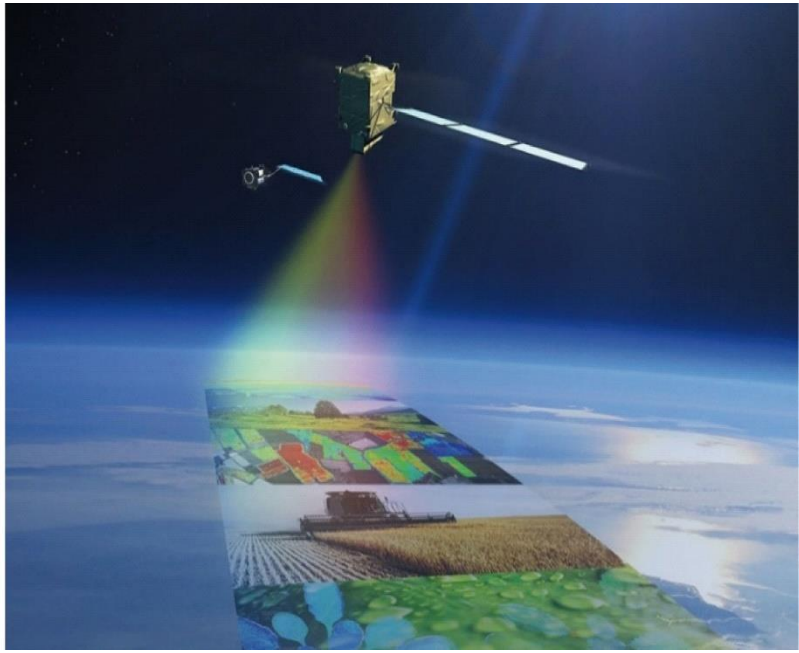




MEASURING PLANT STRUCTURE AND FUNCTION USING OPTICAL REMOTE SENSING

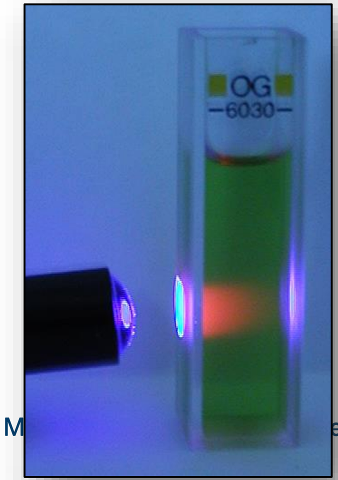
current status and recent developments of airborne and satellite remote sensing and their potential for disease detection

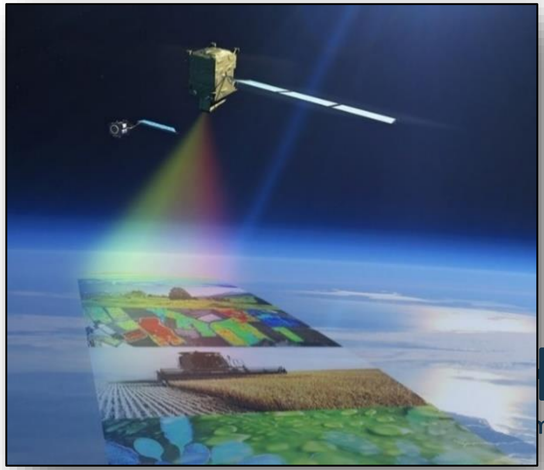
Uwe Rascher – Research Centre Jülich (Forschungszentrum Jülich), IBG-2: Plant Sciences, Germany

19. AUGUST 2023

Outline

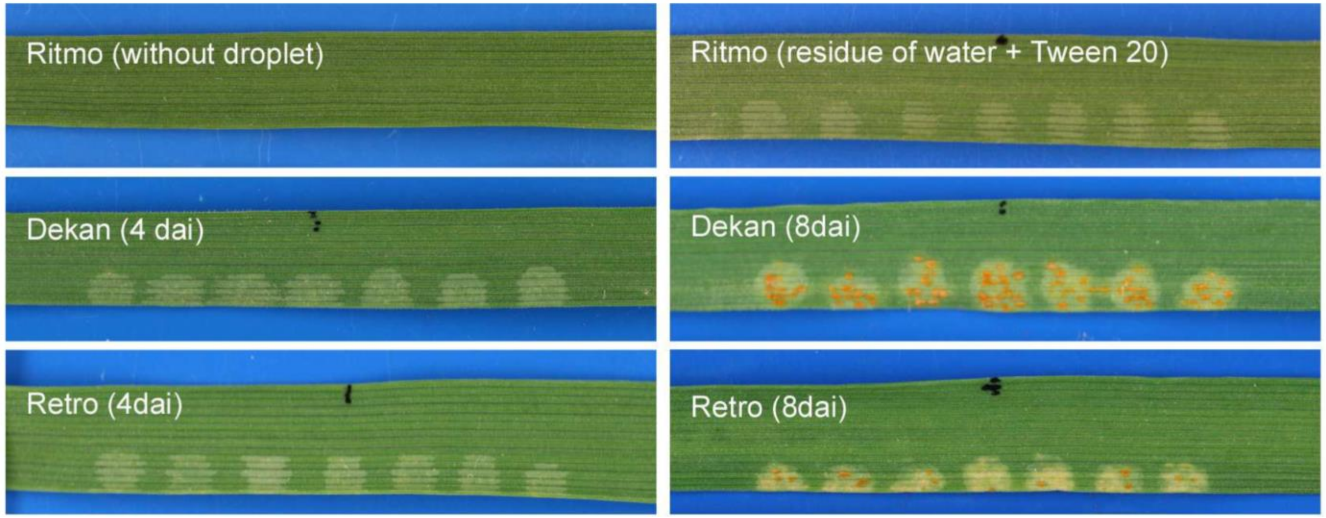
- ❑ Optical remote sensing – measuring with light (photons) and the challenge of scale
- ❑ Laboratory studies – transferability to the field – increasing the scale with drones and aircrafts – possibilities and limitations for satellite based remote sensing
- ❑ Disease detection with optical approaches – spectrally resolved measurements, fluorescence and thermal approaches
- ❑ Possibilities to detect diseases on the large scale – the balance between spectral, spatial and temporal resolution
- ❑ Direct detection of disease symptoms and confounding factors



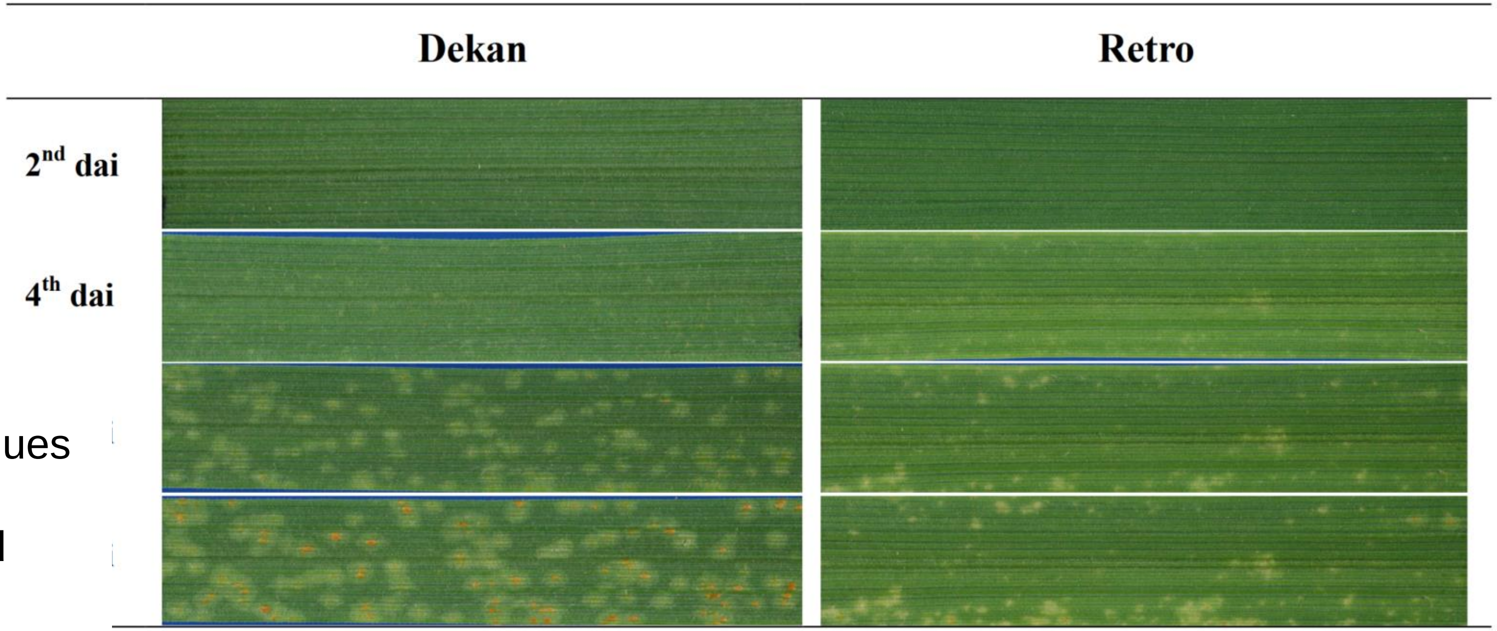


Disease detection using spectrally resolved and fluorescence imaging - going back 10-15 years and into the laboratory

- Well-controlled laboratory studies to develop approa-ches for disease detection with optical sensors



wheat leaves 4 and 8 days
after inoculation with *P. triticina*

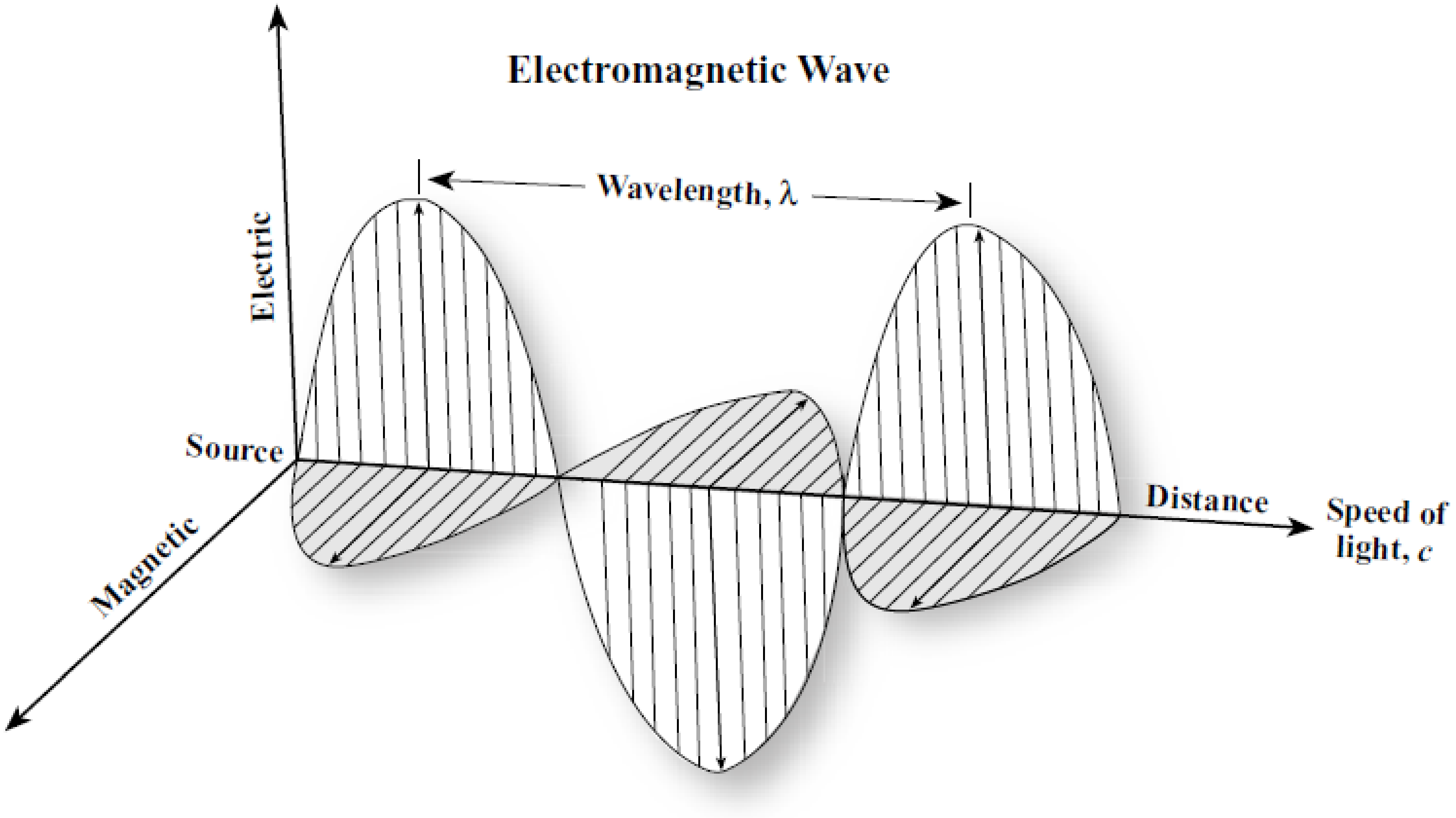


Leaf Rust on wheat leaves
suceptible cultivar, Dekan (left)
resistant cultivar, Retro (right)

Katrin Bürling (2010) Potential of fluorescence techniques with special reference to fluorescence lifetime determination for sensing and differentiating biotic and abioticstresses in Triticum aestivum L. – Dissertation University Bonn, Agricultural Faculty

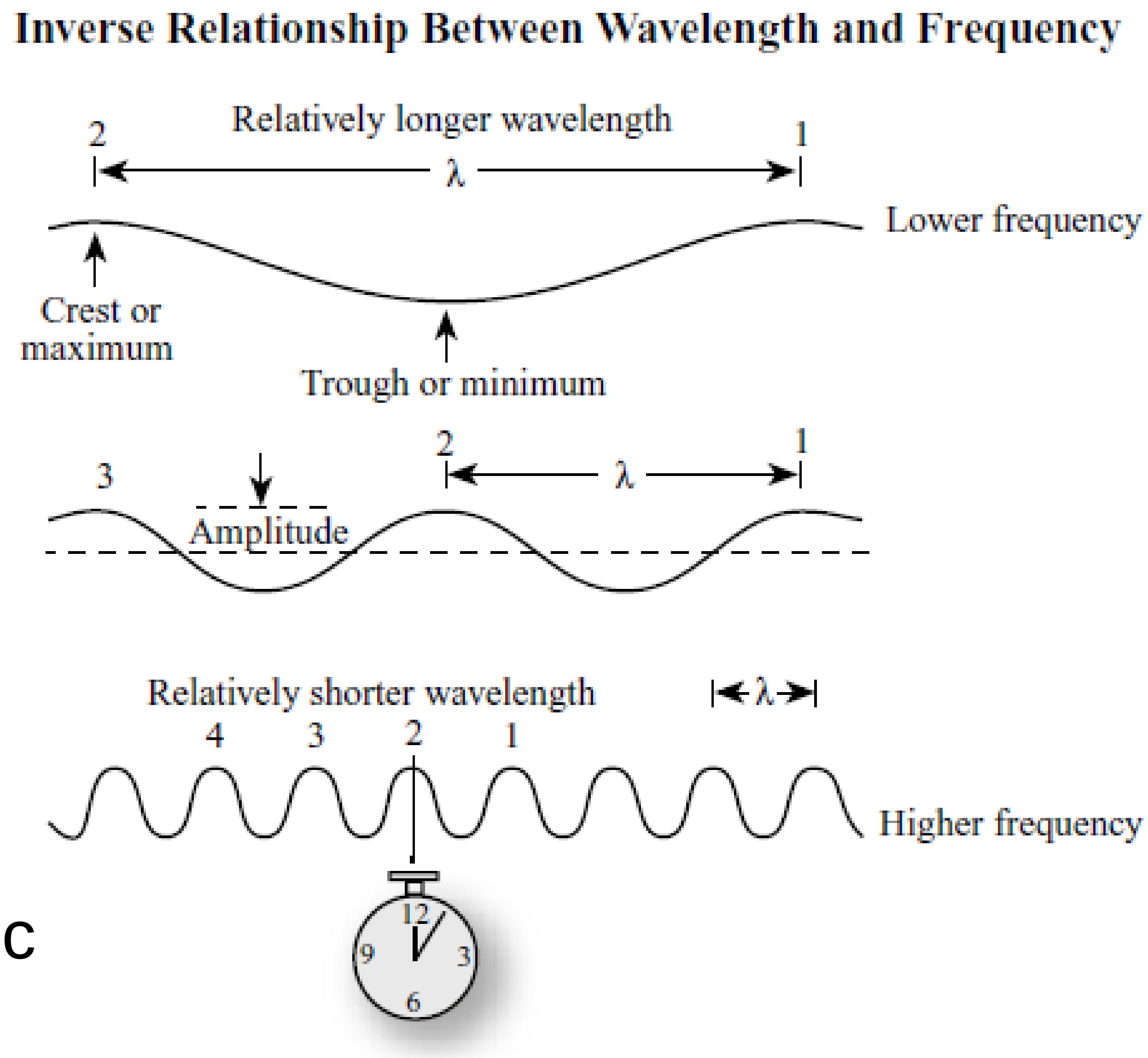
What is light – a concept for the non-physicist

