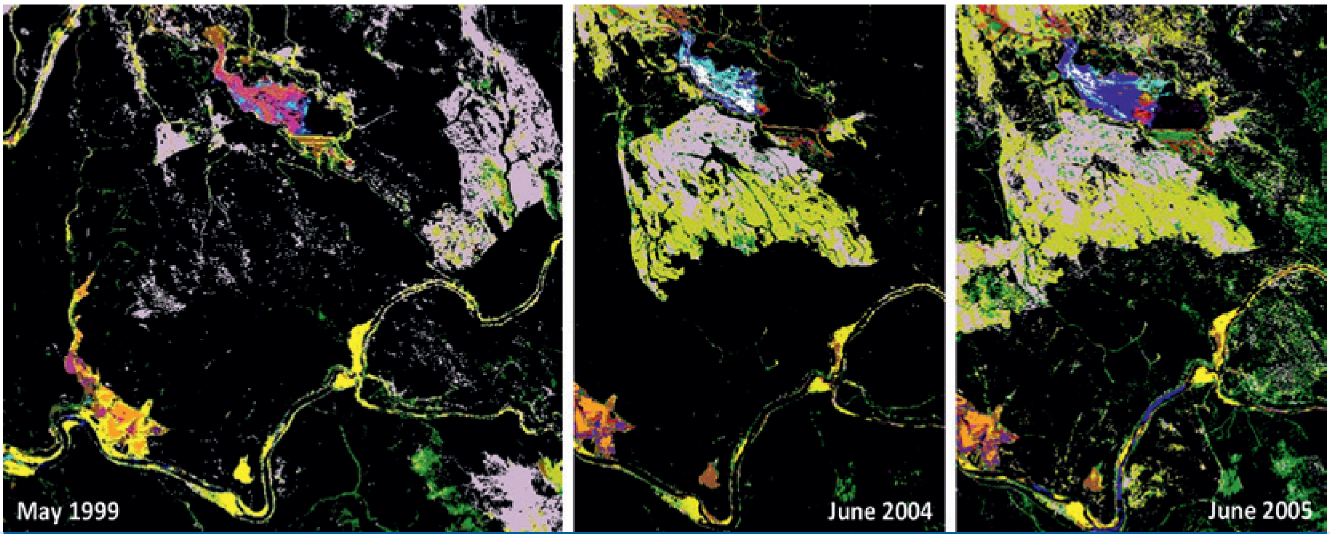


Fig. 28: Maps of secondary minerals (yellows, orange, reds and brown colours) and efflurescent salts (blue and cyan colours) resulting from acid mine drainage mapped from multi-temporal imaging spectroscopy data acquired in the Soteil Migollas Mine, Andalucia, Spain. Changes in the tailings pond (fan shape in middle of image) can be seen from 1999 to 2005 due to the development of efflorescent salts as the pond dries out with the drought in 2004 and 2005. The analysis is based on hyperspectral images acquired with the HyMap sensor at 5 m spatial resolution.

explosion on the Deepwater Horizon (DWH) offshore drilling rig released ~780,000 m³ of crude oil into the Gulf of Mexico. Airborne imaging spectroscopy was able to assist in the initial clean-up providing an estimate of the distribution and volume of the oil slick on the surface of the ocean (Fig. 29). Additionally, airborne imaging spectroscopy data were used to characterize the impact of oil on the terrestrial ecosystem. Multi-temporal data were also used to determine the progress of rehabilitation of the affected ecosystems.

EnMAP and anthropogenic pollution

EnMAP will assist in the characterization, monitoring and rehabilitation of areas affected by different types of anthropogenic pollution.

EnMAP will allow timely assessments of the spatial distribution of potentially hazardous dust, oil spills, contaminants and mine waste and thus provide valuable information for emergency responders.

