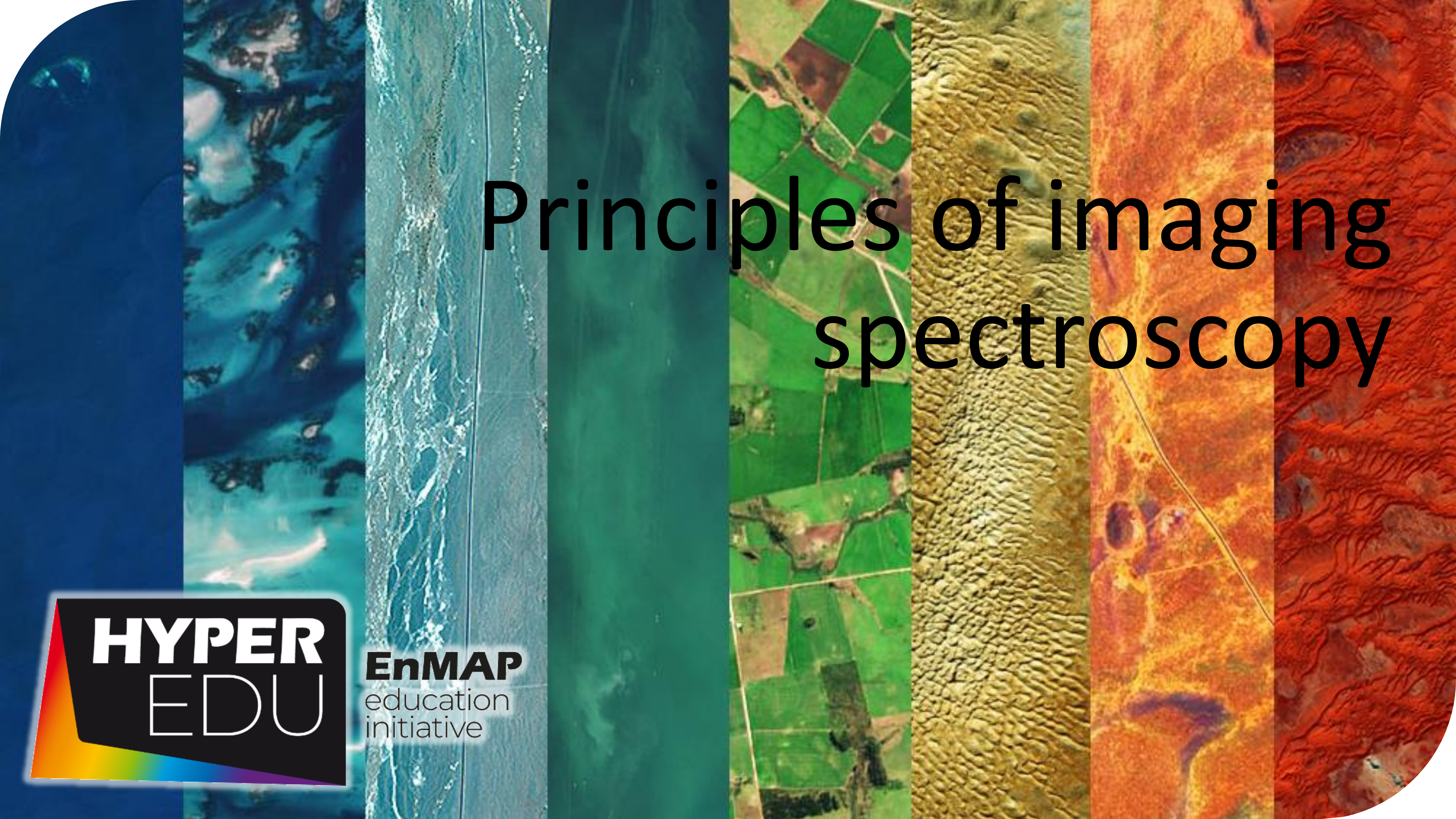
Principles of imaging spectroscopy



HYPER EDU

EnMAP education initiative

Spaceborne Imaging Spectroscopy of Agricultural Systems

EnMAP
education
initiative

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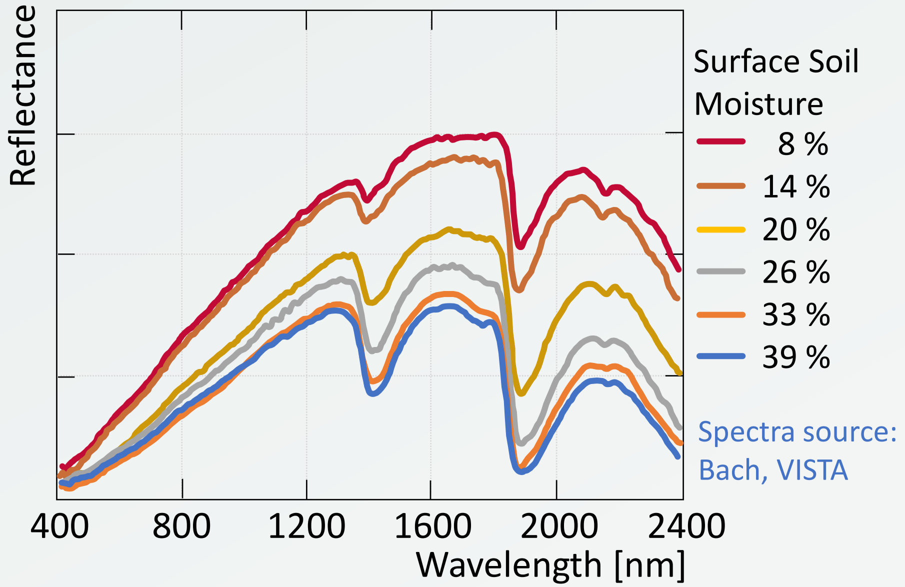
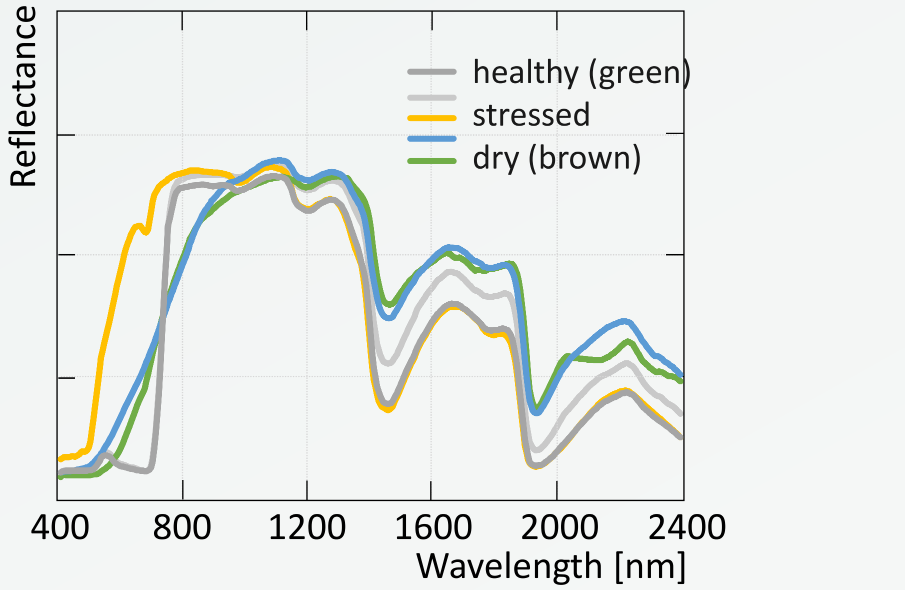
Image credits & references

Berger et al. 2021

Influencing factors: physics

- Moisture content
- Minerals
- Soil type
  - Organic content
  - Grain size
- Water
  - Organic matter
  - Phyto pigments
- Vegetation
  - Species
  - Vitality
  - Age
  - Phenology