- „Light is a flux of photones, which travel with light speed and which can best be described with a wave function
- Speed of light (c) is constant and is 300 000 km/s



What is light – a concept for the non-physicist

- The amplitude of the wave is ± constant
- The wavelength (λ) describes the distance between two maxima [measured in m]
- The frequency (ν) is the number of oszillations per seconds [measured in Hz]
- $\lambda = c / \nu$
- The higher the frequency the more energy an electromagnetic radiation carries



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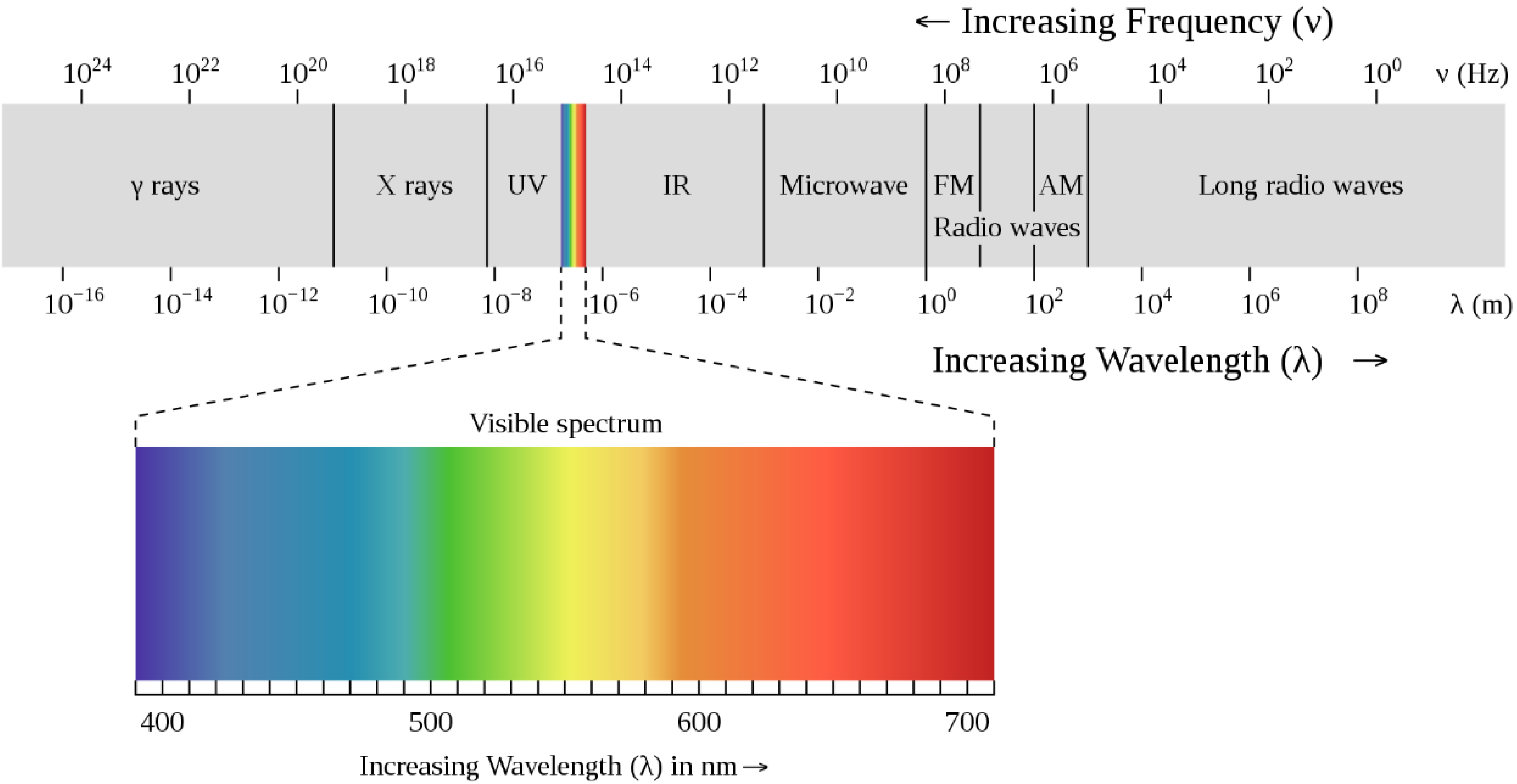
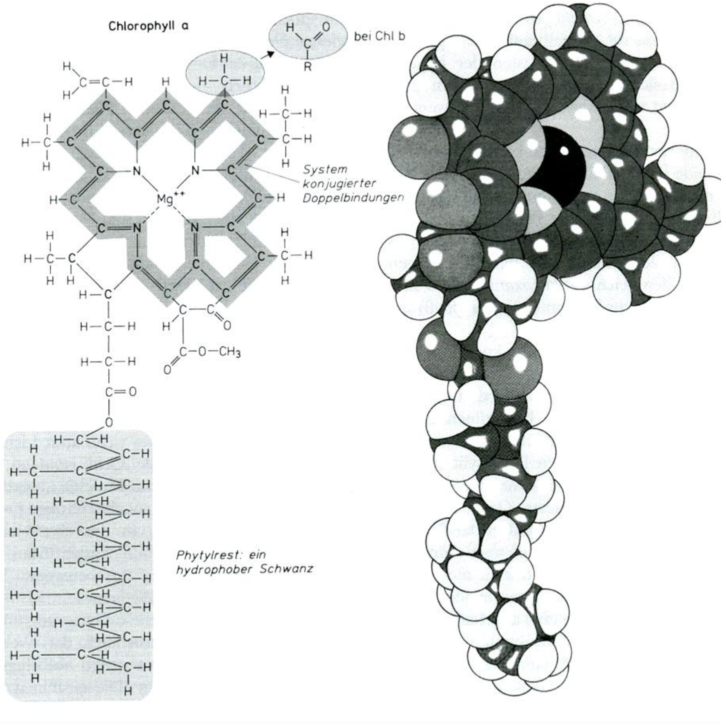
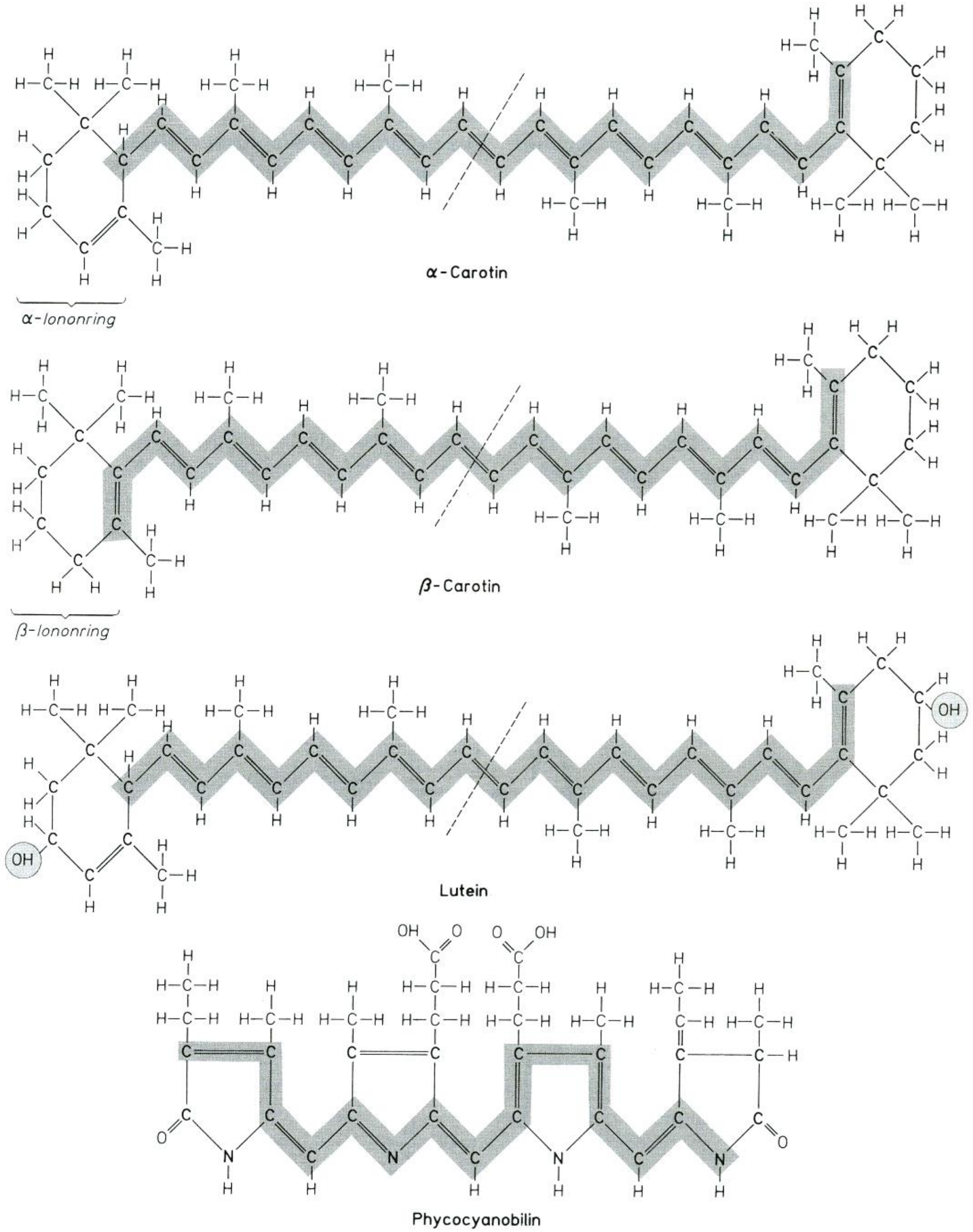


Light absorption: Lets have a closer look – what happens if photons interact with a leaf

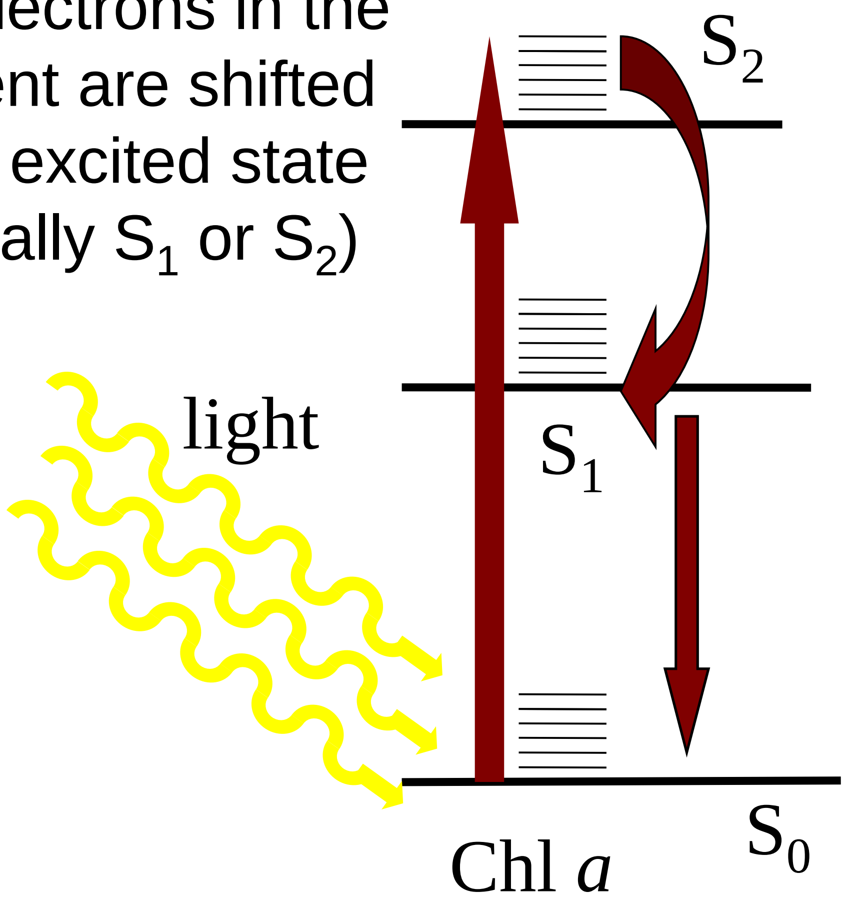
- Light interacts with pigments – photons in the visible spectral window are absorbed by plant pigments
  - Chlorophylls
    chlorophyll a
    chlorophyll b
  - Carotenoids
    α carotin
    β carotin
    lutein
    violaxanthin
    antheaxanthin
    …
  - Anthocyanins
  - Betalaine

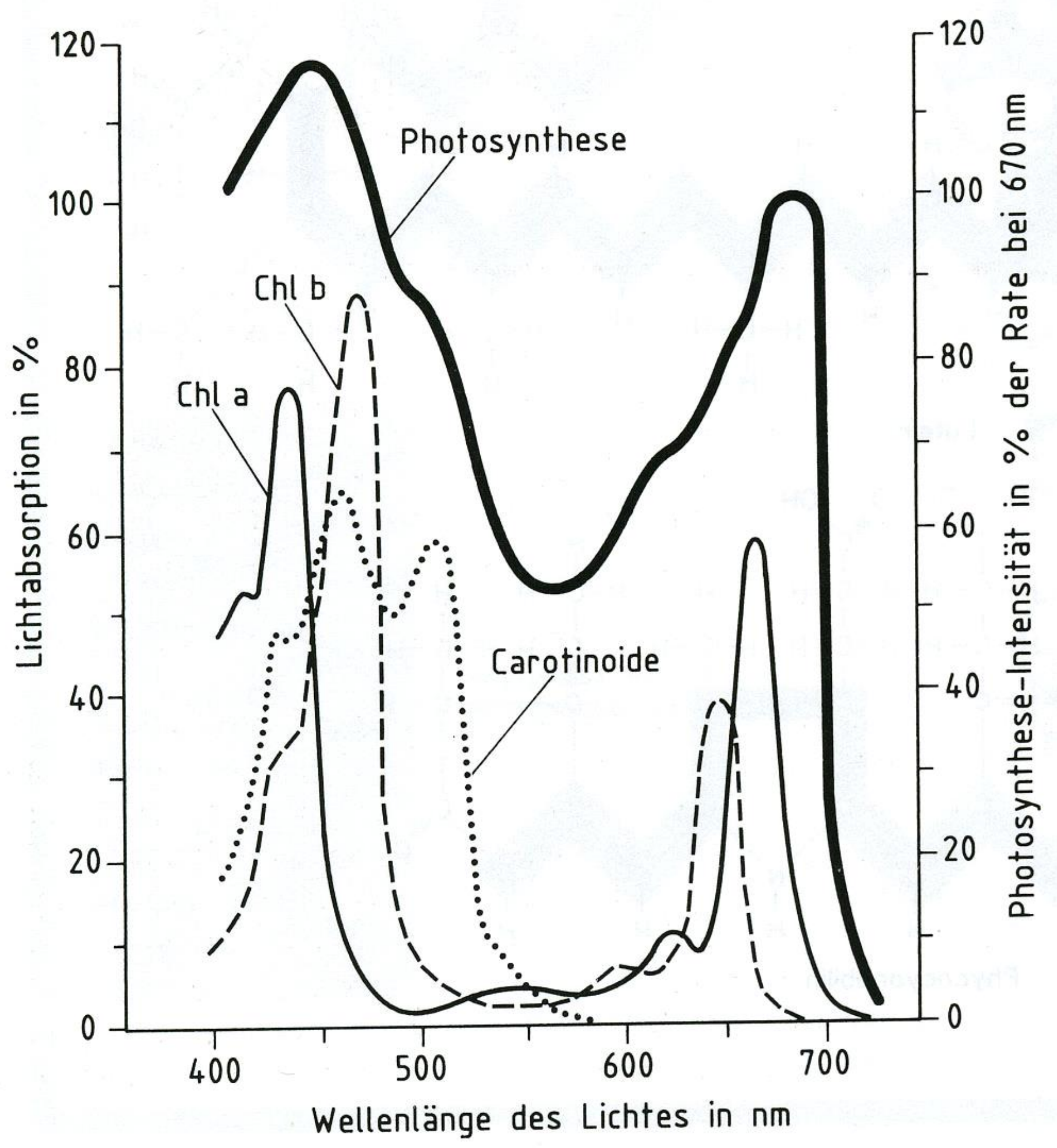




Light absorption: Lets have a closer look – what happens if photons interact with a leaf