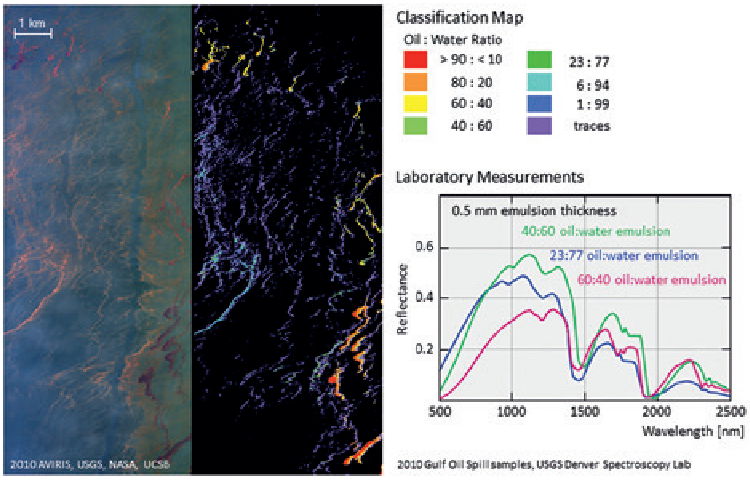


Fig. 29: Map of the oil contamination in the Gulf of Mexico in 2010 after an explosion on the Deepwater Horizon (DWH) offshore drilling rig (left) and spectral laboratory measurements of oil spill samples taken in the Gulf of Mexico (right)

EnMAP sees the Earth from various viewing angles

Signal variance of multitemporal off-nadir views

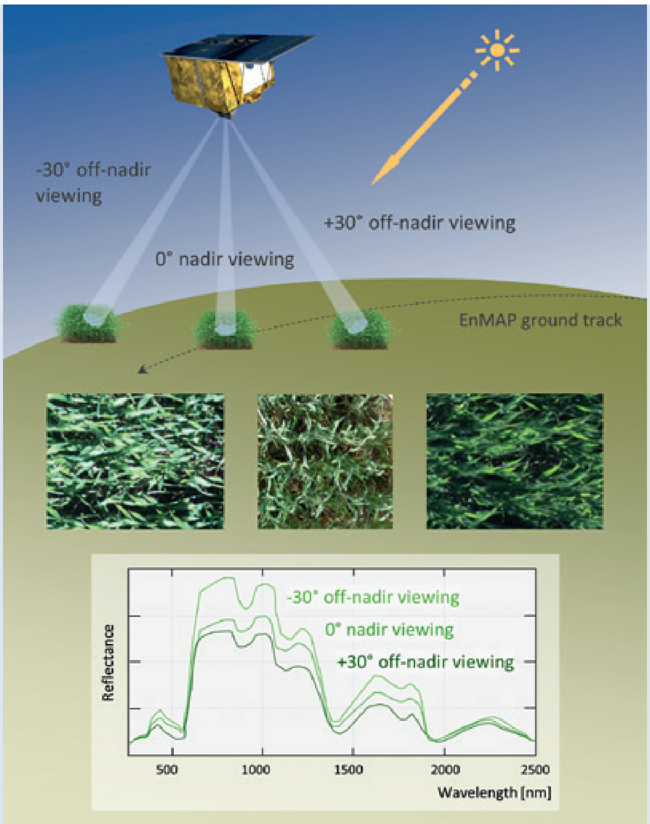


Fig. 30: Schematic representation of EnMAP's signal variance as a function of viewing angle.

EnMAP is designed to record land surface processes globally. The sensor has a revisit rate in nadir view (perpendicular to the ground) of 27 days, due to its 30 km swath width. However, by rotating the satellite across-track up to ± 30° any point on Earth except for the pole regions can be revisited in less than four days. This higher repetition rate will be used for special applications and scientific studies. It has the disadvantage that the spectral signal recorded for a given area is significantly altered when viewed from different directions. Vegetated surfaces are especially problematic in this context, due to large differences in the relationships between signal mixtures at different viewing angles. A part of the signal emanates from the ground and from plants with shaded and illuminated surfaces in between (Fig. 30).

A spectral, spatial and temporal simulation system was developed at GFZ, to record and correct these effects. It can be used to model the reflectivity of any kind of vegetation. The core of this simulation are 4D (3D geometry + temporal development) plant models whose individual geometries are overlaid with the relevant spectral information, after which they are linked using a ray tracing methodology taking into account all possible viewing angles (Fig. 31).