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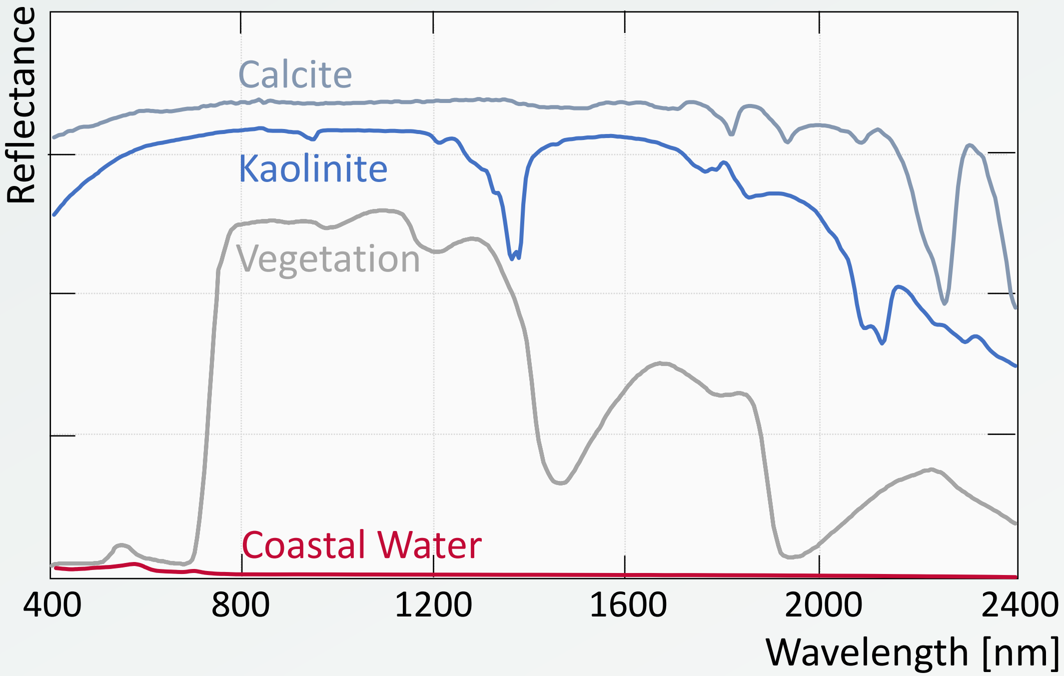
Spectral surface reflectance

- **Spectral surface reflectance → Spectral signature of surface materials → characterising the observed surface**
- Derived after data pre-processing: radiometric calibration, geometric correction, atmospheric correction → independent of solar radiation and atmospheric state
- Starting variable for most of hyperspectral remote sensing applications



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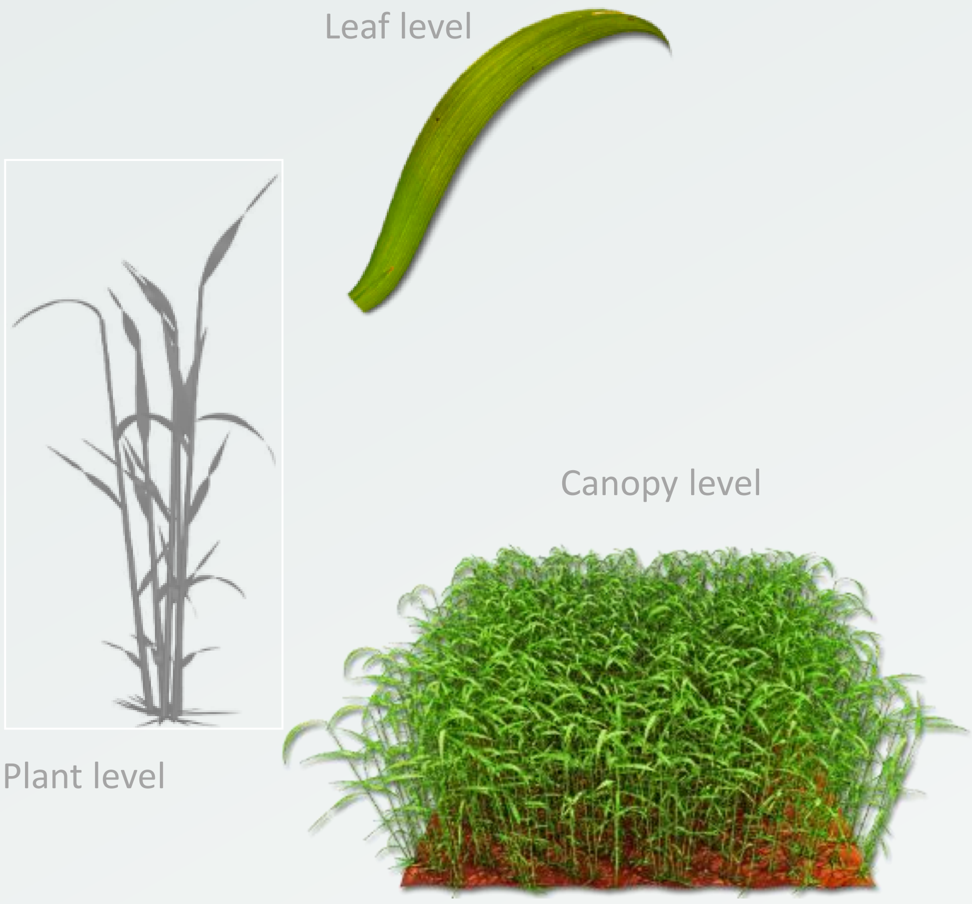
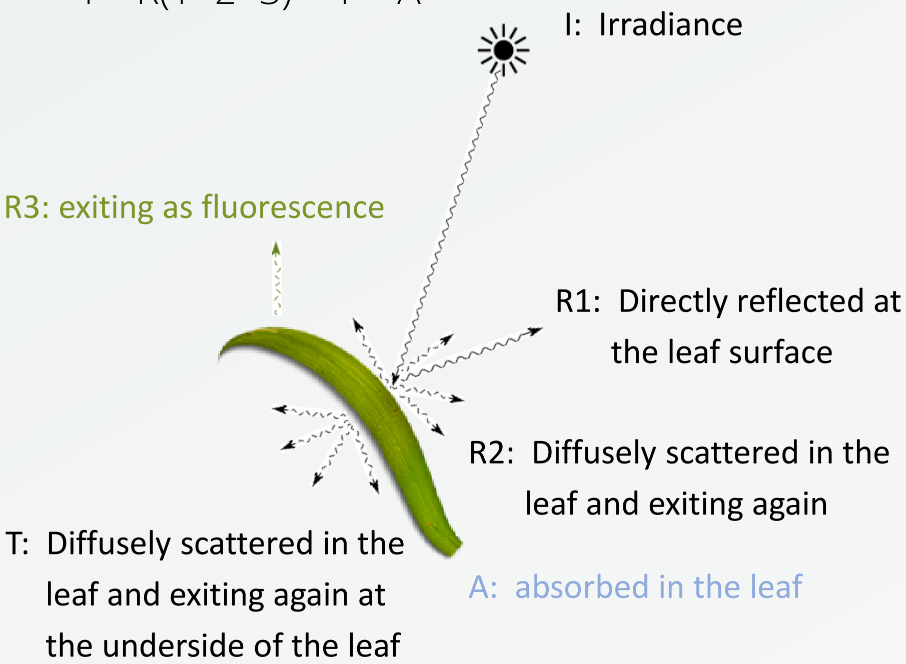
Radiance regime of vegetation

- Effects on 3 scales



At leaf level

- Leaves are radiation receivers !
  80% - 90% of the absorbed radiation occurs in the leaves
- Radiation interaction:
  I = R(1+2+3) + T + A