Light absorption means that the energy in the photon is transferred to the pigment, the photon disappears and electrons in the pigment are shifted to the excited state (normally S_1 or S_2)



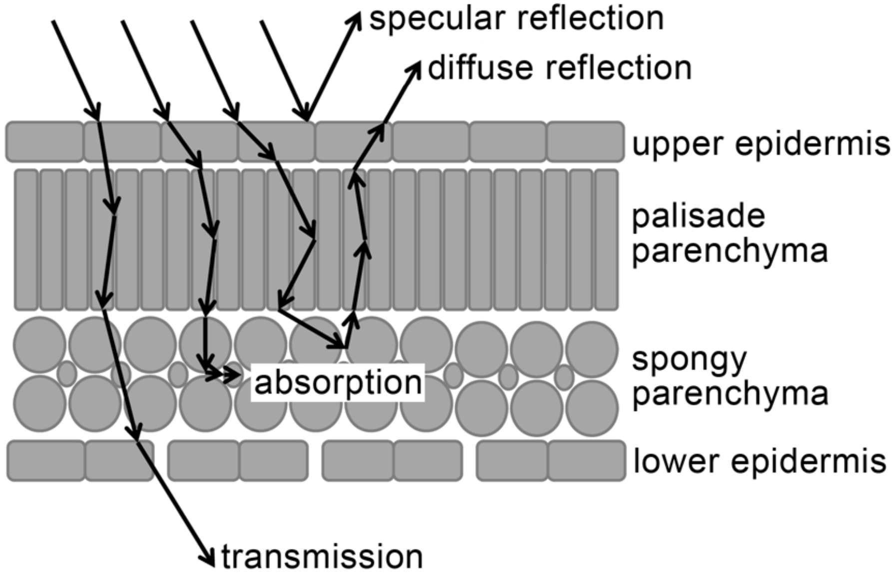


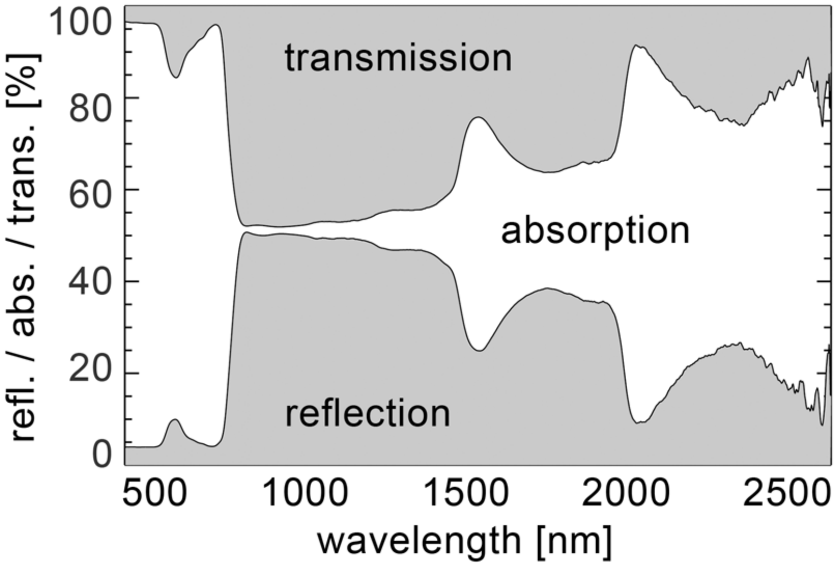
Light absorption: Lets have a closer look – what happens if photons interact with a leaf

- Photons describe a complex path within a leaf, but at the end they are either ***absorbed***, ***reflected*** or ***transmitted***

$$Reflection\ [\%] = \frac{Reflected\ irradiance\ [energy\ unit]}{Incoming\ irradiance\ [energy\ unit]}$$

$$Transmittance\ [\%] = \frac{Transmitted\ irradiance\ [energy\ unit]}{Incoming\ irradiance\ [energy\ unit]}$$





Rascher et al. (2010) Sensing of photosynthetic activity of crops. In Precision Crop Protection - the Challenge and Use of Heterogeneity. Springer Science+Business Media B.V., doi 10.1007/978-90-481-9277-9_6.

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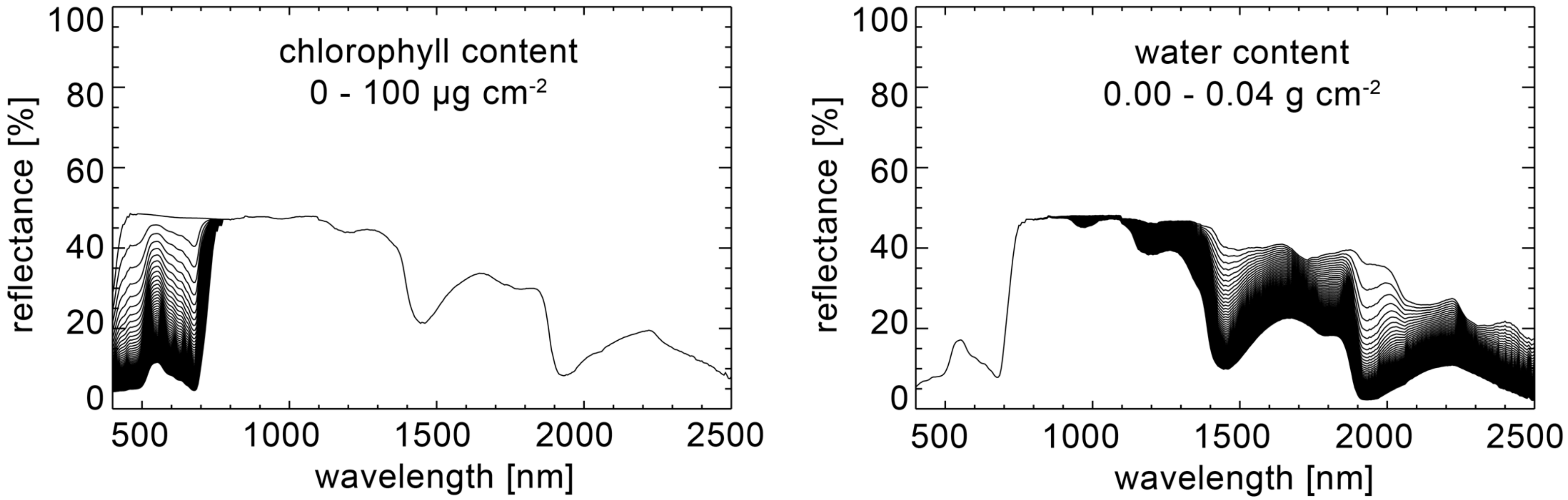
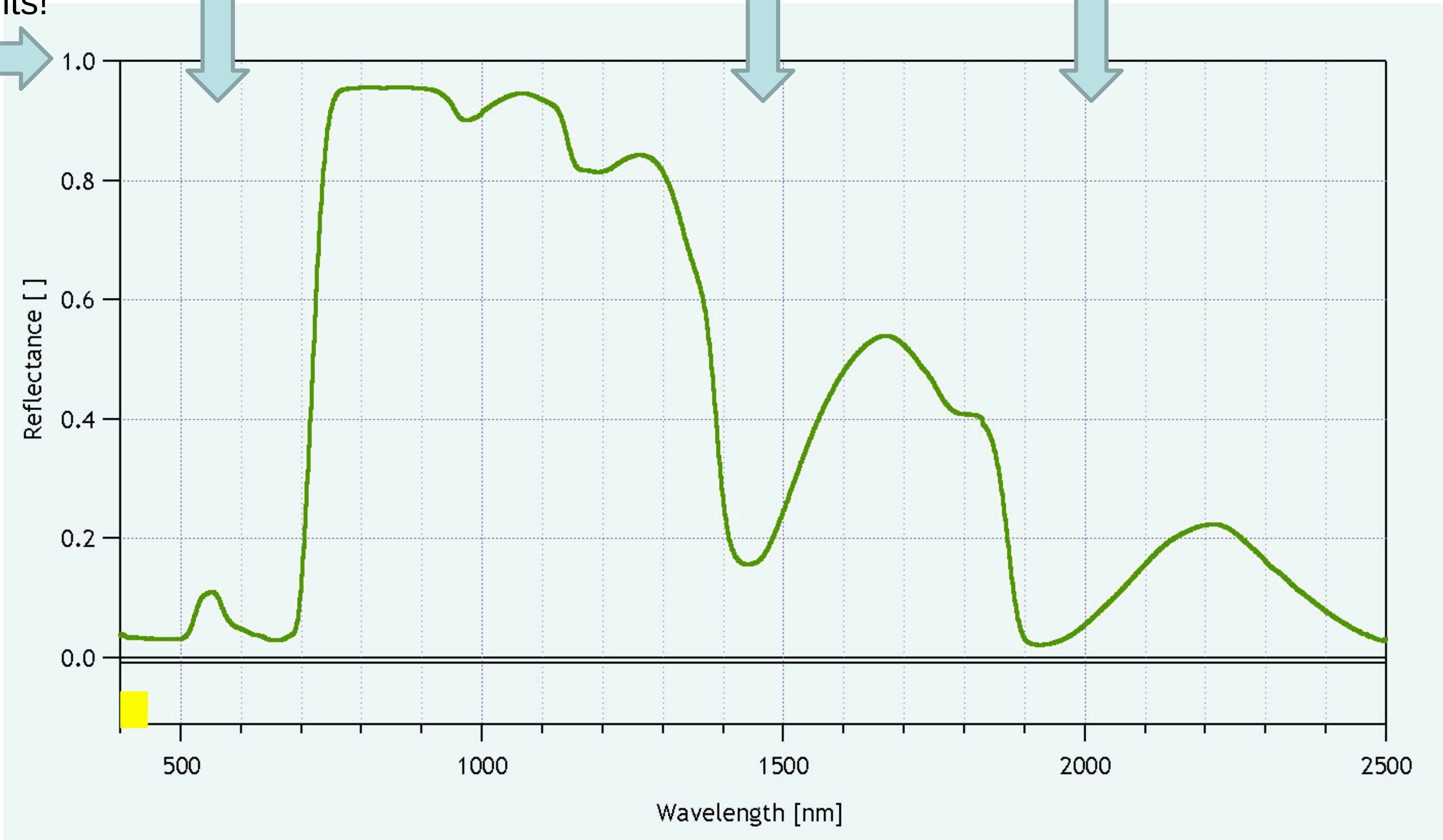


Light absorption: Lets have a closer look – what happens if photons interact with a leaf

wrong units!

Pigments

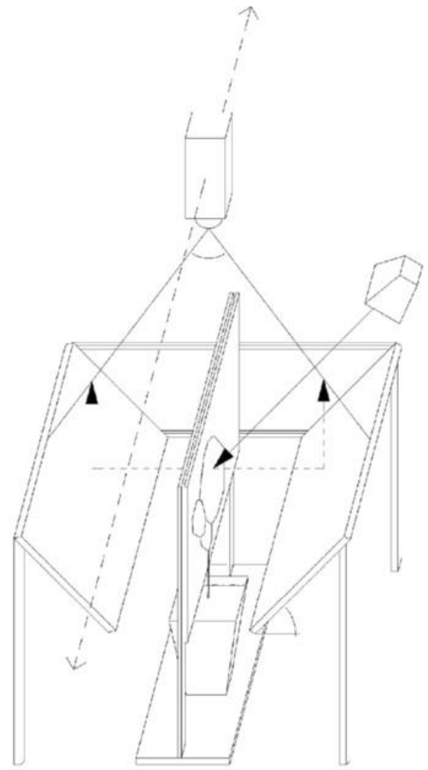
Water absorption bands

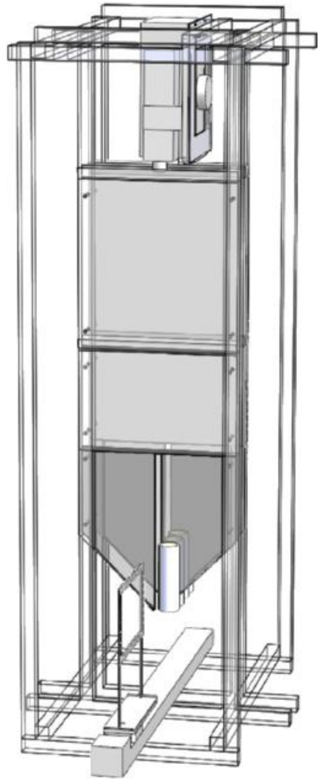


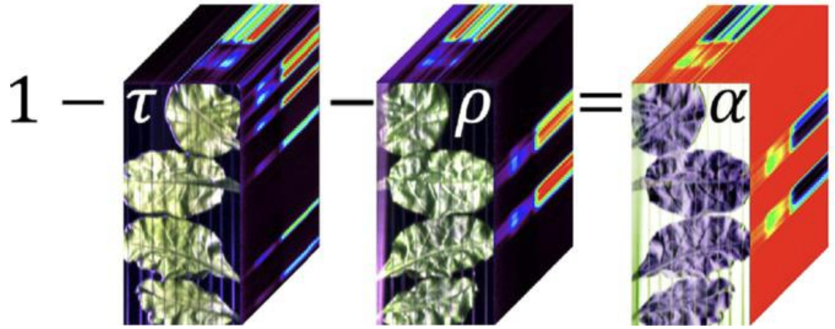
8 hours during which the healthy leaf
(i) dries out and
(ii) looses its pigments

Light absorption / transmission / reflection changes after disease infection – a case study

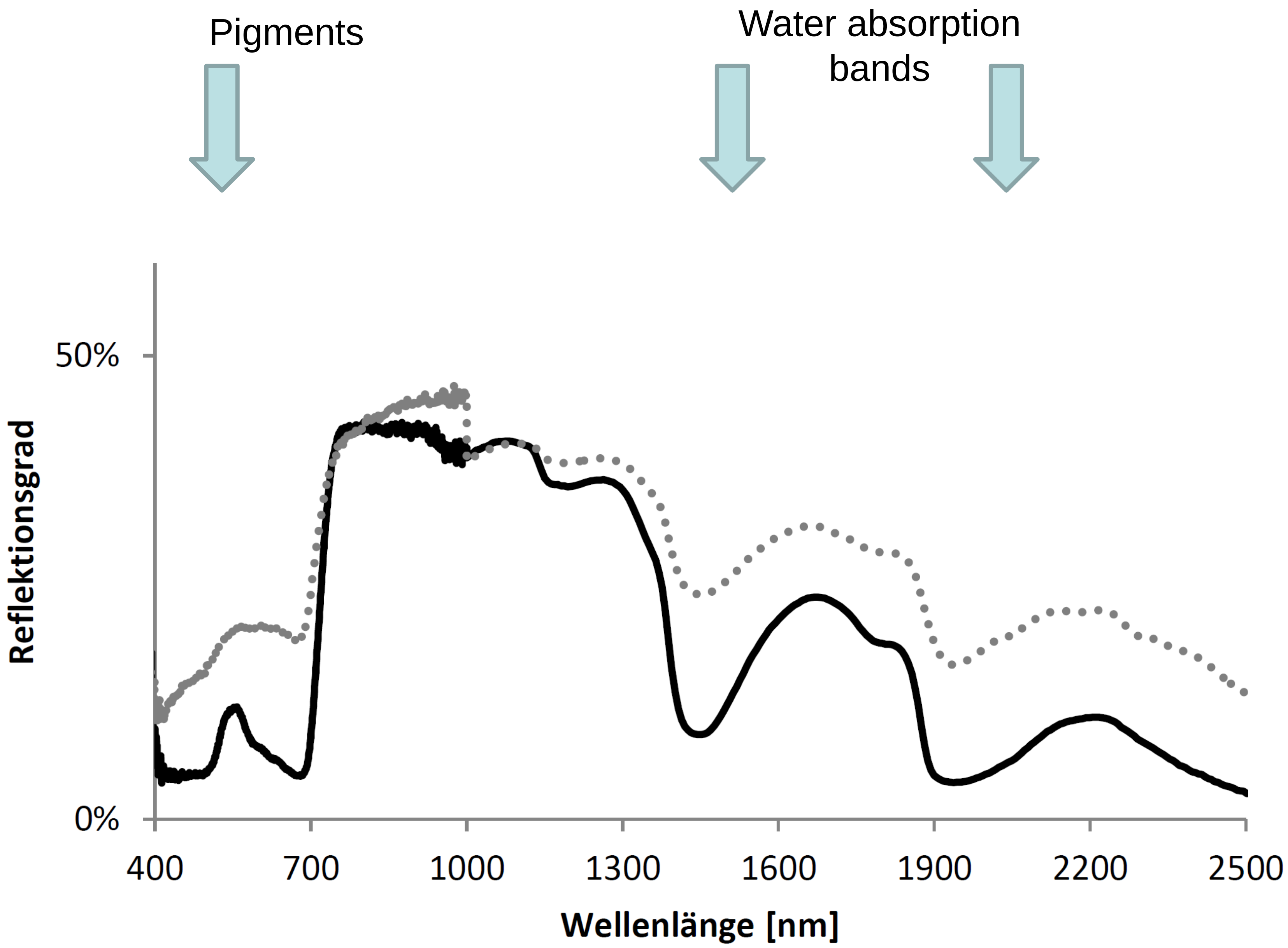
- Disease infection leaves a characteristic signature in reflectance / transmission / absorbance