As a first step the viewing-angle-dependent variations in the reflectivity of grain crops were investigated using simulated reflectance data. Then the extent to which these variations affect the quantitative prediction of bio-physical (e. g. leaf area index) and bio-chemical (e. g. chlorophyll content) vegetation parameters were analyzed. Such vegetation parameters allow to draw conclusions on the condition and, if monitored over time, on the development of the observed canopy. They can also be used for ecosystem modeling. A good prediction quality was achieved with machine learning techniques for vegetation parameters of individual angle observations even with very strong tilting (± 30°). However, the prediction quality deteriorates considerably if the observation geometries differ between training and prediction data sets. Including all observed geometries in the training of the data lead again to a good prediction quality. These results show that the prediction of bio-physical and biochemical vegetation parameters is also possible with off-nadir data sets, if all observation geometries which are representative for this data set are included in the analysis.

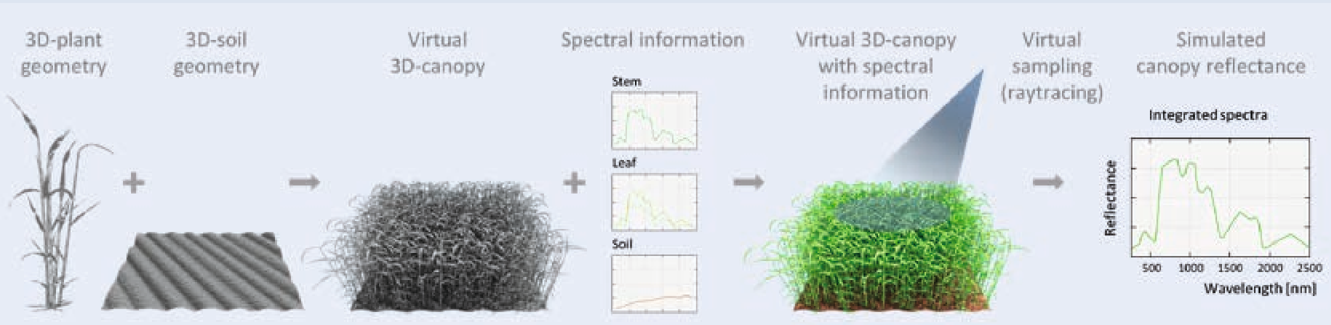


Fig. 31: Visualization of the spectral, spatial and temporal simulation system for one growth stage of a cereal canopy.

HYPERedu: Learn hyperspectral basics, methods and applications for EnMAP data

The online training program for hyperspectral remote sensing

Fig. 32: Detail from the online course on hyperspectral remote sensing on the teaching platform EO-College

With EnMAP and other future hyperspectral satellite missions, an increasing interest in hyperspectral data analysis is expected in the coming years. However, training opportunities and teaching materials are currently limited. To fill this gap, the online training program HYPERedu was developed in conjunction with the EnMAP satellite mission under the leadership of the GFZ in Potsdam in cooperation with a number of partner institutions in Germany and abroad.

HYPERedu includes teaching materials on the fundamentals, methods and applications of hyperspectral remote sensing and exercises (based on the EnMAP-Box software). The program is aimed at university students and teachers as well as professionals in research, companies and public institutions. An initial course on the fundamentals of imaging spectroscopy, titled „Beyond the Visible: Introduction to Hyperspectral Remote Sensing,“ was launched in November 2021. In it, the fundamentals of imaging spectroscopy, sensor technologies, and data acquisition techniques, as well as data sources and software, are taught using modern eLearning approaches. In addition to short texts and videos, the course includes various opportunities for activity and interaction, such as interactive graphics, quizzes, and discussion forums, and is self-led to be completed at the participants' own pace. The basic course is supplemented by other shorter courses on specific applications such as agriculture, soils and urban areas.

All teaching materials and courses are hosted on the EO-College teaching platform and provided free of charge. More information about the HYPERedu program is available at:
www.enmap.org