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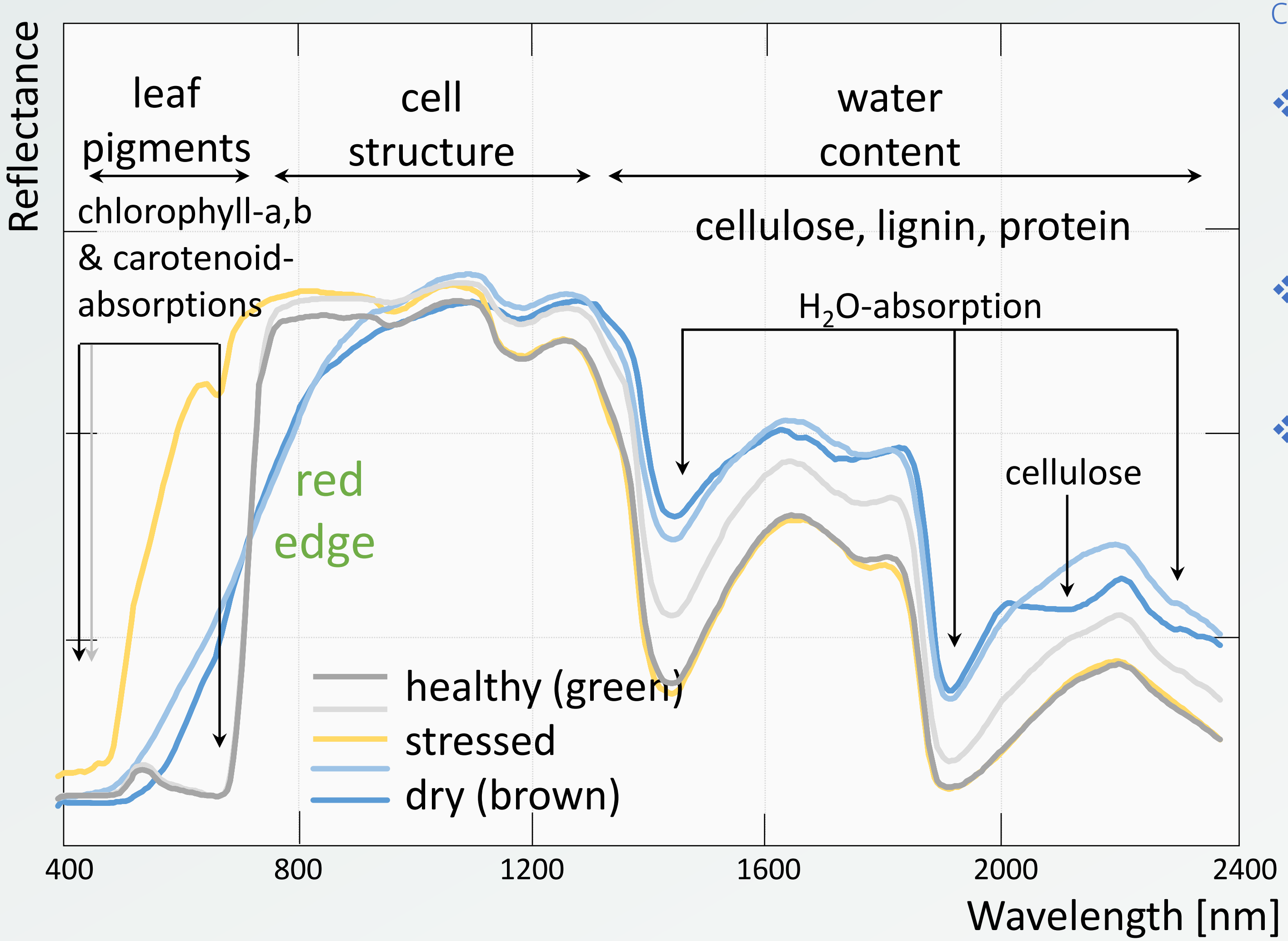
Factors controlling leaf reflectance



measured at leafs of Prunus plant

Shape of the leaf spectra is characterized by:

- Low reflectance across visible wavelengths (due to absorption by photosynthetic pigments).
- High reflectance in the NIR, with only ~ 10% of absorbed radiation.
- Intermediate reflectance in the SWIR, where energy is mainly absorbed by water or plant residues in case of dry/stressed leaves. Cell wall compounds (cellulose, lignin, proteins and sugars) lead to overlapping absorption features.

(Ustin & Jacquemoud 2020)

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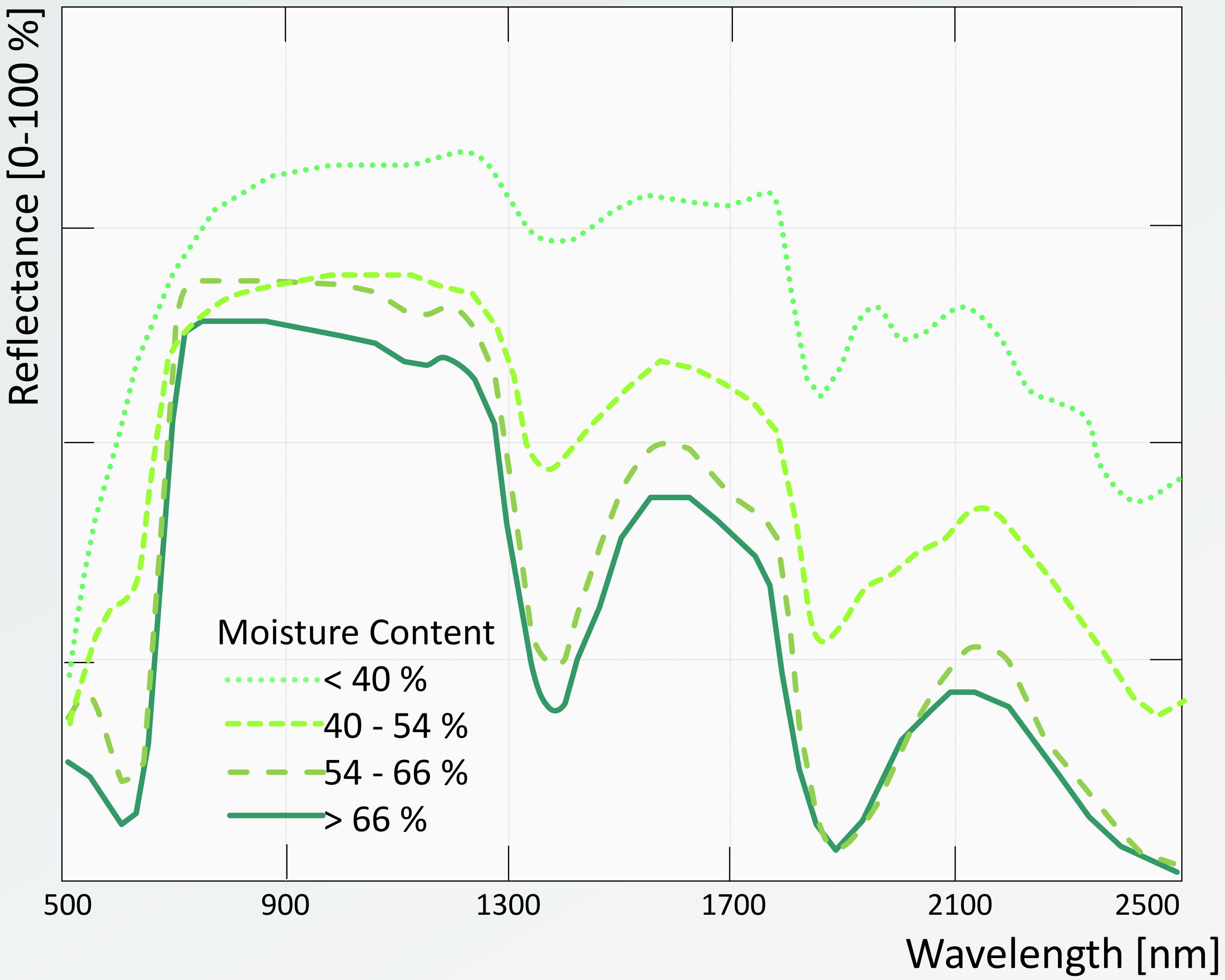
Reflectance of vegetation (II)