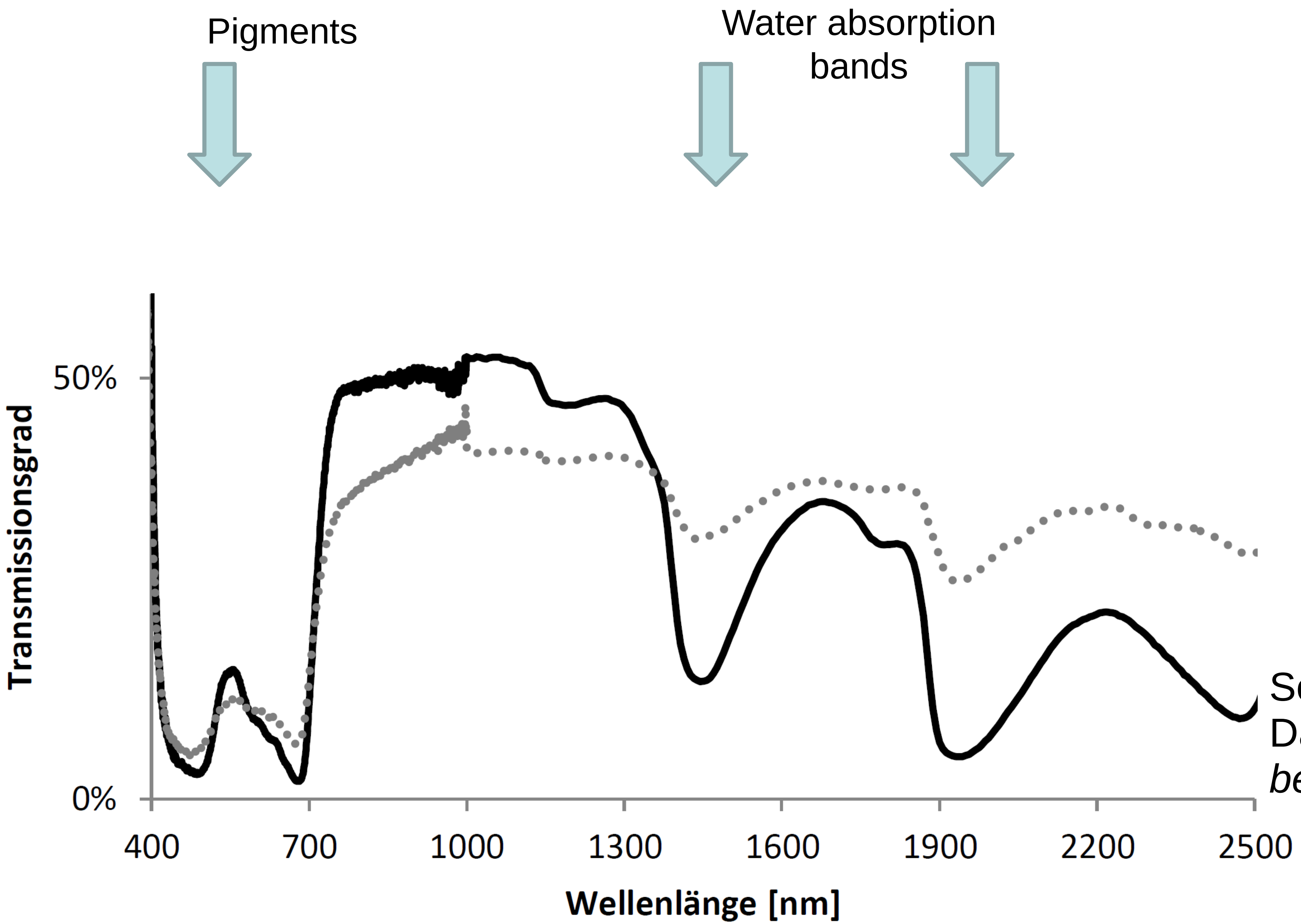


Light absorption / transmission / reflection changes after disease infection – a case study



Solid line: healthy leaves
Dashed lines: *Cercospora beticola* infection on sugar beet

Light absorption / transmission / reflection changes after disease infection – a case study



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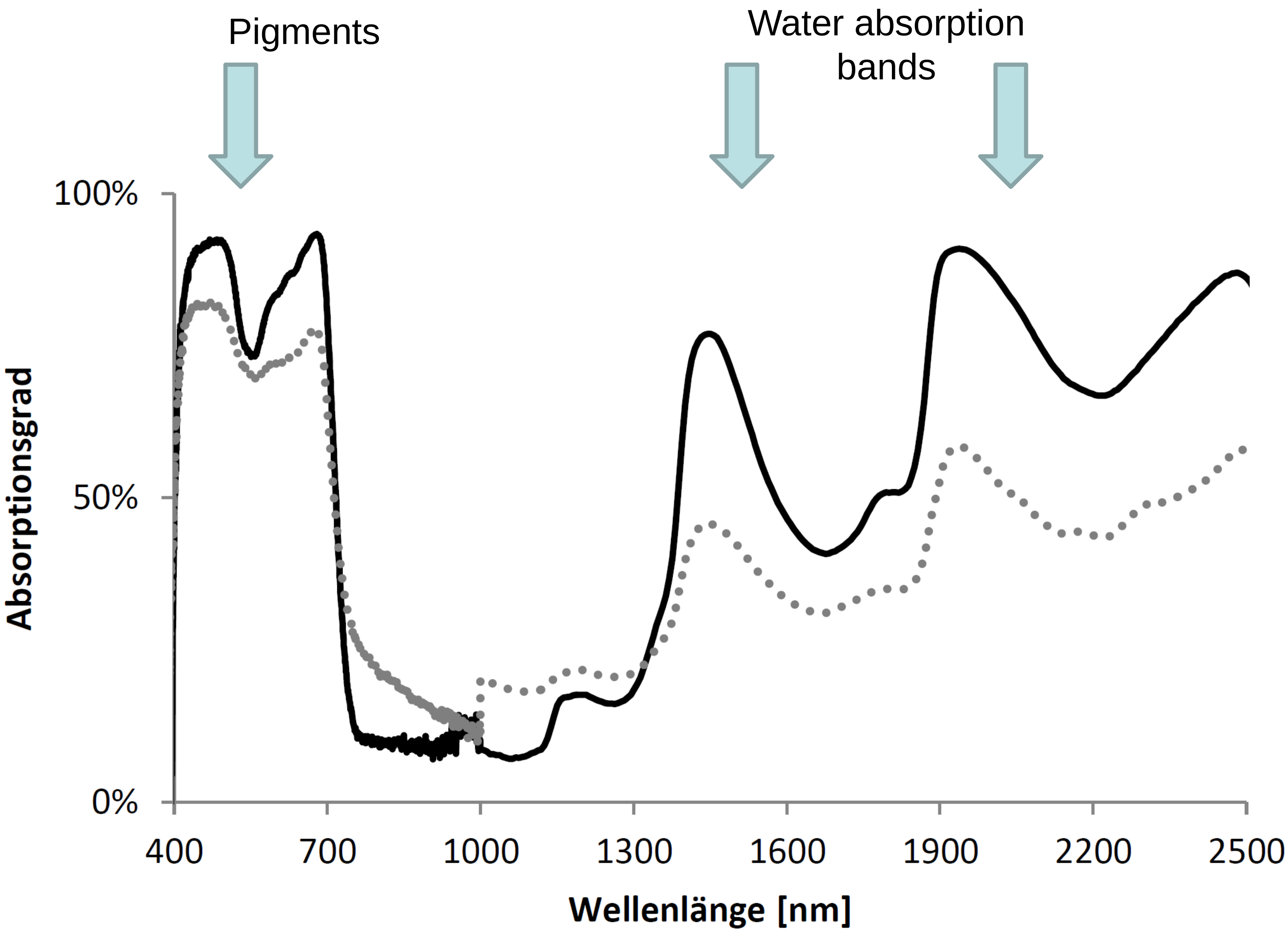
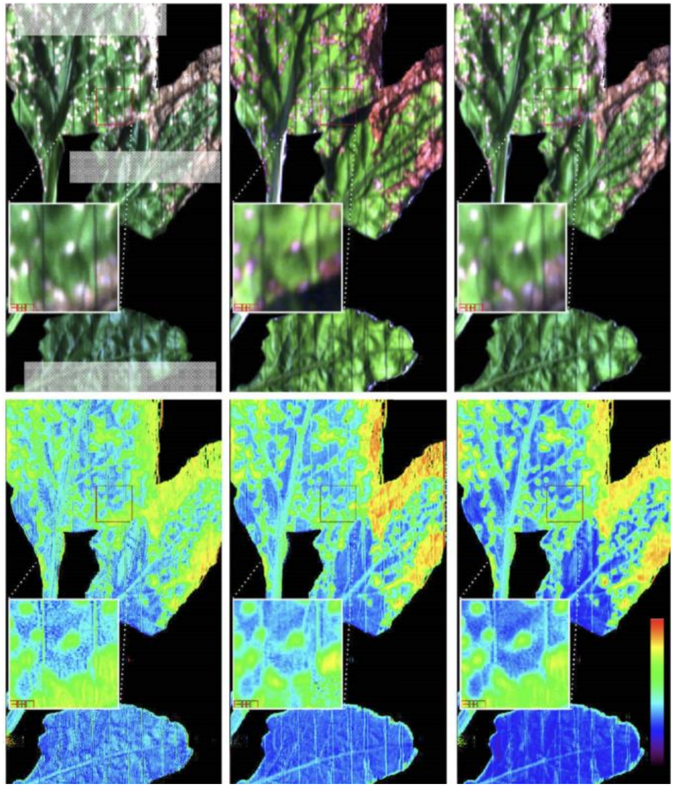
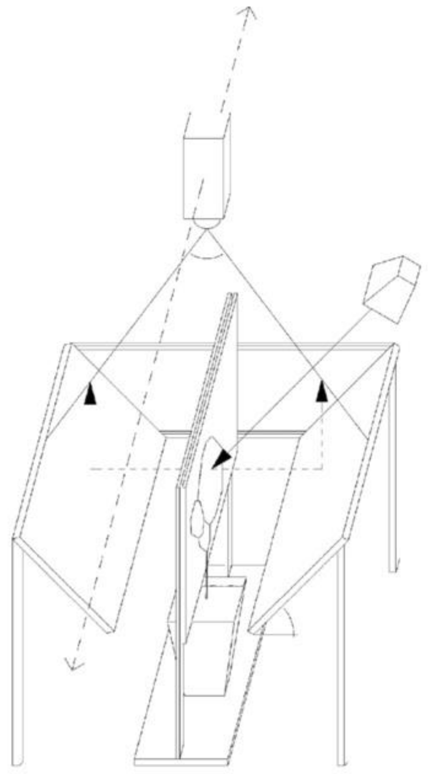


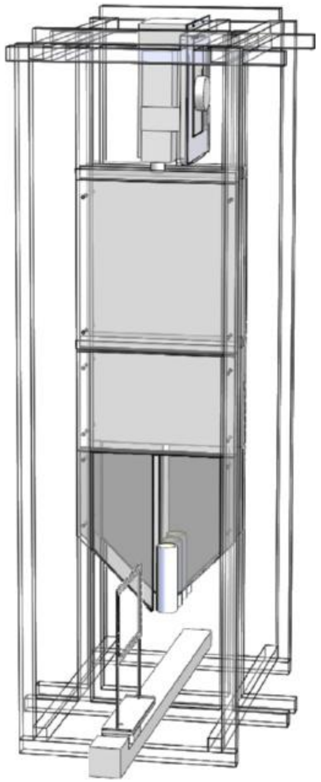
Solid line: healthy leaves
Dashed lines: *Cercospora beticola* infection on sugar beet

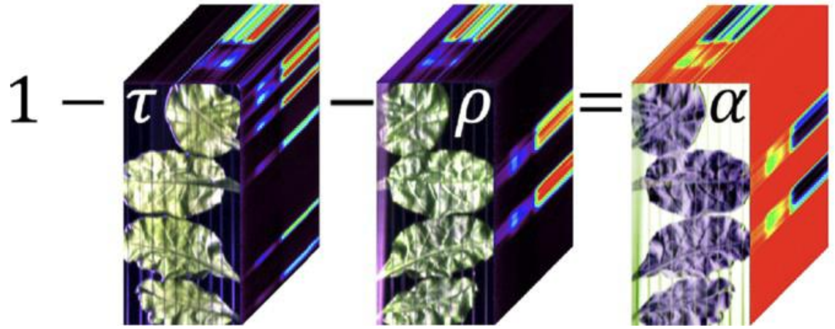
Light absorption / transmission / reflection changes after disease infection – a case study

- Disease infection leaves a characteristic signature in reflectance / transmission / absorbance
- High performance spectroscopy has been shown to detect plant disease symptoms





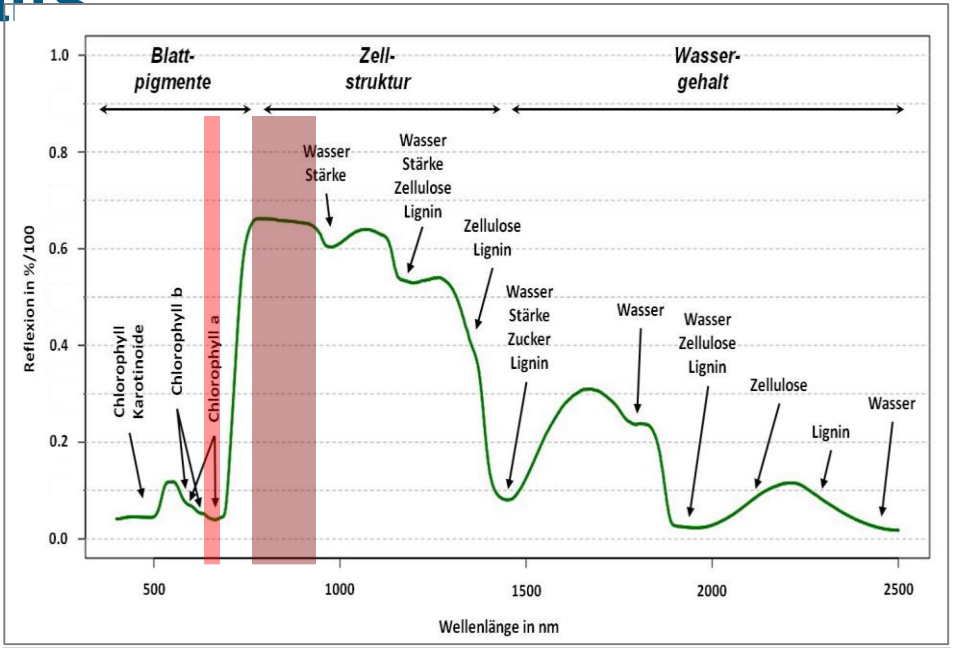




Bergsträsser et al. (2015) HyperART: non-invasive quantification of leaf traits using hyperspectral absorption-reflectance-transmittance imaging. *Plant Methods, 11:1*, doi:10.1186/s13007-015-0043-0

Vegetation Indices: An easy way to empirically translate spectrally resolved reflectance into plant traits