The EnMAP-Box: EnMAP data analysis for everyone

Free and open source EnMAP data analysis with state-of-the-art methods

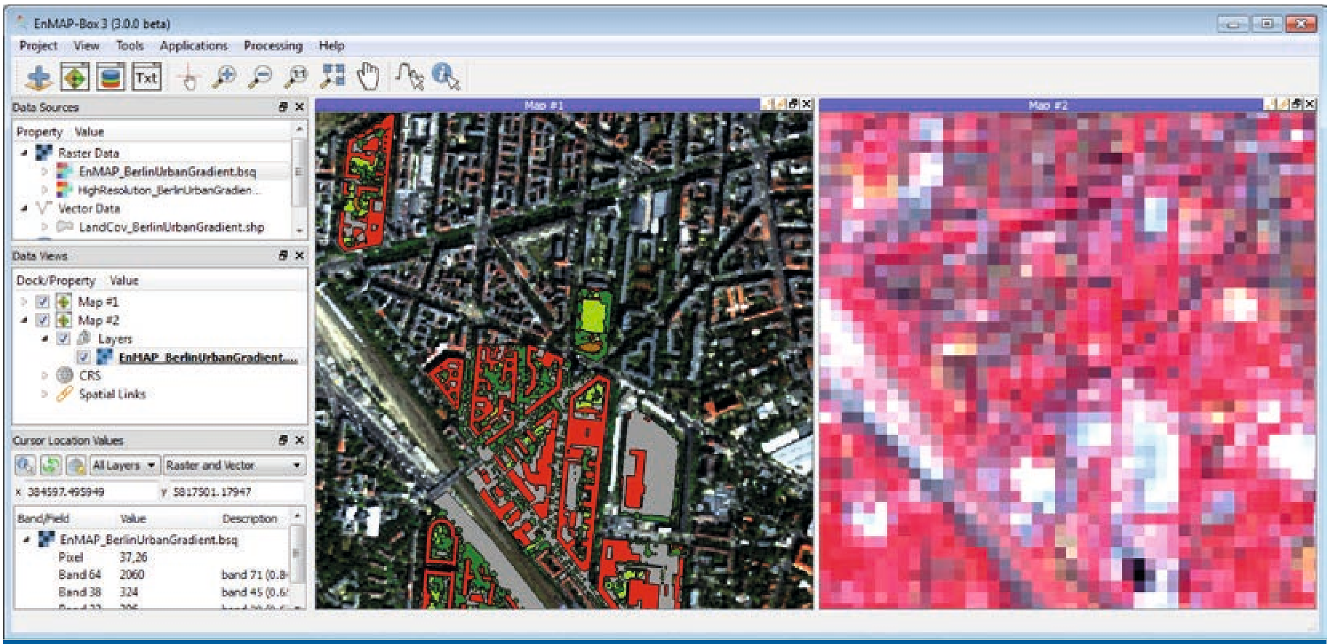


Fig. 33: Overlay of vector information on a hyperspectral airborne image (left) and simulated EnMAP data from Berlin, Germany, in the EnMAP-Box Version 3.0

The availability of EnMAP data will mark a major step forward from airborne case studies, i.e. single observations of limited spatial extent, towards a more operational use of imaging spectroscopy data. Current analysis approaches from the field of imaging spectroscopy will have to be adapted to be used on larger areas. Classical workflows for spaceborne multispectral data have to be refined to make best use of the additional spectral information content. The use of image spectral libraries collected from a global EnMAP image archive or the work with radiative transfer models can be expected to enter the world of more applied users. Several algorithmic developments have been accomplished as part of the EnMAP mission preparations and further developments are underway. All of them are distributed in a toolbox the EnMAP-Box.

The EnMAP-Box provides algorithms and applications for the processing and analysis of the EnMAP data. For each application domain, e.g. geology, forestry or agriculture, state-of the-art workflows for the analysis of EnMAP data are provided. Various user-friendly machine learning applications for image classification and regression or tools for integrating spectral library information are available as well. The EnMAP-Box includes algorithms for a customized data preprocessing. It is developed for and serves the needs of a variety of users, reaching from imaging spectroscopy novices over experienced users to scientific programmers.

The EnMAP-Box is realized as a plugin for the geographic information system QGIS. The plugin is programmed in Python and builds on selected packages, e.g. GDAL, NumPy, scikit-learn or PyQt, plus an application programming interface (API). The EnMAP-Box has its own graphical user interface to offer a bridge between the worlds of GIS and imaging spectroscopy. Most of the algorithms that are made available through the EnMAP-Box can be used directly in the QGIS Geoalgorithm framework or Model Builder.

The free and open source nature of the EnMAP-Box and its packages for the easy use of Python resources on imaging spectroscopy data opens the floor to external developers. Anyone is invited to share new approaches that proved successful for the work with EnMAP data. Efforts to provide those in a standardized manner are minimized. This way, sharing of algorithms and the enhanced availability of latest developments shall be increased within the growing EnMAP community.

The EnMAP-Box and all related resources, including documentation and application tutorials are available through:
www.enmap.org

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