After Hoffer and Johannsen

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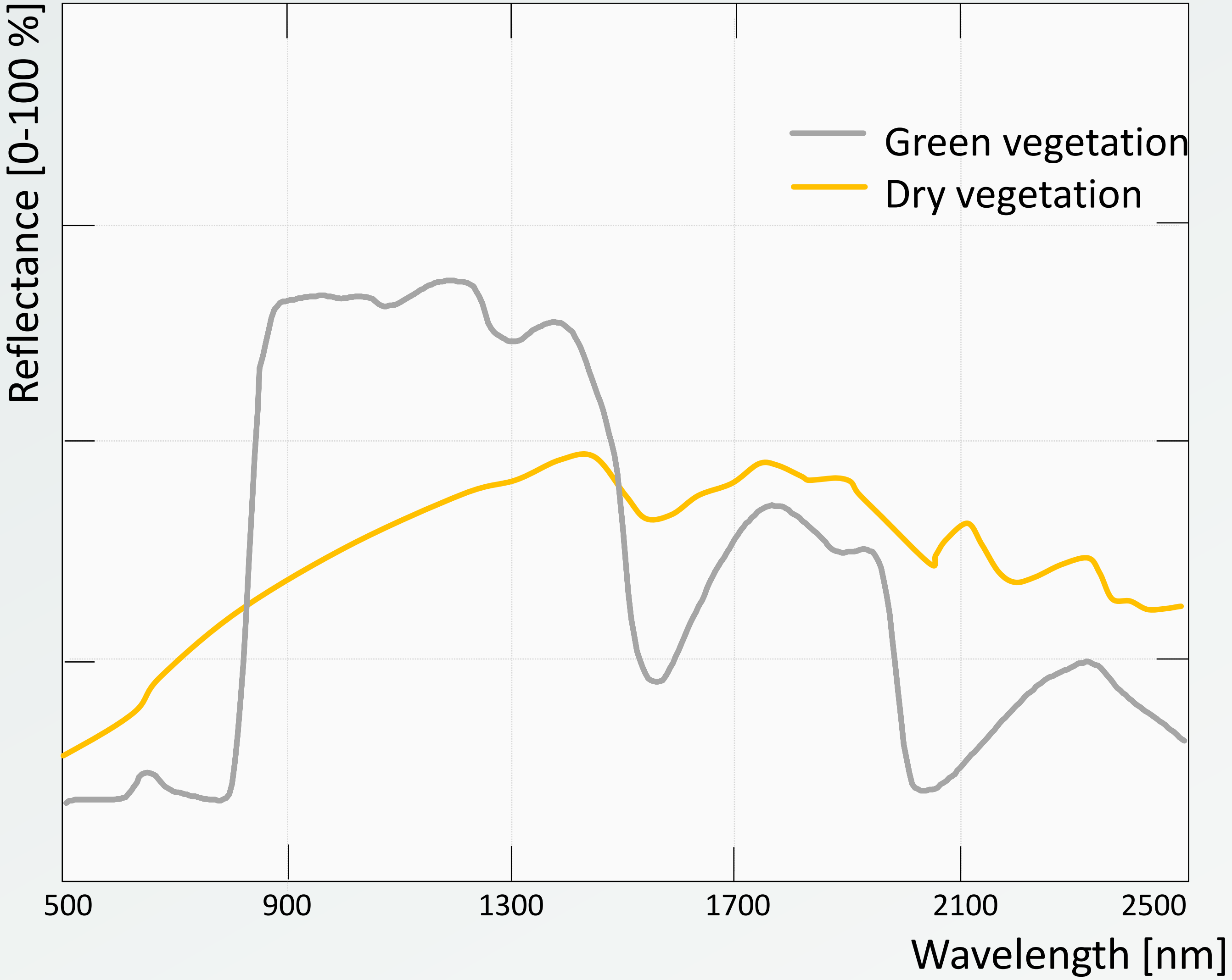
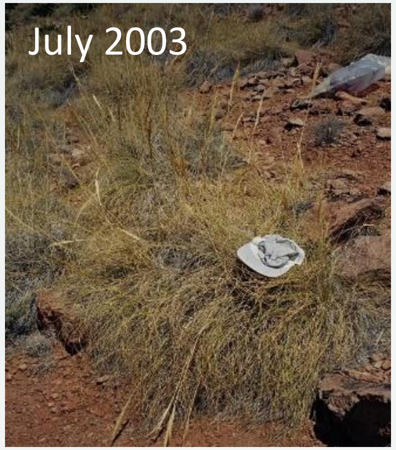
Reflectance of vegetation (III)





Stipa *(Stipa tenacissima)* , Cabo de Gata, Spain

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Leaf biochemical composition

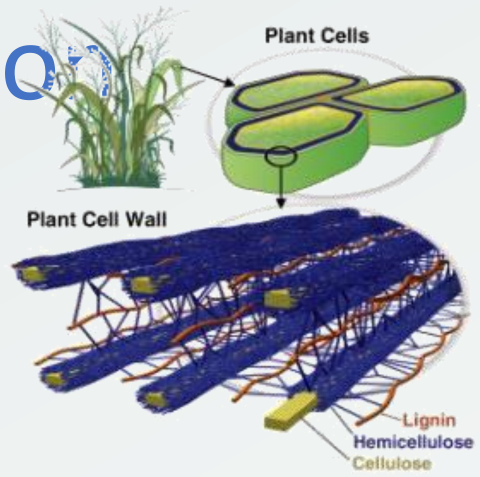


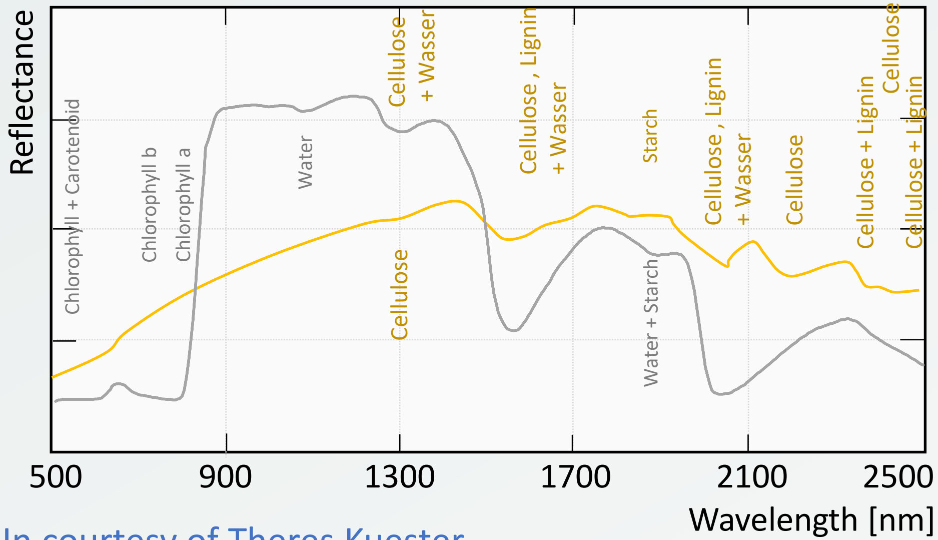
Figure reprinted from Sannigrahi et al. (2010) with permission from Elsevier

- ❖ Main compounds: Water, cellulose, hemicellulose, lignin
- ❖ plant nutrients: z.B. Nitrogen, Phosphor, substances produced by the plant for energy storage (e.g. starch)