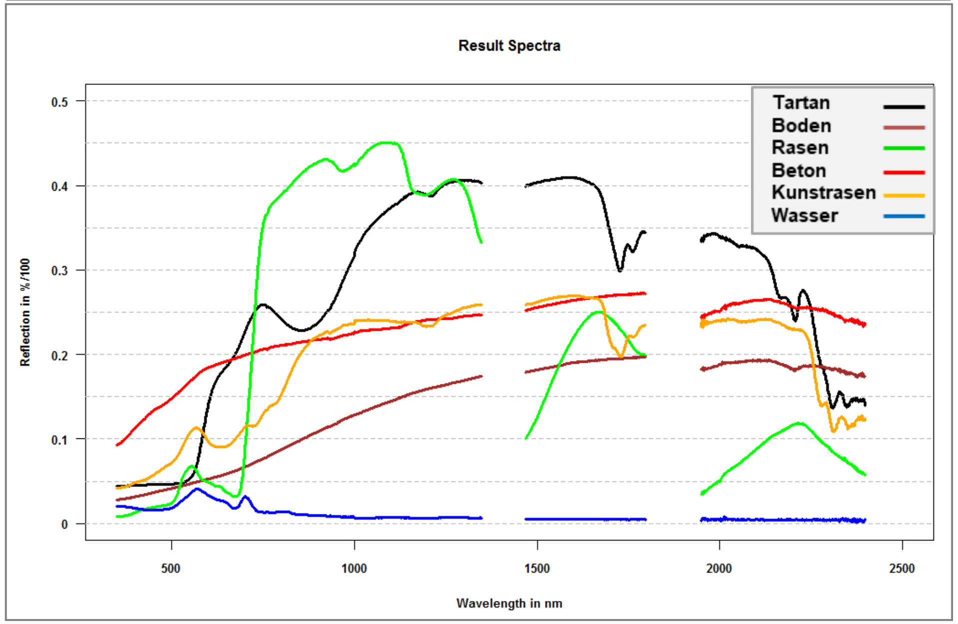
1. Classical greenness indices
   i. measure chlorophyll and LAI
   ii. widely used and can be derived from broad band sensors
   iii. require red and infra-red bands only



value range

$$Simple\ Ratio\ (SR) = \frac{R_{infra-red}}{R_{red}}$$ 0 - 7

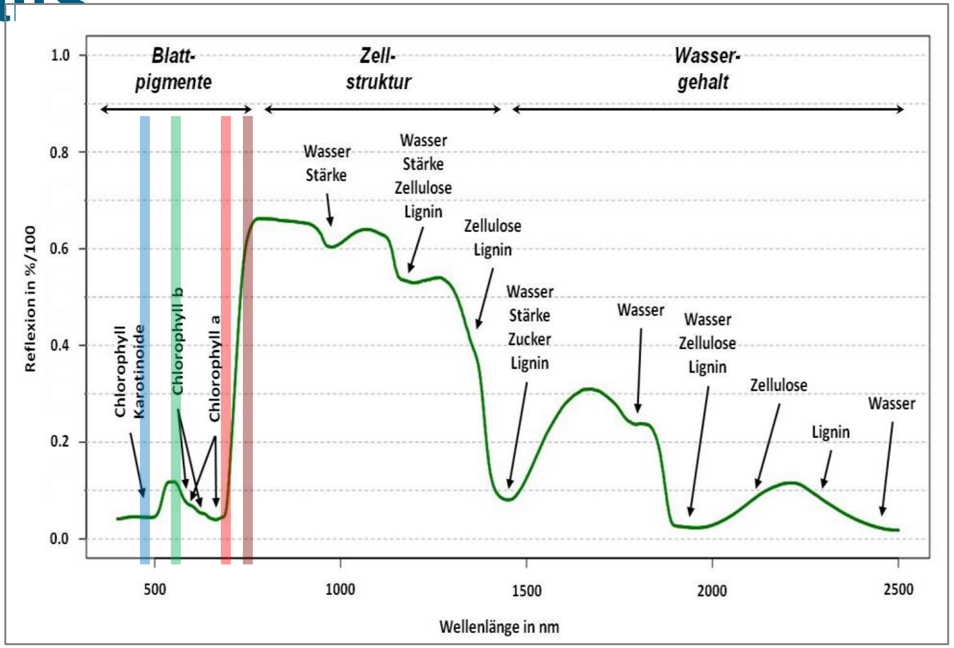
$$NDVI = \frac{R_{infra-red} - R_{red}}{R_{infra-red} + R_{red}}$$ 0 - 1



Normalized Difference Vegetation Index (NDVI) is independent to additive and multiplicative shifts in the data

Vegetation Indices: An easy way to empirically translate spectrally resolved reflectance into plant traits

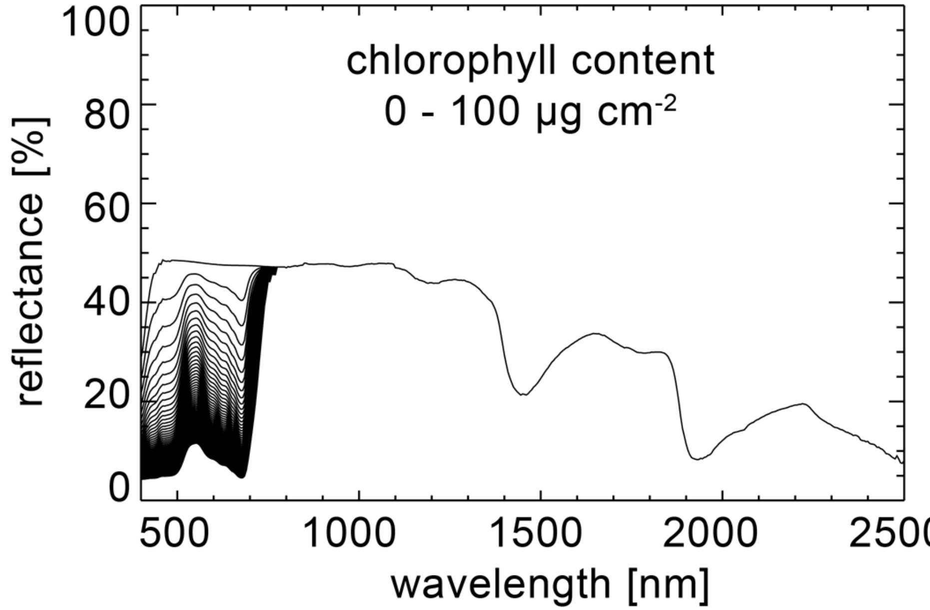
2. More advanced greenness indices
   i. measure chlorophyll and LAI
   ii. can also be used at dense vegetation
   iii. use smaller spectral windows or additional spectral bands



$$NDVI_{re} = \frac{R_{735-750} - R_{695-710}}{R_{735-750} + R_{695-710}}$$

$$EVI = 2.5\left[\frac{R_{795-810} - R_{665-680}}{R_{795-810} + 6R_{665-680} - 7.5R_{475-490} + 1}\right]$$

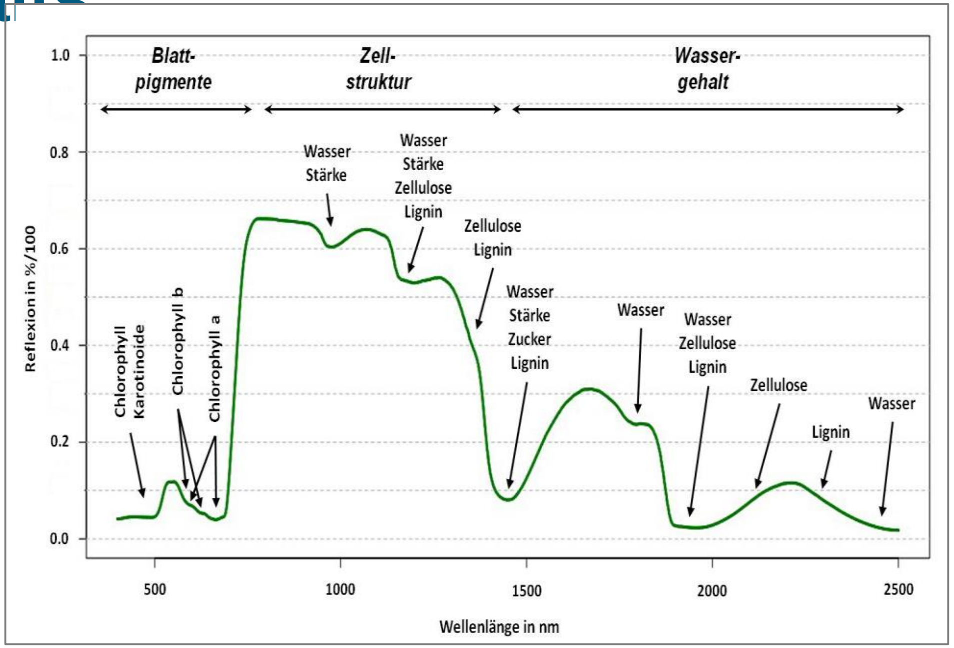
$$TCARI = 3\left[(R_{700\pm4} - R_{670\pm4}) - 0.2(R_{700\pm4} - R_{550\pm4})\left(\frac{R_{700\pm4}}{R_{670\pm4}}\right)\right]$$



$NDVI_{re}$: red-edge Normalized Difference Vegetation Index
EVI: Enhanced Vegetation Index
TCARI: Transformed Chlorophyll Absorption Reflectance Index

Vegetation Indices: An easy way to empirically translate spectrally resolved reflectance into plant traits

3. Other plant pigments / components
   i. large number of ‘dedicatd’ indices
   ii. Examples are
      - NDNI: Normalized Difference Nitrogen Index (N absorption at 1510 nm)
      - NDLI: Normalized Difference Lignin Index (lignin absorption at 1754 nm)
      - CAI: Cellulose Absorption Index (absorption at 2000 – 2200 nm)
      - PSRI: Plant Senscence Index (empirically correlated with senescens and fruit ripening)
      - …..
      - *CLSI*: *Cercospora* Leaf Spot Index
      - ……
   iii. use with extreme care as many of these indices are not specific



$$CLSI = \frac{R_{698} - R_{570}}{R_{698} + R_{570}} + R_{734}$$

Mahlein, A. K., Rumpf, T., Welke, P., Dehne, H. W., Plümer, L., Steiner, U. and Oerke, E. C. (2013). Development of spectral indices for detecting and identifying plant diseases. *Remote Sensing of Environment* **128**, 21-30.

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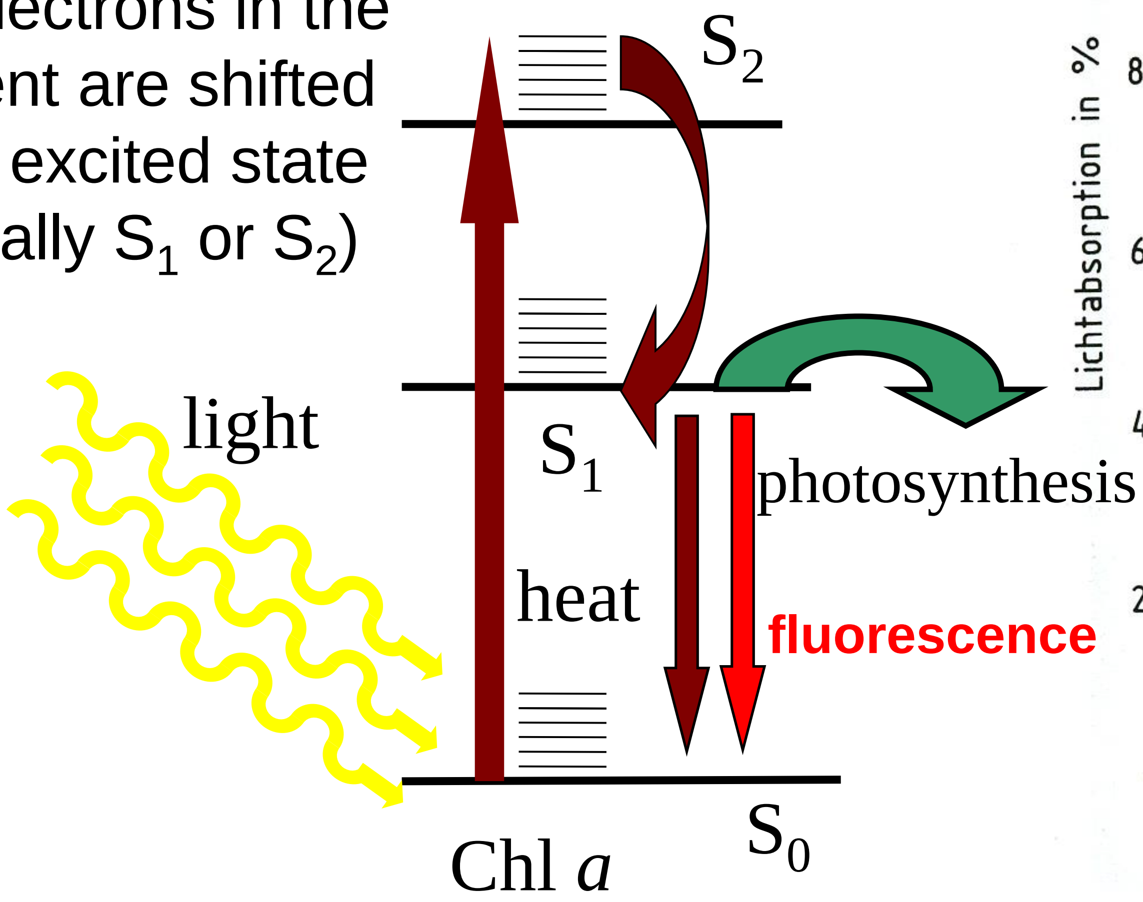
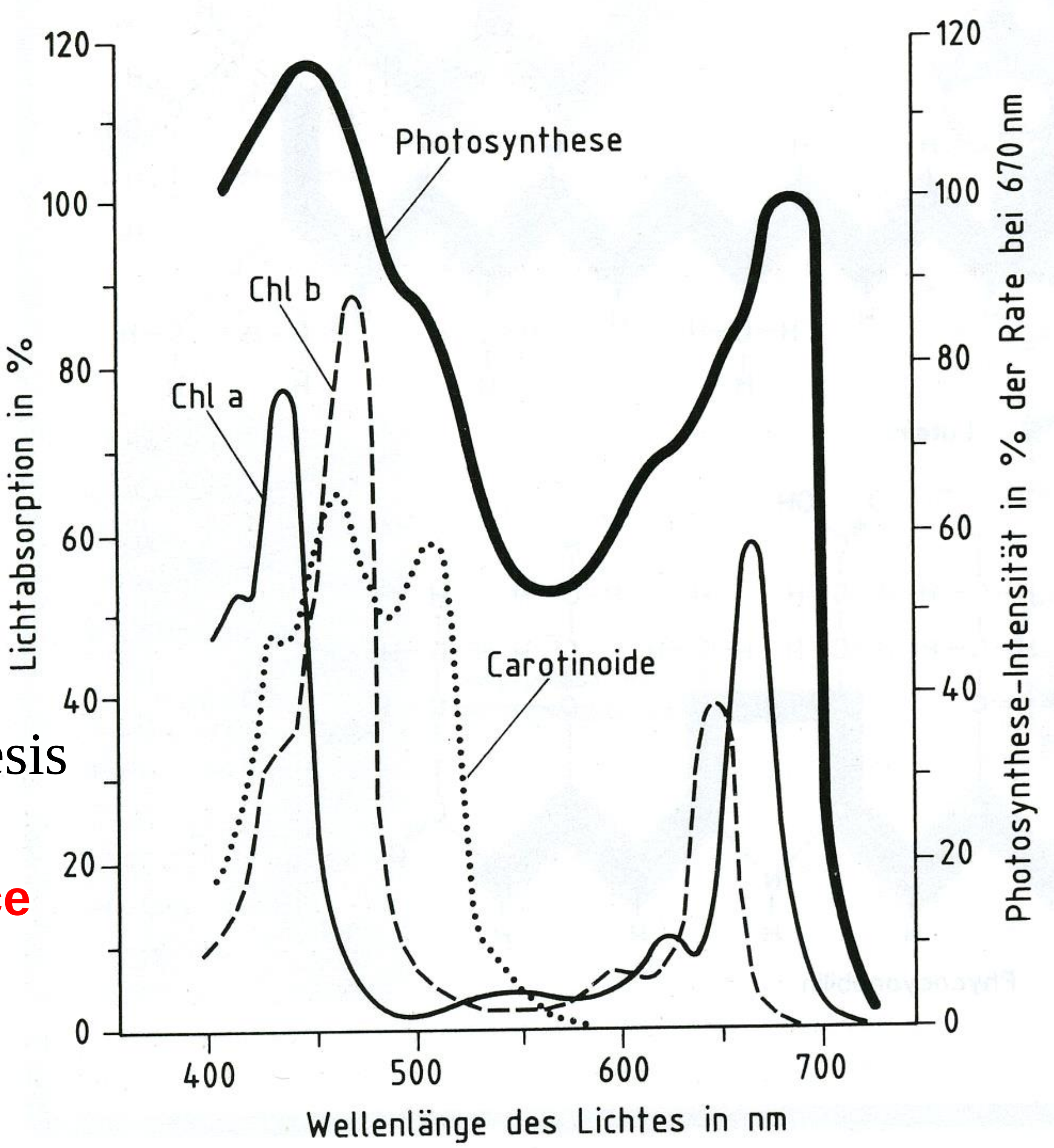
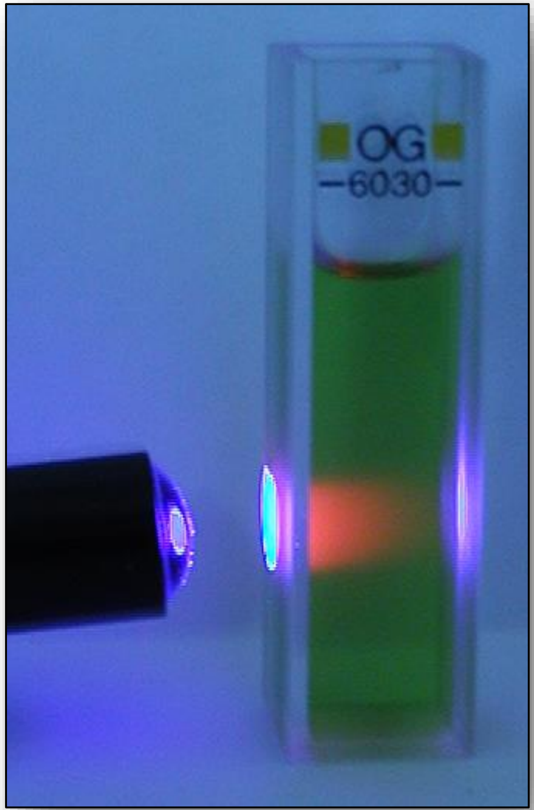
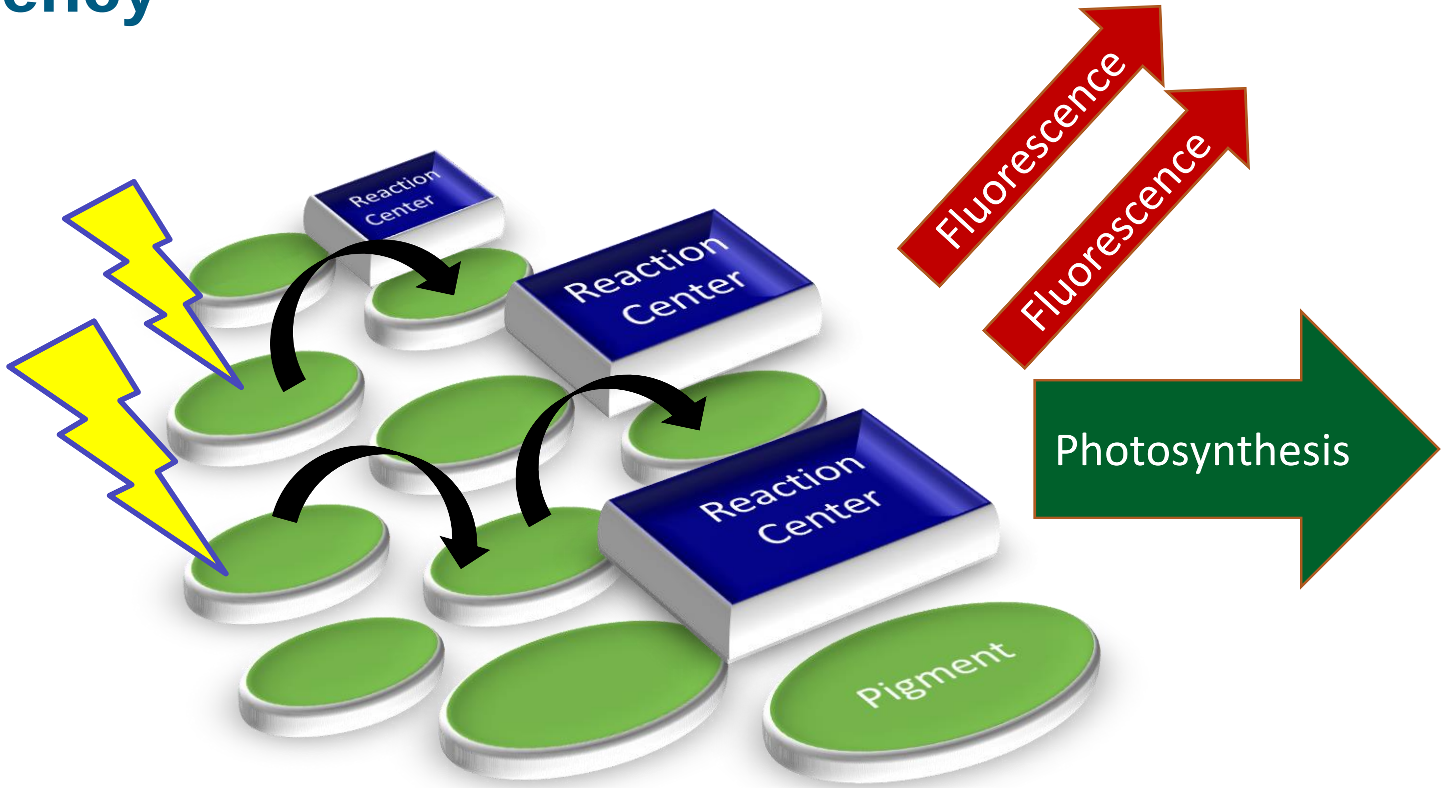




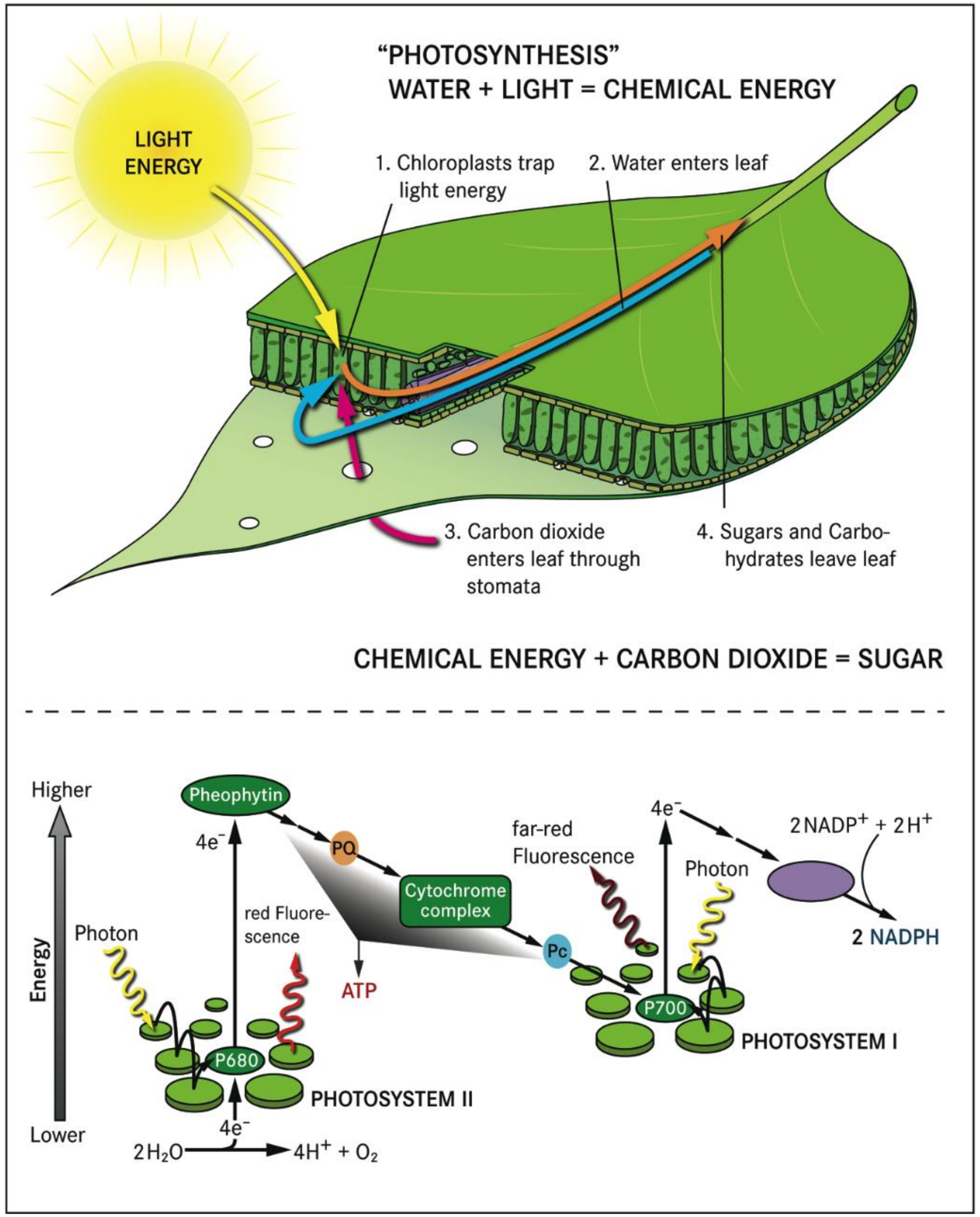
The origin of fluorescence – an indicator for photosynthetic efficiency



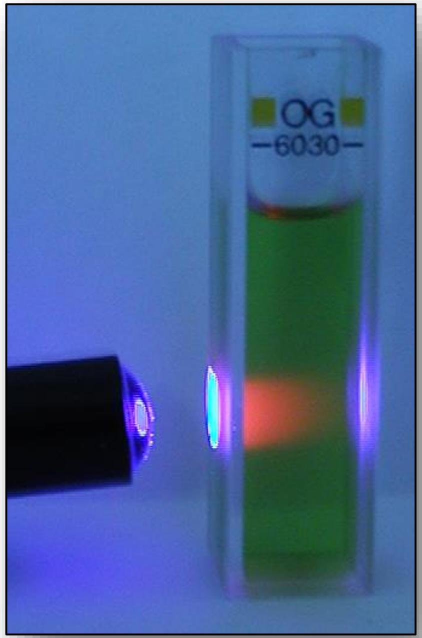


1. Chlorophyll molecules emit fluorescence. The intensity of the fluorescence signal is a function of light intensity and the concentration of chlorophyll
2. Additionally, the functional status of photosynthesis modulates the intensity of the fluorescence signal

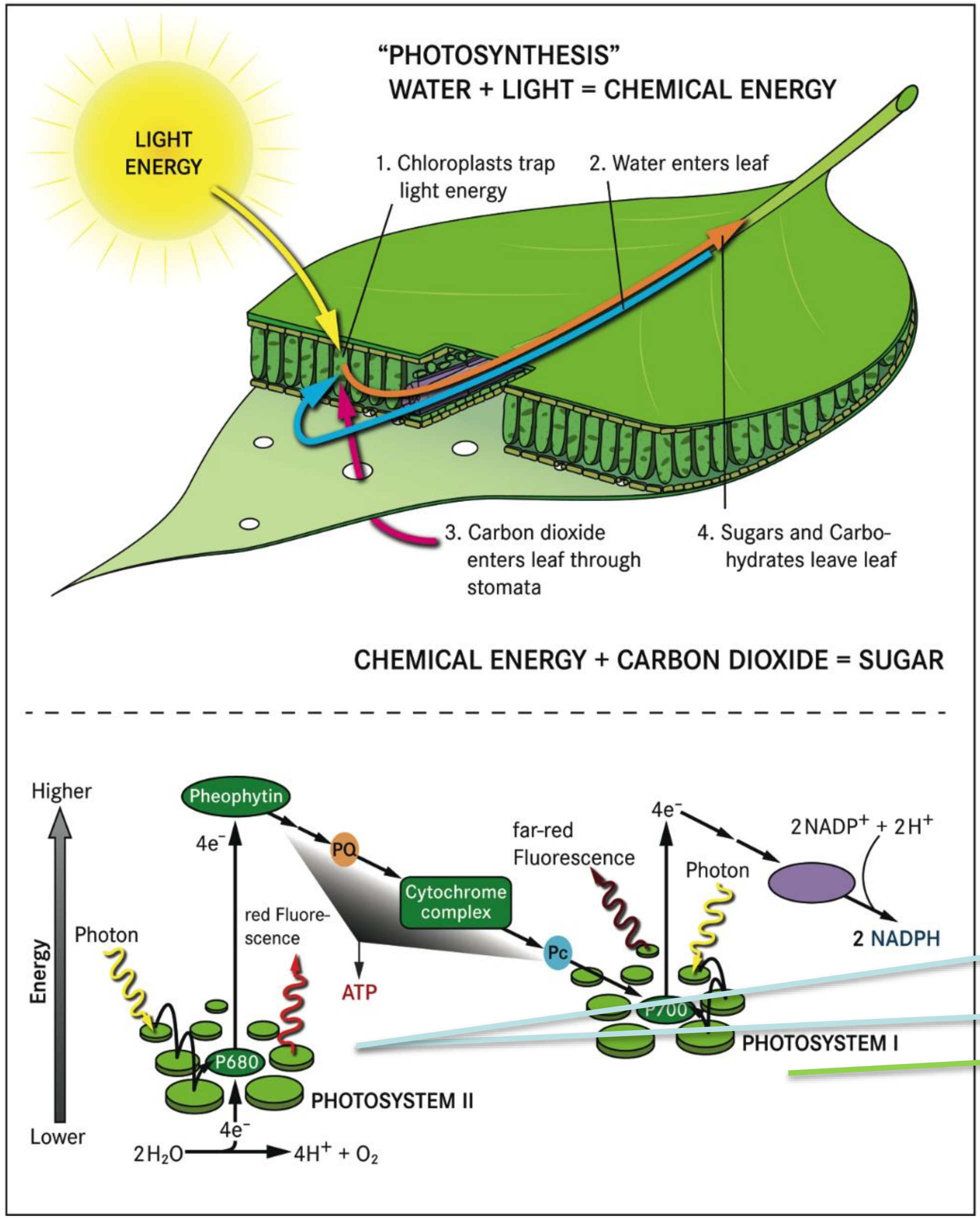
The origin of fluorescence – an indicator for photosynthetic efficiency



- Photosynthesis is a highly regulated process that involves a cascade of electron transfers (*Light reaction*) to fuel carbon fixation (*Calvin cycle*)
- Fluorescence is emitted from the cores of the photosynthetic machinery: Photosystems I and II



The origin of fluorescence – an indicator for photosynthetic efficiency



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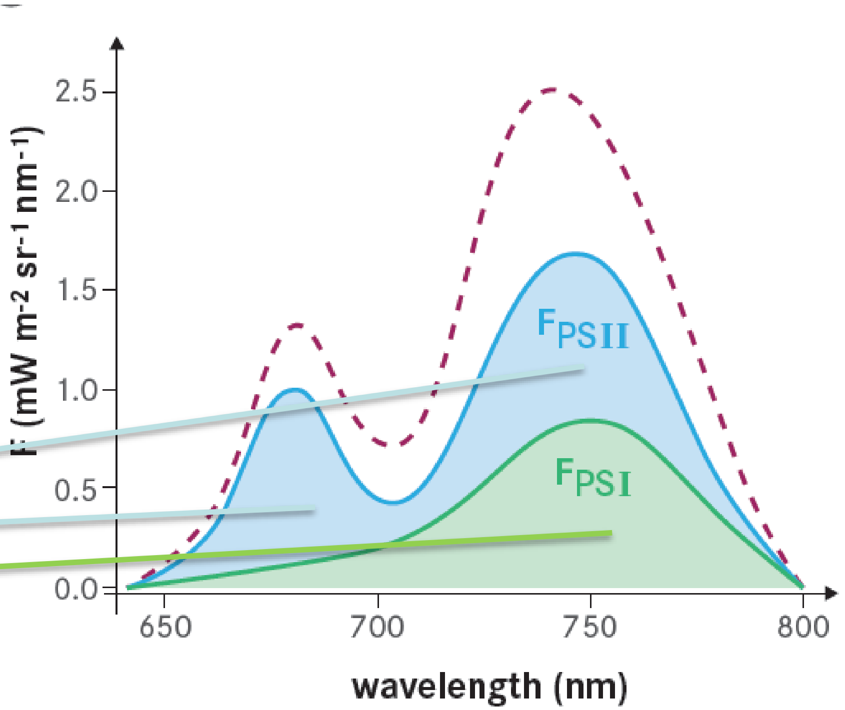
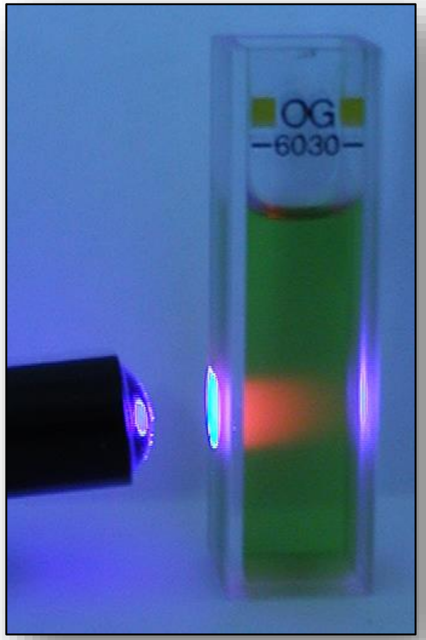
- Fluorescence is emitted from the cores of the photosynthetic machinery: Photosystems I and II
- Two-peak feature of fluorescence