Lignin: 3D Macromolecule

Starch: $(C_6H_{12}O_5)_n$, spiral-shaped macromolecule, short-chain

Cellulose: $(C_6H_{12}O_5)_n$, linea macromolecule, long-chain



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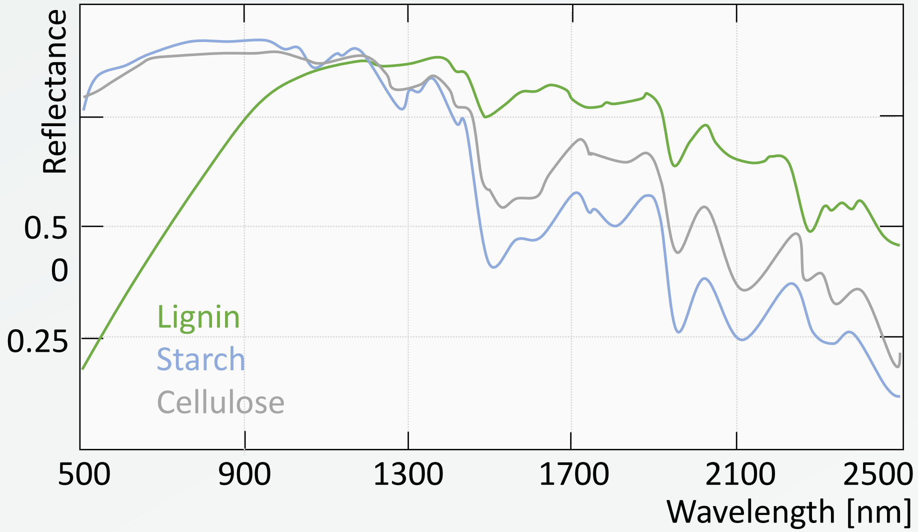

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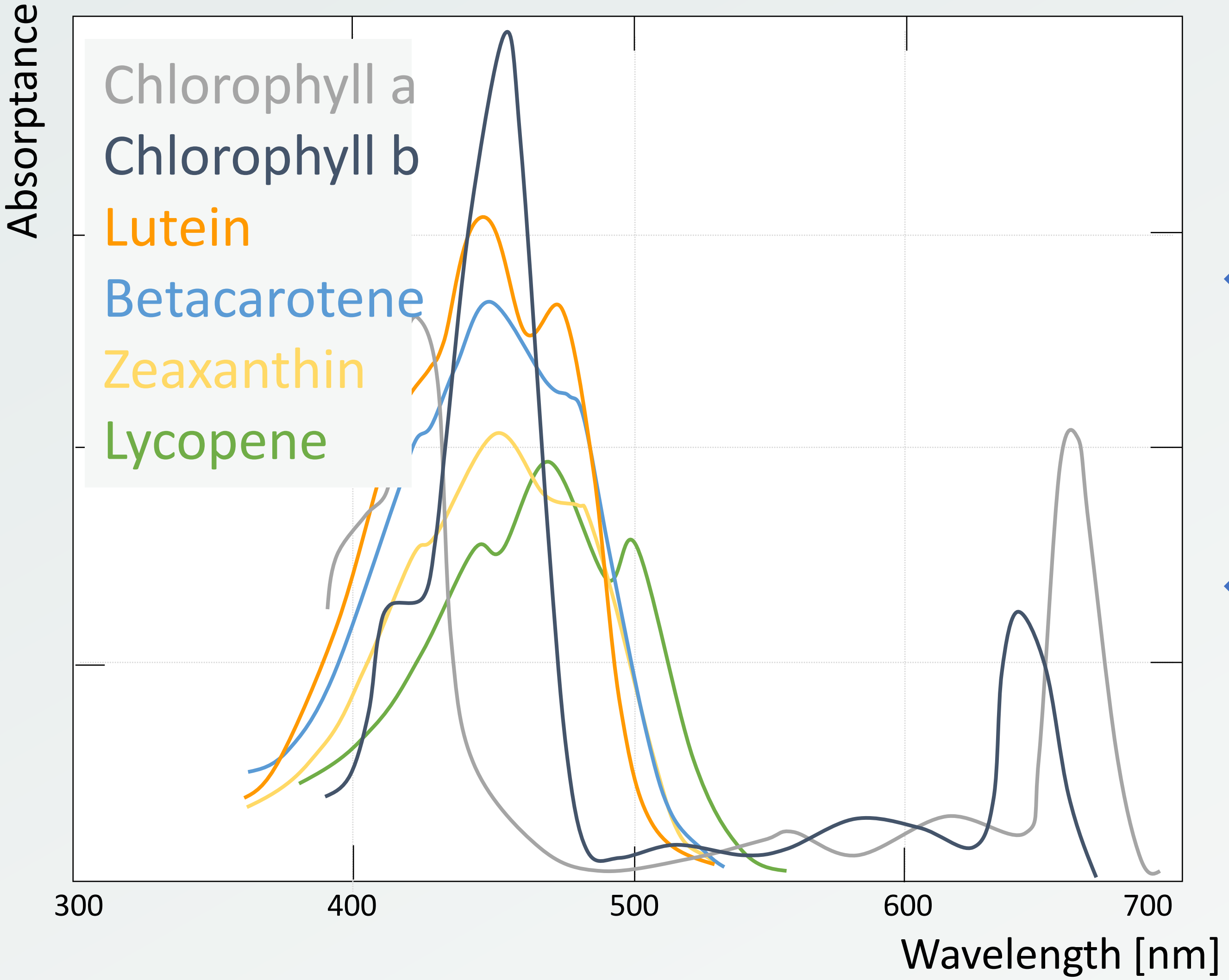
Leaf pigments



In courtesy of Luis Guanter

- Light absorption by pigments in the chloroplast produces a unique absorption pattern in the visible spectrum, with higher absorption in the blue and red wavelengths than in the green wavelengths
- Photosynthetic pigments, primarily chlorophylls and carotenoids (e.g. lutein, betacarotene, zeaxanthin, lycopene) strongly absorb light.
- Other non-photosynthetic pigments also absorb in this wavelength region, such as anthocyanins (large diverse group of flavonoids creating leaf, flowers and fruit color).

(Ustin & Jacquemoud 2020)

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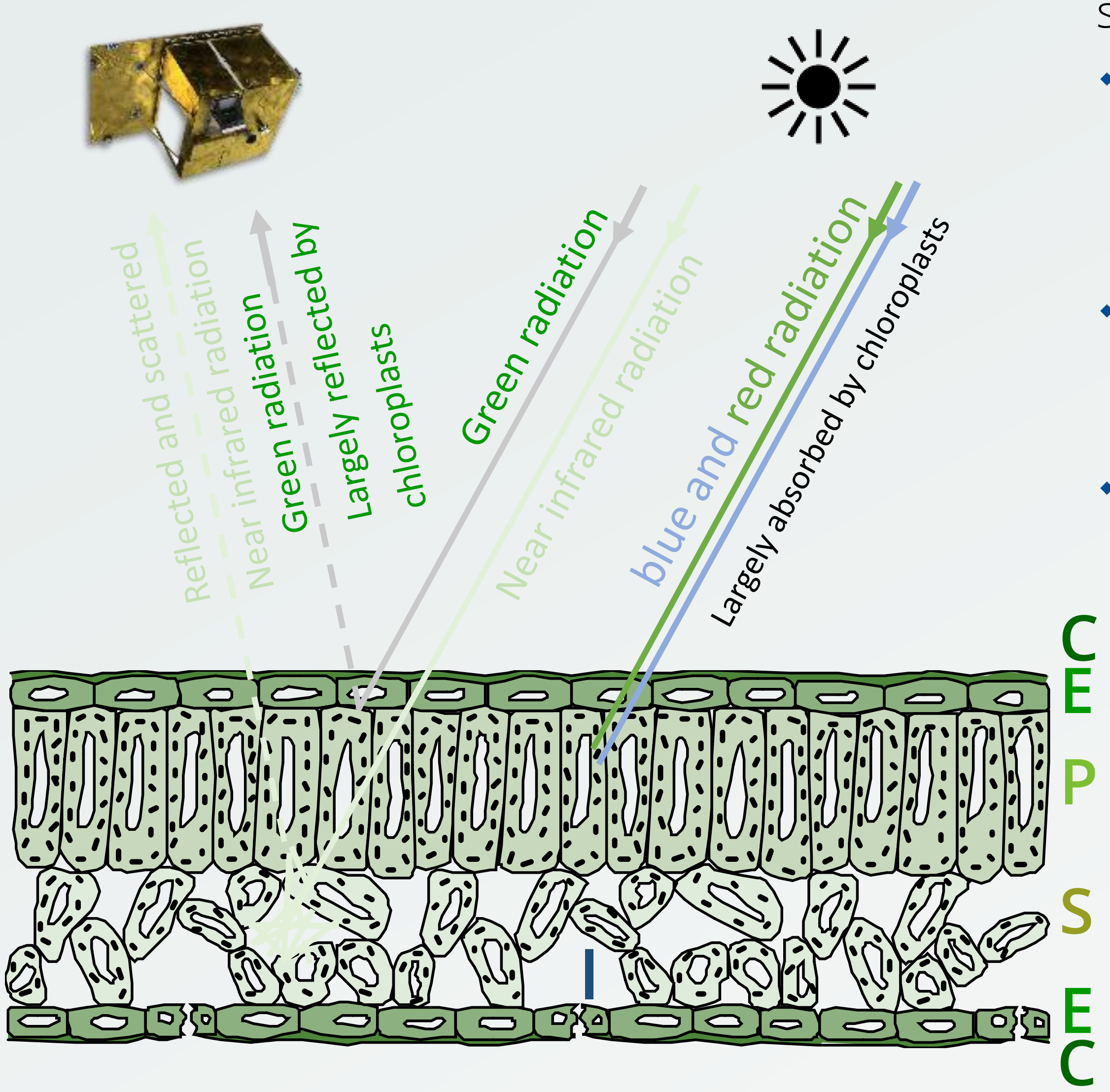
Leaf cell structure