Leaf fluorescence – two photosystems and two dynamically adapting signals

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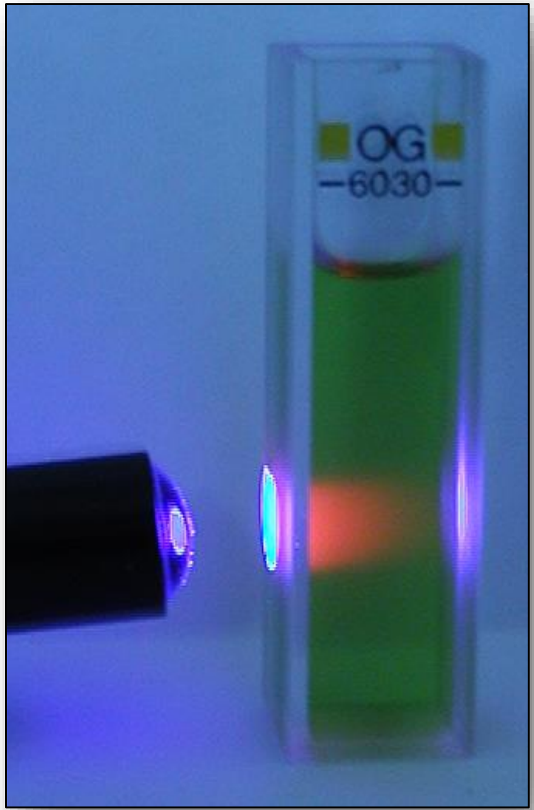


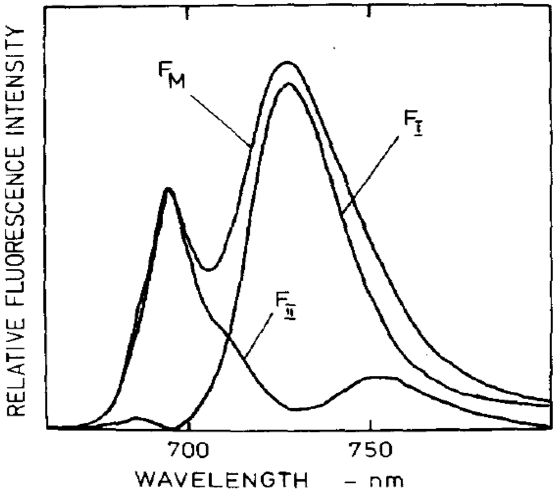
Biochimica et Biophysica Acta, 462 (1977) 307–313

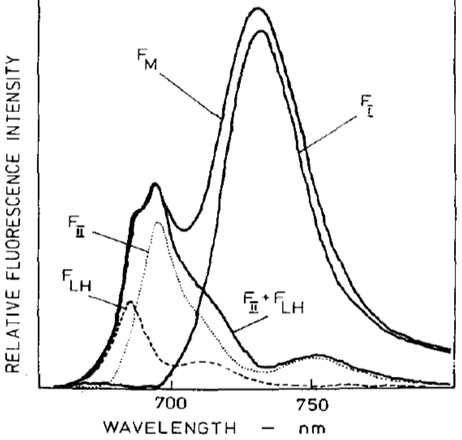
BBA 47380

FLUORESCENCE EMISSION SPECTRA OF PHOTOSYSTEM I, PHOTOSYSTEM II AND THE LIGHT-HARVESTING CHLOROPHYLL *a/b* COMPLEX OF HIGHER PLANTS

RETO J. STRASSER and WARREN L. BUTLER

Department of Biology, University of California, San Diego, La Jolla, Calif. 92093 (U.S.A.)





Fluorescence techniques are the most widely used approaches to investigate photosynthesis

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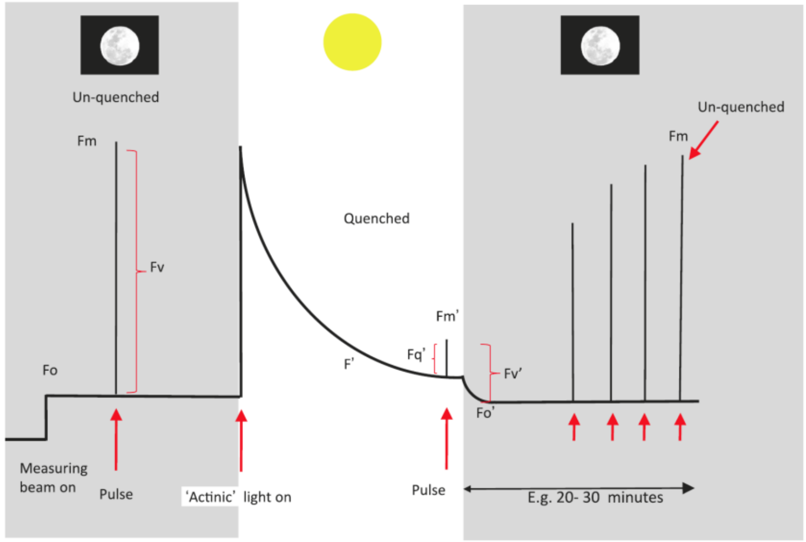
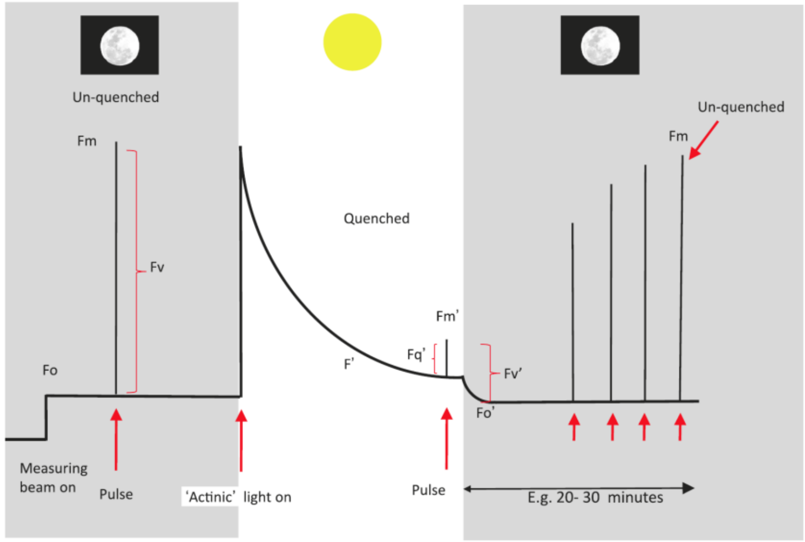
- Various leaf level instruments available and currently ~750 Papers published per year
- Most methods use active approaches, such as PAM, saturating light pulses or lasers induced fluorescence transients

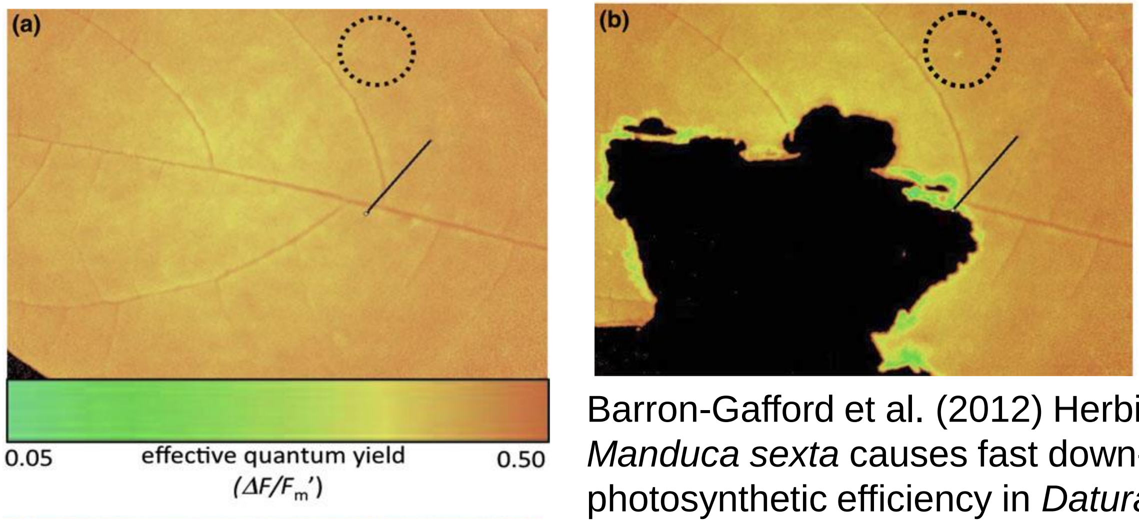


Rascher et al. (2010) Sensing of photosynthetic activity of crops. In Precision Crop Protection - the Challenge and Use of Heterogeneity. Springer Science+Business Media B.V., doi 10.1007/978-90-481-9277-9_6.
Murchie et al. (2018) Annals of Botany, 122, 207-220
Keller et al. (2019) Photosynthesis Research, in press; doi: 0.1007/s11120-018-0594-9.

Fluorescence techniques are the most widely used approaches to investigate photosynthesis

- Various leaf level instruments available and currently ~750 Papers published per year
- Most methods use active approaches, such as PAM, saturating light pulses or lasers induced fluorescence transients
- Fluorescence techniques are widely used to detect plant diseases
- Pest affect photosynthetic machinery and we can use this link for disease detection

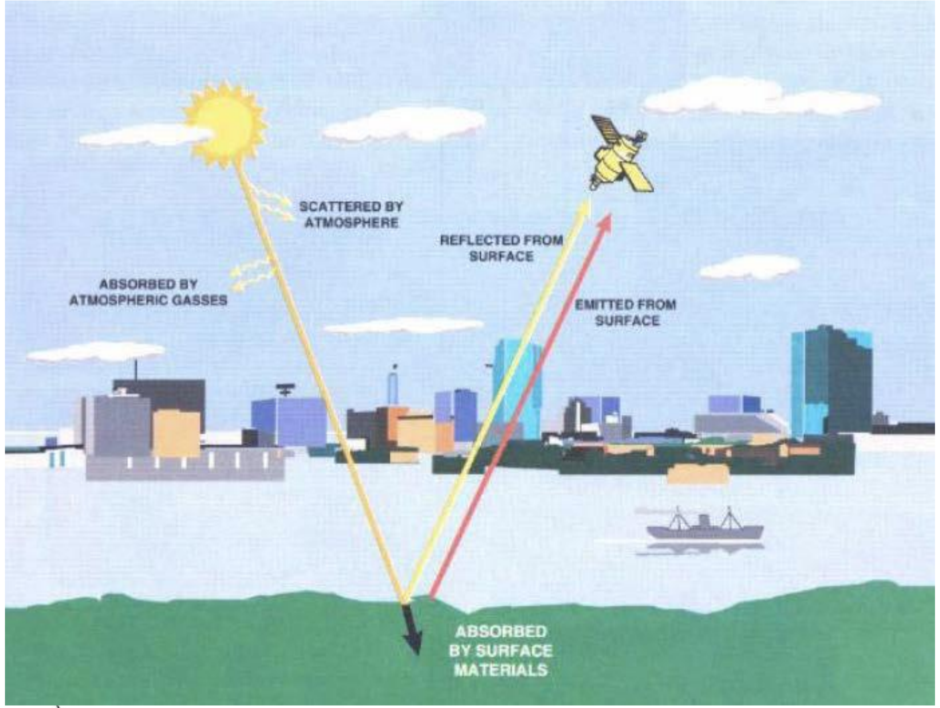




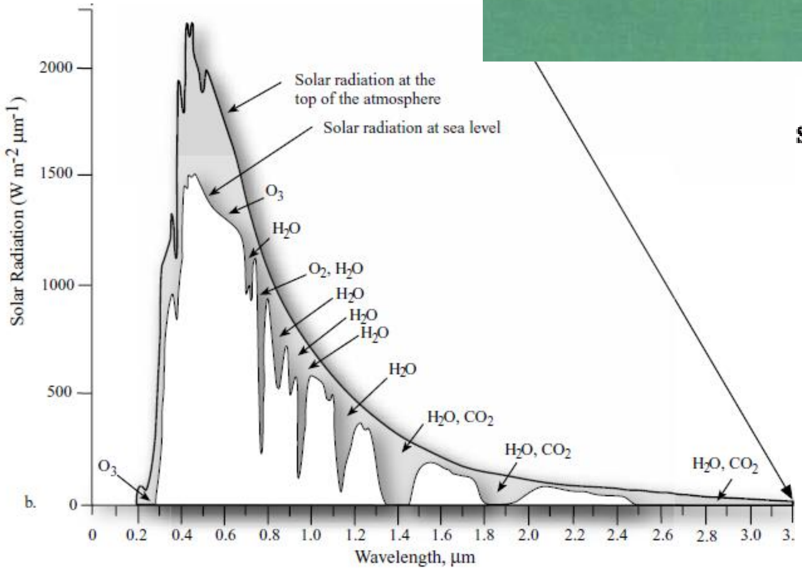
Barron-Gafford et al. (2012) Herbivory of wild *Manduca sexta* causes fast down-regulation of photosynthetic efficiency in *Datura wrightii*: an early signaling cascade visualized by chlorophyll *fluorescence. Photosyn Res, 113*, 249-260.