In courtesy of Theres Kuester; illustration of the EnMAP satellite with permission from DLR Space Administration

The radiation penetrating into the leaf is subject to numerous processes:

- Multiple scattering and refraction on the cell walls within the cells, but especially in the air-filled intercellular spaces.
- Multiple scattering and refraction at chloroplasts and other cell organelles in cells
- Absorption by leaf pigments in chloroplasts, cell water and other leaf constituents

Cell structur of a broadleaf

K = Cuticule

E = Epidermis

P = Pallisade tissue

S = Spongy tissue

I = Intercellularia

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Mapping vegetation traits from satellite imaging spectroscopy

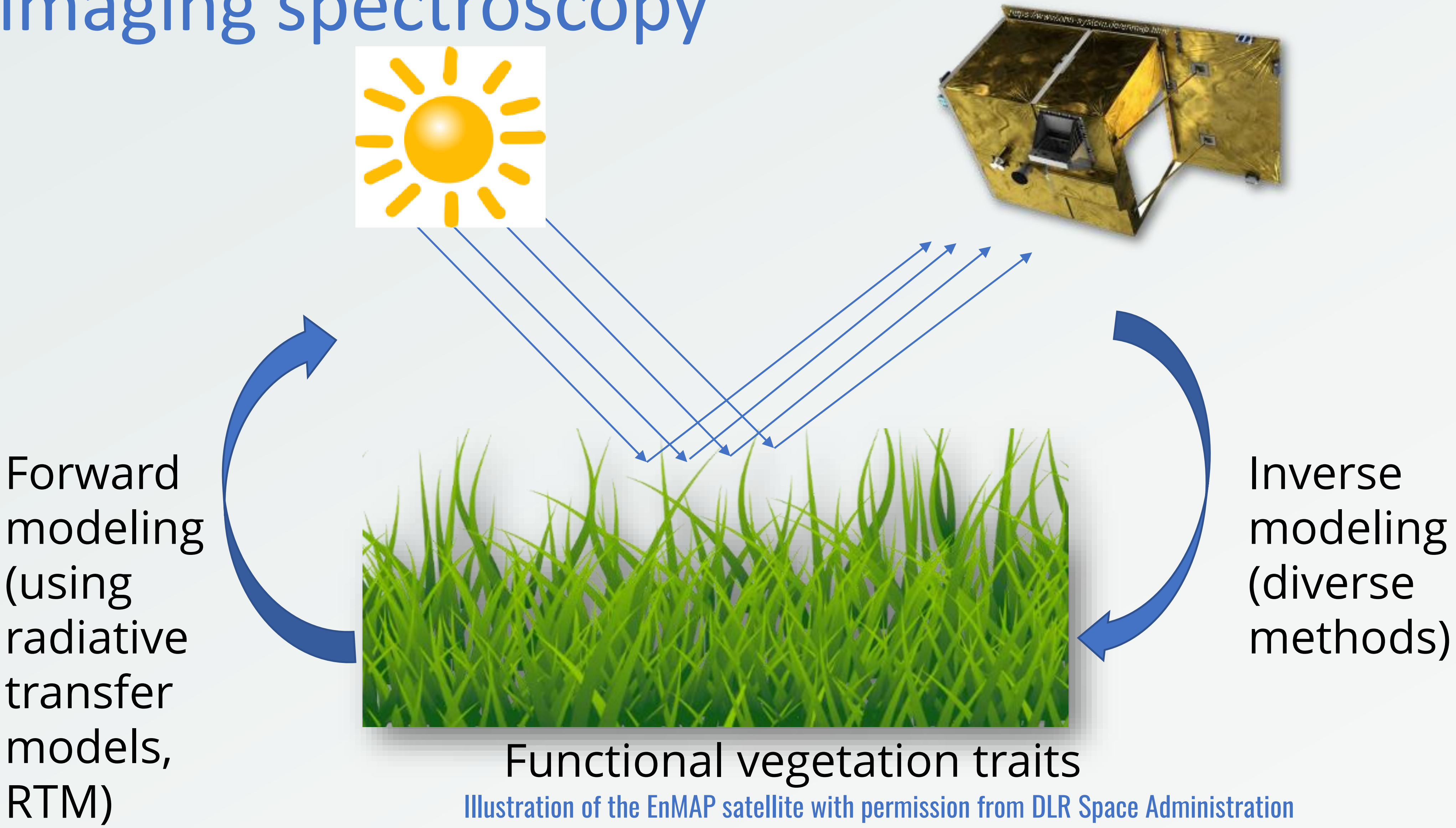

Illustration of the EnMAP satellite with permission from DLR Space Administration

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Spaceborne hyperspectral sensing for agricultural monitorin

- *"Remote sensing data can greatly contribute to the monitoring task by providing timely, synoptic, cost efficient and repetitive information about the status of the Earth's surface"* (Atzberger, 2013)
- **Nowadays, a multitude of remote sensing platforms are available,** providing either high spatial resolution, high spectral resolution, high revisit cycle, or a combination of two of these aspects. Platforms range from drones and vehicles to planes and satellites.
- **Spaceborne sensors** provide the huge advantages of no or limited cost for the user and a long-term archive, hence representing a central possibility for frequent near-real time monitoring over large areas, as needed in world agricultural systems.
- Current **Earth observation (EO) mission Sentinel-2** opened the door for revisiting agricultural mapping and monitoring, and for addressing new challenges, related to the diversity of cropping systems at global scale. This is very important for climate adaptation: i.e. looking at a place having the same climate as another place in some decades, so it is possible to learn and predict.
- **A new generation of spaceborne imaging spectroscopy missions is underway**, which will enable to repetitively estimate more challenging traits, such as pigments, nitrogen content and non-photosynthetic vegetation, and hence will provide *enhanced understanding of underlying physiological processes of functional traits.*

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Spaceborne hyperspectral sensing for agricultural monitorin

- There is a range of agricultural applications that *potentially* can be supported by spaceborne hyperspectral remote sensing:
  - Monitoring of vegetation status and dynamics
  - Nutrient and water status
  - Crop evapotranspiration
  - Weed identification and management
  - Pest and disease infestation
  - Crop yield and production forecasting
  - Precision agriculture

While few of these applications already are beginning to become operational, we are still far away from some.

For all these purposes, crop characteristics or functional vegetation traits need to be inferred from hyperspectral data:

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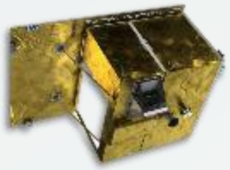
Spaceborne hyperspectral sensing for agricultural monitoring



Why should we prefer hyperspectral sensors over multi-spectral systems?

A recent review study elaborated this for ecological applications.

All citations from Ustin & Middleton (2021):

- *"There is an unprecedented array of new satellite technologies with capabilities for advancing our understanding of ecological processes and the changing composition of the Earth's biosphere at scales from local plots to the whole planet."*
- *"Hyperspectral (or spectroscopy-based) imagery allows identification of detailed chemical composition because the large number of bands, especially when they are narrow and contiguous or overlapping, can directly describe relevant absorption or reflectance features…"*
- *„High-frequency monitoring of agriculture will increase the likelihood of obtaining timely data throughout a growing season, especially at critical developmental stages in a crop's life cycle or when affected by environmental stresses (e.g., drought or disease)."*

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Berger et al. 2021

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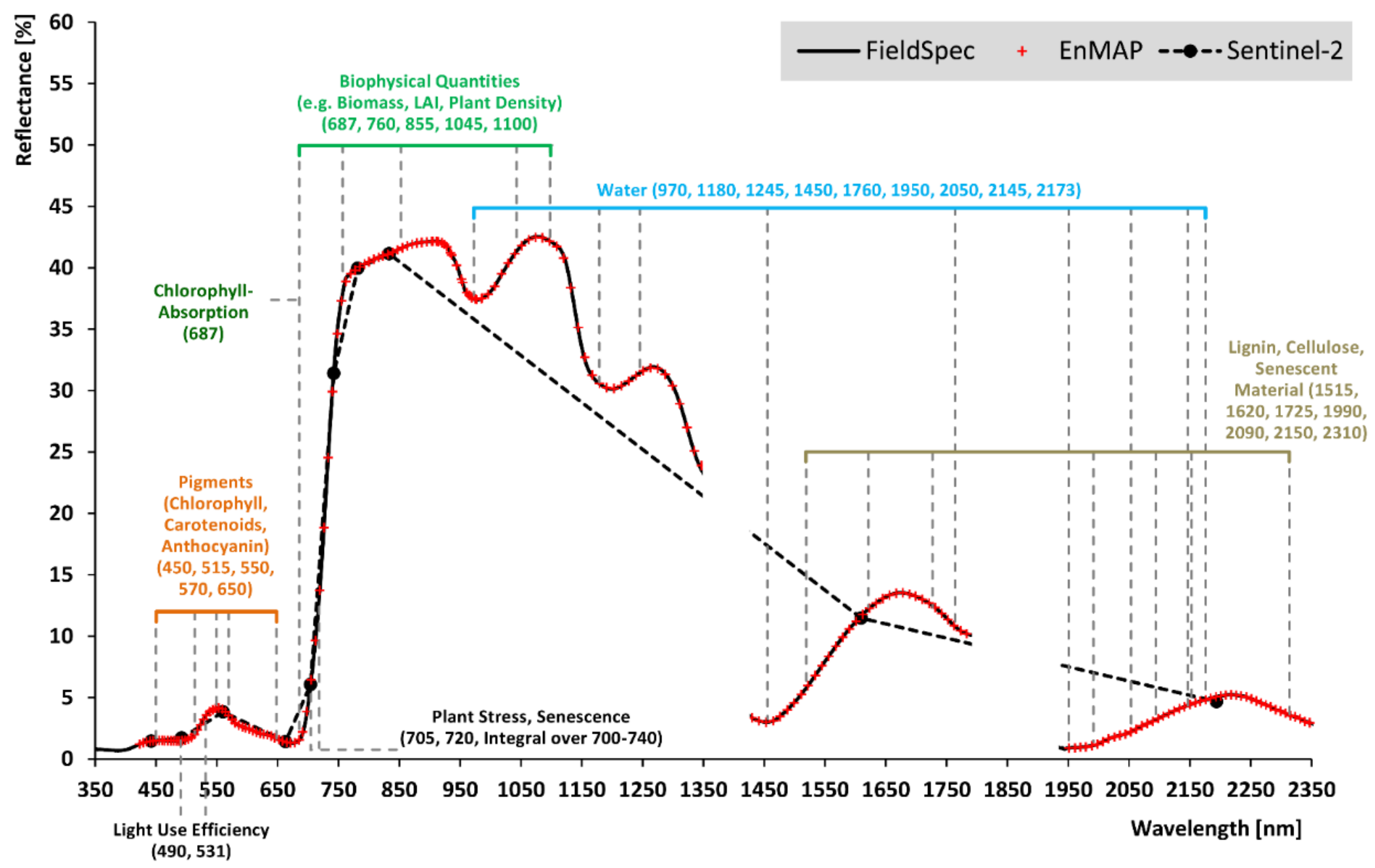
Satellite imaging spectroscopy

Enhanced information content from hyperspectral data opposed to multi-spectral sensing:



Hank et al., 2019

- Spectral domains that respond to changes of specific variables in vegetation [absorption lines modified after Thenkabail et al. (2013).
- Vital vegetation (*Triticum aestivum*) spectra in the background are displayed for a quasi-continuous spectral resolution of:
  - ASD FieldSpec4 Standard (black solid line),
  - multispectral configuration corresponding to the spectral bands of ESA Sentinel-2 (black dashed line) and
  - for the narrow-band configuration of the future EnMAP Hyperspectral Imager (red crosses).
  - Note that LAI is the dominant variable across the whole spectrum

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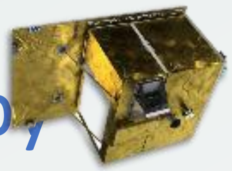
Recent and near-term satellite imaging spectroscopy



- After the two initial experimental Hyperion/EO-1 and CHRIS/PROBA missions, two primarily science-driven spaceborne sensors started to pave the way for future operational missions: the launched PRecursore IperSpettrale della Missione Applicativa (PRISMA, Loizzo et al., 2019) and planned Environmental Mapping and Analysis Program (EnMAP, Guanter et al., 2015).
- Among these future missions are: the FLuorescence EXplorer (FLEX, Drusch et al., 2017), the NASA Surface Biology and Geology observing system (SBG, NASA 2018) and the Copernicus Hyperspectral Imaging Mission for the Environment (CHIME, Nieke & Rast 2019).
- Apart from FLEX being dedicated to vegetation fluorescence retrieval, all these hyperspectral missions will observe reflected sunlight across a wide range of wavelengths from visible to shortwave infrared (SWIR) domains ("VSWIR", approximately 400-2500 nm) with the purpose of providing mapping and monitoring services for multiple civil and environmental domains (Verrelst et al., 2021).

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Next-generation spaceborne hyperspectral sensors

Mission (organiz., country)	Spectral range (SSD, no. of bands)	Spatial resolution (swath)	Repeat interval (days)	Launch	Purpose	Reference
DESIS (DLR, Germany)	400-1000 nm (2.55 nm , 235 bands)	30 m (30 km)	3 (63 TOD)	29.06.2018	Scientific precursor	Krutz et al. (2019)
PRISMA (ASI, Italy)	400-2500 nm (6-12 nm, 240 bands)	30 m (30 km)	29 (7, repeat roll m.)	22.03.2019	Technology demonstrator	Loizzo et al. (2019)
HISUI (METI, Japan)	400-2500 nm (10-12 nm, 185 bands)	20 m (cross-track) x 30 m (along-track) (20 km)	3 (63 TOD)	05.12.2019	Operational	Matsunaga et al. (2017)
EnMAP (DLR, Germany)	400-2500 nm (6.5-10 nm, 242 bands)	30 m (30 km)	27 (4 off-nadir)	12/2021	Scientific precursor	Guanter et al. (2015)
SHALOM (Italian-Israeli)	400-2500 nm (10 nm, 275 bands)	10 m (30 km)	?	2022	Operational/ commercial	Feingersh & Ben Dor (2015)
CHIME (ESA)	400-2500 nm (225 bands)	20-30 m (290 km?)	10-12.5	2025-2030	Copernicus high-priority mission candidate	Nieke & Rast (2018), Ustin & Middleton (2021)
SBG (NASA, U.S)	VSWIR: 380-2500 nm (10 nm, 210 bands)	30-45 m (150 km)	≤ 16	2026/2027	Operational	NASA (2018); Cawse-Nicholson et al. (2021)
FLEX/FLORIS (ESA)	500-780 nm (434 bands)	300 m (150 km)	27	planned for 2024	Scientific precursor	Coppo et al. (2017)

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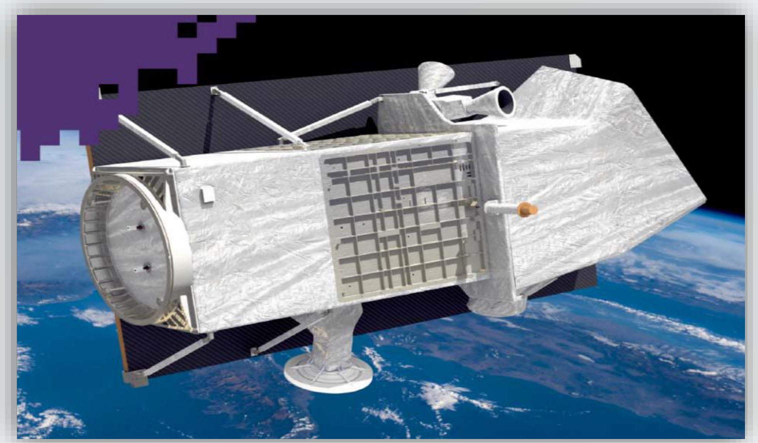
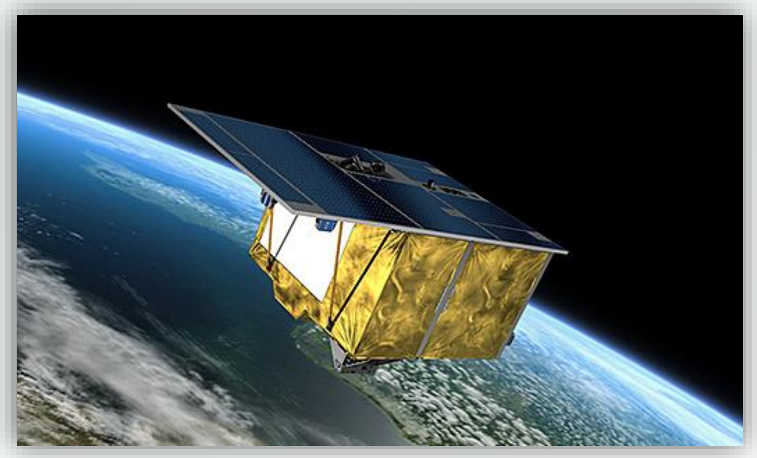
Technology demonstrator and scientific precursor missions

PRISMA: PRecursore IperSpettrale della Missione Applicativa


Facchinetti et al., 2019

The Italian mission aims to offer data for multiple applications within environmental monitoring and resources management, among those agriculture. PRISMA combines an hyperspectral sensor with a medium-resolution panchromatic camera. This combination offers the advantages of conventional earth observation by recognizing the geometric characteristics of a landscape.

EnMAP: Environmental Mapping and Analysis Program



The German hyperspectral satellite mission that aims at monitoring and characterising Earth's environment on a global scale. EnMAP measures and models key dynamic processes of Earth's ecosystems by extracting geochemical, biochemical and biophysical variables that provide information on the status and evolution of various terrestrial and aquatic ecosystems. See also: https://www.enmap.org/mission

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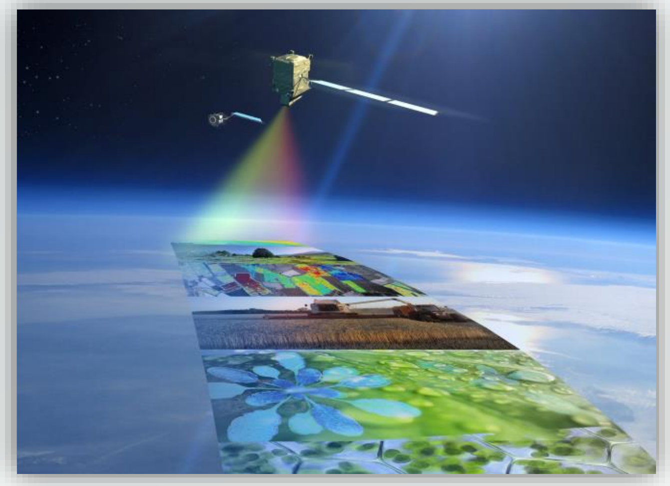
Berger et al. 2021

Promising ESA next-generation sensors

CHIME: Copernicus Hyperspectral Imaging Mission for the Environment

CHIME, foreseen to become part of the Copernicus fleet, shall provide free access to Level 1B, 1C and 2A products. CHIME sensor will be designed with the goal to provide routine hyperspectral observations and to provide a set of downstream-products, among others vegetation functional traits, as part of the mission catalogue to encourage the operational use of the data.

FLEX: Fluorescence Explorer



FLEX, a vanguard for a future operational mission, will fly ahead of Sentinel-3, overlapping swaths of OLCI and SLSTR instruments. FLEX shall support a large variety of services, for instance early detection and warning of stress-induced strain in perennial food crops, evaluation of land-use management strategies, or phenotyping assessments of food and feed crops.

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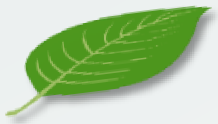


- In this chapter we will provide an overview of the most relevant agricultural traits that can be predicted from remote sensing observations with examples of (spaceborne) hyperspectral mapping.
- Information of interest consists of *functional traits* or *variables* or *features* of the agricultural systems, and especially how these vary in space and time (Weiss et al., 2020). Note that the term "*variable*" is something that is measurable and has a physical or agronomical meaning (Jeuffroy et al., 2014). A parameter is something resulting from an empirical fitting. Hence, we prefer the term variable or trait in these contexts.
- Nature of these agronomic traits can be:
  - *typological* (e.g. crop type),
  - *biophysical* (e.g. soil moisture),
  - *morphological* (e.g. foliage height diversity, leaf dry mass per leaf area)
  - *biochemical* (e.g. leaf nitrogen content),
  - *biological* (e.g. crop phenology),
  - *structural-geometrical* (e.g. leaf inclination, LAI).
- Some variables of interest, such as crop productivity, irrigation needs or phenology, result from a series of intertwined biophysical processes within the soil-plant-atmosphere continuum. These secondary variables are not directly related to the radiative transfer mechanisms and thus cannot be inferred directly from imaging spectroscopy data (Weiss et al., 2020). They can, however, be accessed via process modelling.

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Classification of variables

Hereby, we distinguish between variables that are directly involved in radiative transfer mechanisms!

Vegetation traits & radiative transfer

Directly drive radiative transfer:
Primary variables

Leaf level traits

- Pigment content (chlorophyll, carotenoid, & anthocyanin contents)
- Leaf mesophyll structure
- Leaf water

Canopy level traits

- LAI (green LAI, brown LAI)
- Leaf inclination
- Green cover fraction
- fAPAR
- Albedo
- Soil moisture?

Indirectly drive radiative transfer:
Secondary variables

- Evapotranspiration
- Nitrogen content
- Phenology
- Crop yield
- Water stress
- Irrigation needs
- Crop coefficient

Berger et al. 2021