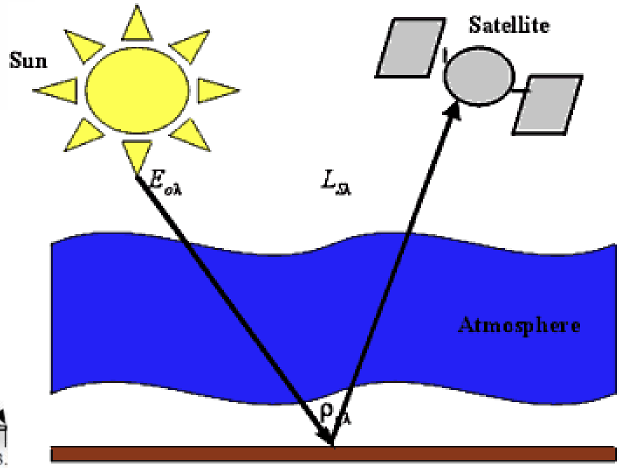
Passive remote sensing – optical remote sensing

- Passive remote sensing inherently needs to correct for the path of light through the atmosphere (sun – surface – sensor)
- Physical modelling ('atmospheric correction')
  - Complex atmospheric conditions (clouds, haze, aerosols, etc.) often complicate the atmospheric correction

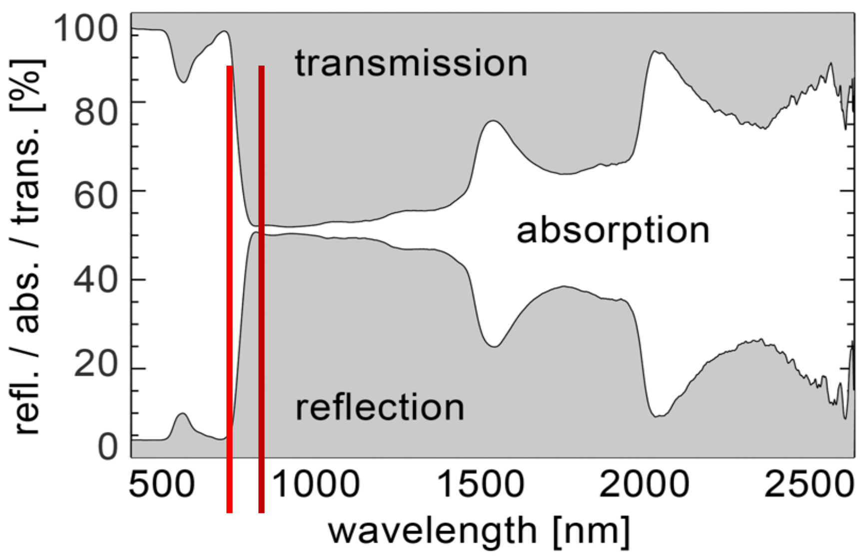


Atmospheric correction, correction for viewing geometry, georegistration and other corrections are normally done by the space agencies. Algorithms have become really good in past years, but they are still not error free

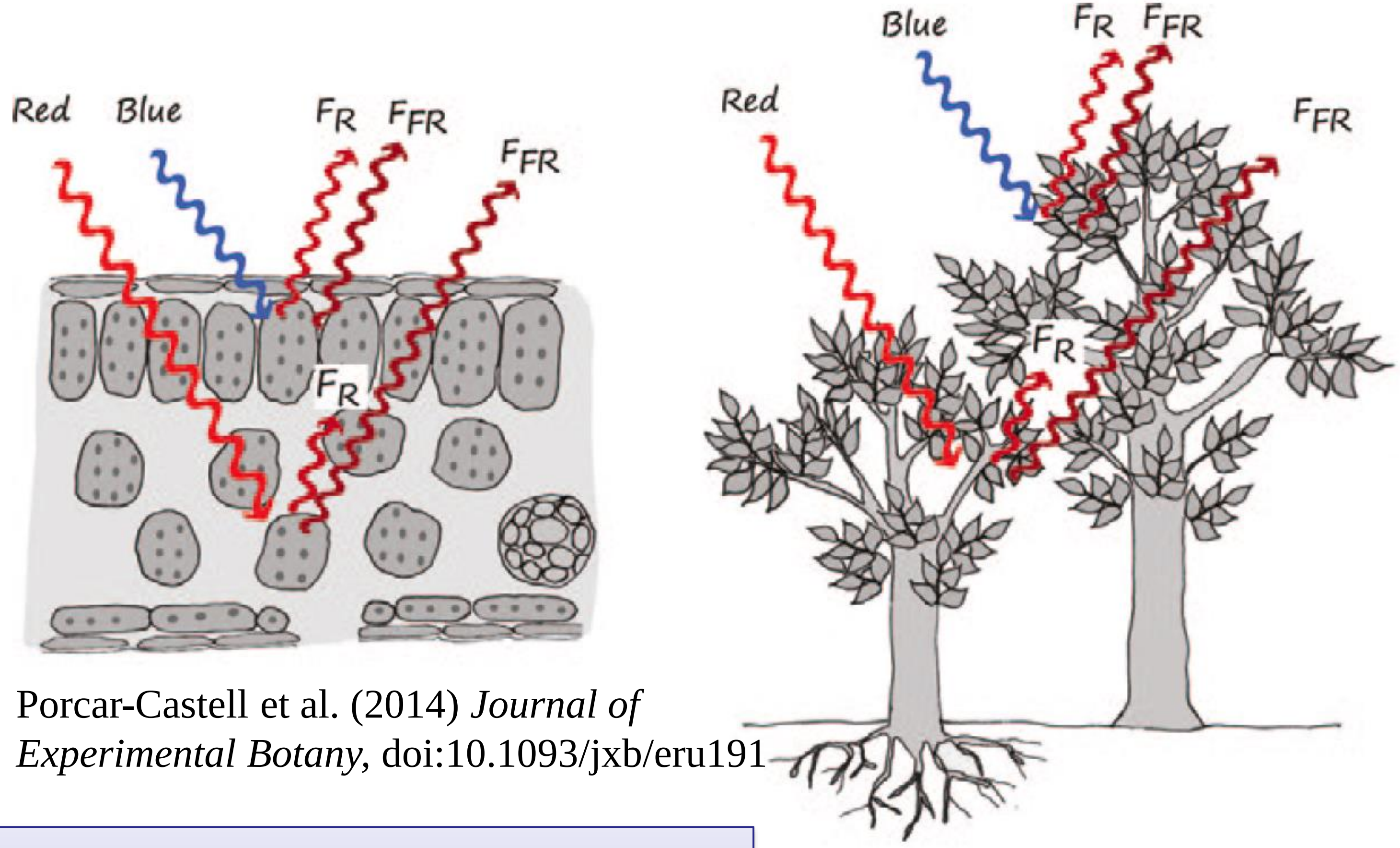




Challenge for disease detection: small features in structurally complex canopies



Rascher et al. (2010) *Precision Crop Protection, Springer, ISBN: 978-90-481-9276-2,* pp 87-100

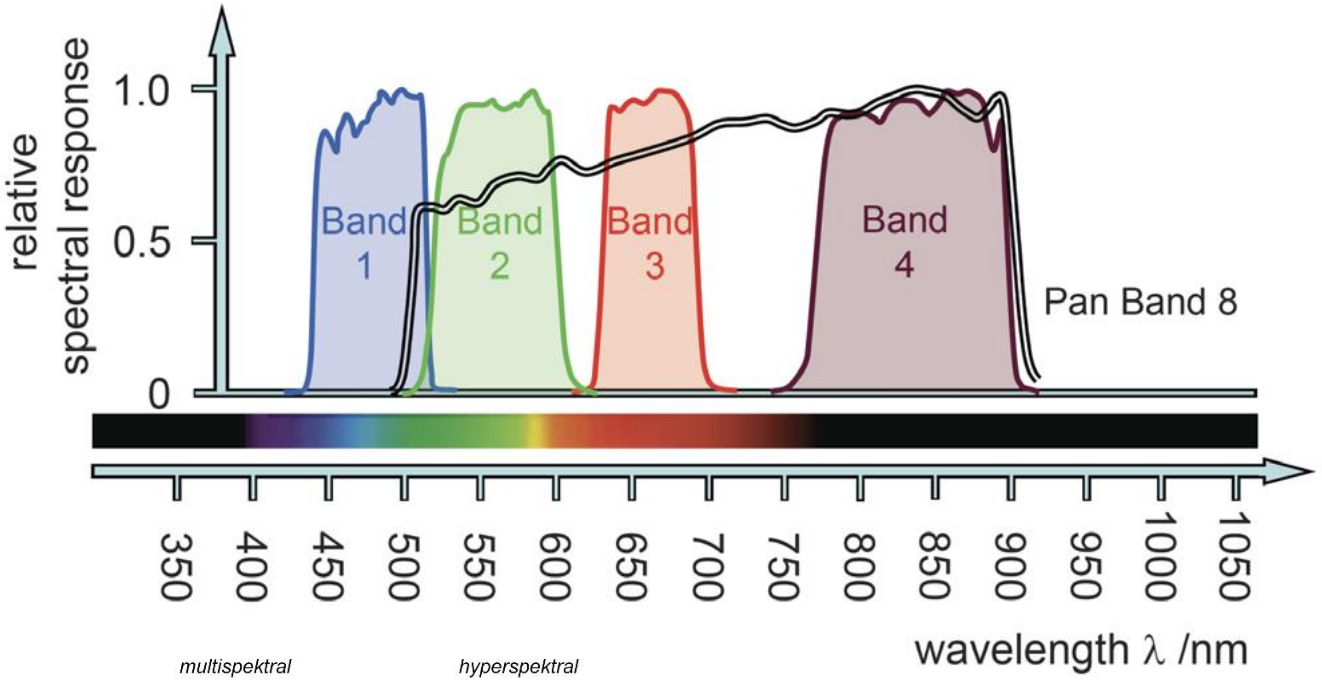


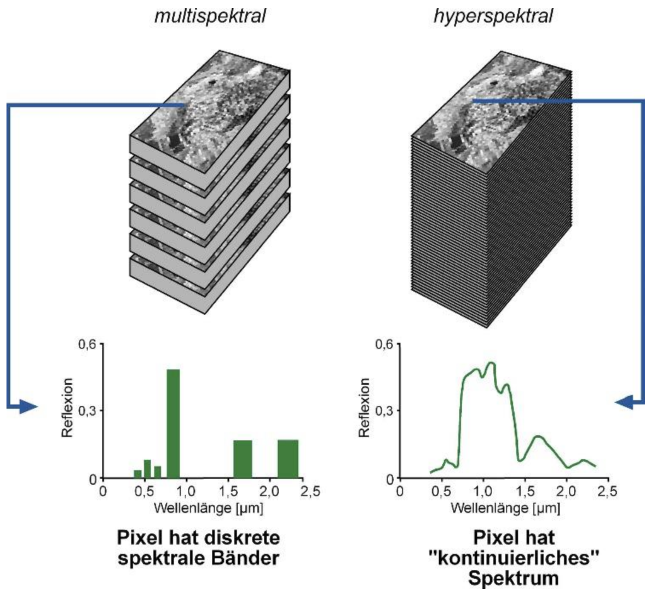
Porcar-Castell et al. (2014) *Journal of Experimental Botany*, doi:10.1093/jxb/eru191

- ➢ Disease sympoms are generally very small and only occur on selected organs of a plant.
- ➢ These small features, which are visible to the human eye are often obscured by changes in the canopy. Such changes often affect reflectance and fluorescence in a larger degree than disease effects

Multispectral vs hyperspectral satellites

- Every satellite or airborne sensor has a specific sensitivity to spectral bands
- Multispectral satellites measure discrete bands (advantage higher sensitivity as more photons are available in these broad bands)
- Hyperspectral satellites measure a continuous spectrum (advantage to resolve also small spectral differences, but lower signal to noise values)





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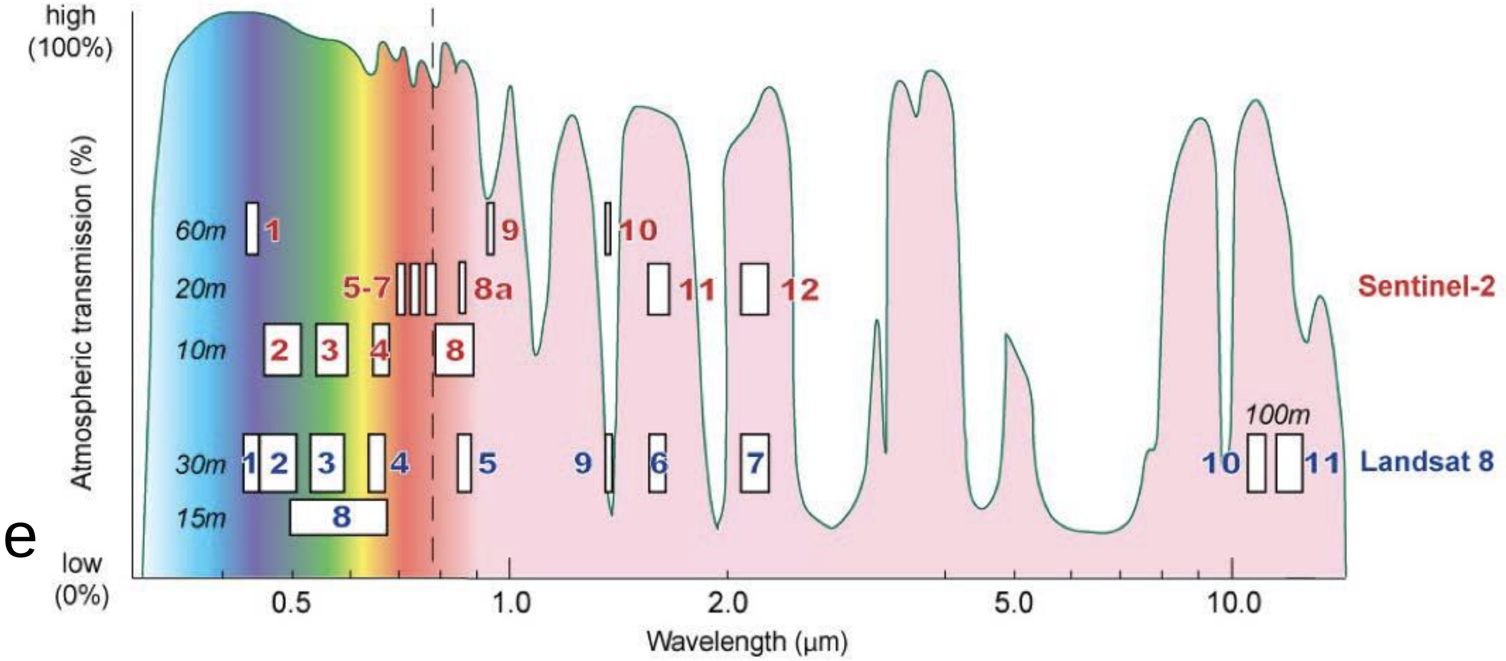

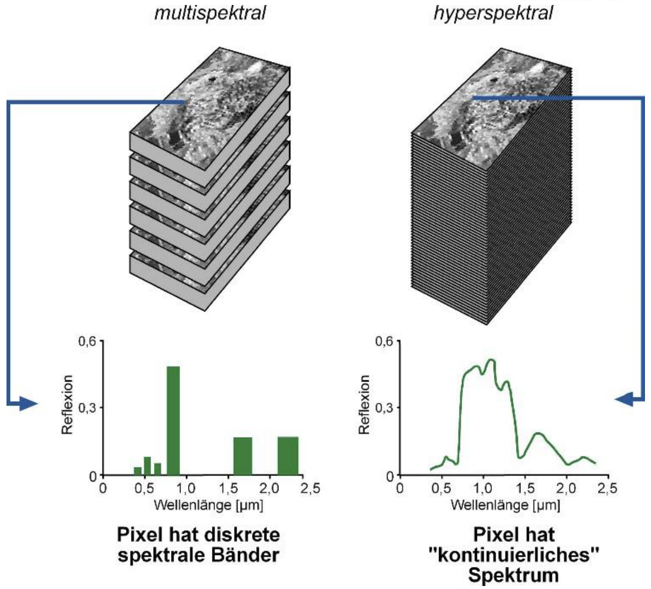

Existing and future satellite for crop monitoring and precision agriculture

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Satellite (year)	Spatial resolution	Spectral resolution	Return frequency	Suitability for PA
Landsat 1/2/3 (1972/75/78)	79 m	4 bands	18 d	L
Landsat 5 (1984)	30 m	6 bands	16 d	M
SPOT 1/2/3 (1986/90/93)	20 m	3 bands	2-6 d	M
IRS 1A (1988)	72 m	4 bands	22 d	M
SPOT 4 (1998)	20 m	4 bands	2–6 d	M
IKONOS (1999)	3.2 m	5 bands	3 d	H
Landsat 7(1999)	30 m	7 bands	16 d	M
EO-1 Hyperion (2000)	30 m	220 bands	16 d	H
EO-1 ALI (2000)	30 m	10 bands	16 d	M
QuickBird (2001)	2.62 m	5 bands	1–4 d	H
PROBA/CHRIS (2001)	18–36 m	19 bands	7 d	H
SPOT 5 (2002)	10–20 m	5 bands	1-4 d	M
RapidEye (2008)	6.5 m	5 bands	1 d	H
GeoEye-1 (2008)	1.6 m	6 bands	2–8 d	H
WorldView-2 (2009)	1.84 m	8 bands	1.1 d	H
Pleiadis-1A/B (2011/12)	2 m	5 bands	1 d	H
SPOT 6/7 (2012/14)	6 m	5 bands	1 d	H

Satellite (year)	Spatial resolution	Spectral resolution	Return frequency	Suitability for PA
Landsat 8 (2013)	30 m	9 bands	16 d	M
SkySat-1/2 (2013/14)	2 m	5 bands	2 d	H
WorldView-3 (2014)	1.24–3.7 m	17 bands	1 d	H
Flock-1 1-28 (2014)	3–5 m	3 bands	1 d	M
Sentinel-2A (2015)	10–60 m	13 bands	10 d	M
WorldView-4 (2016)	1.24 m	5 bands	1 d	H
SkySat-3/4/5/6/7 (2016)	2 m	5 bands	1 d	M
Sentinel-2B (2017)	10–60 m	13 bands	10 d	M
Venµs (2017)	5.3 m	12 bands	2 d	H
PRISMA (2018)	20–30 m	249 bands	16 d	H
EnMAP (2019)	30 m	242 bands	27 d	H
HISUI MS (2019)	5 m	4 bands	60 d	M
HISUI HS (2019)	30 m	185 bands	60 d	H
Landsat 9 (2020)	30 m	9 bands	16 d	M
HyspIRI (2022)	30 m	214 bands	16 d	H
FLEX (2022)	300 m	-	30 d	M
Sentiel-2C/D (???)	10–60 m	13 bands	10 d	M

existing / past

future

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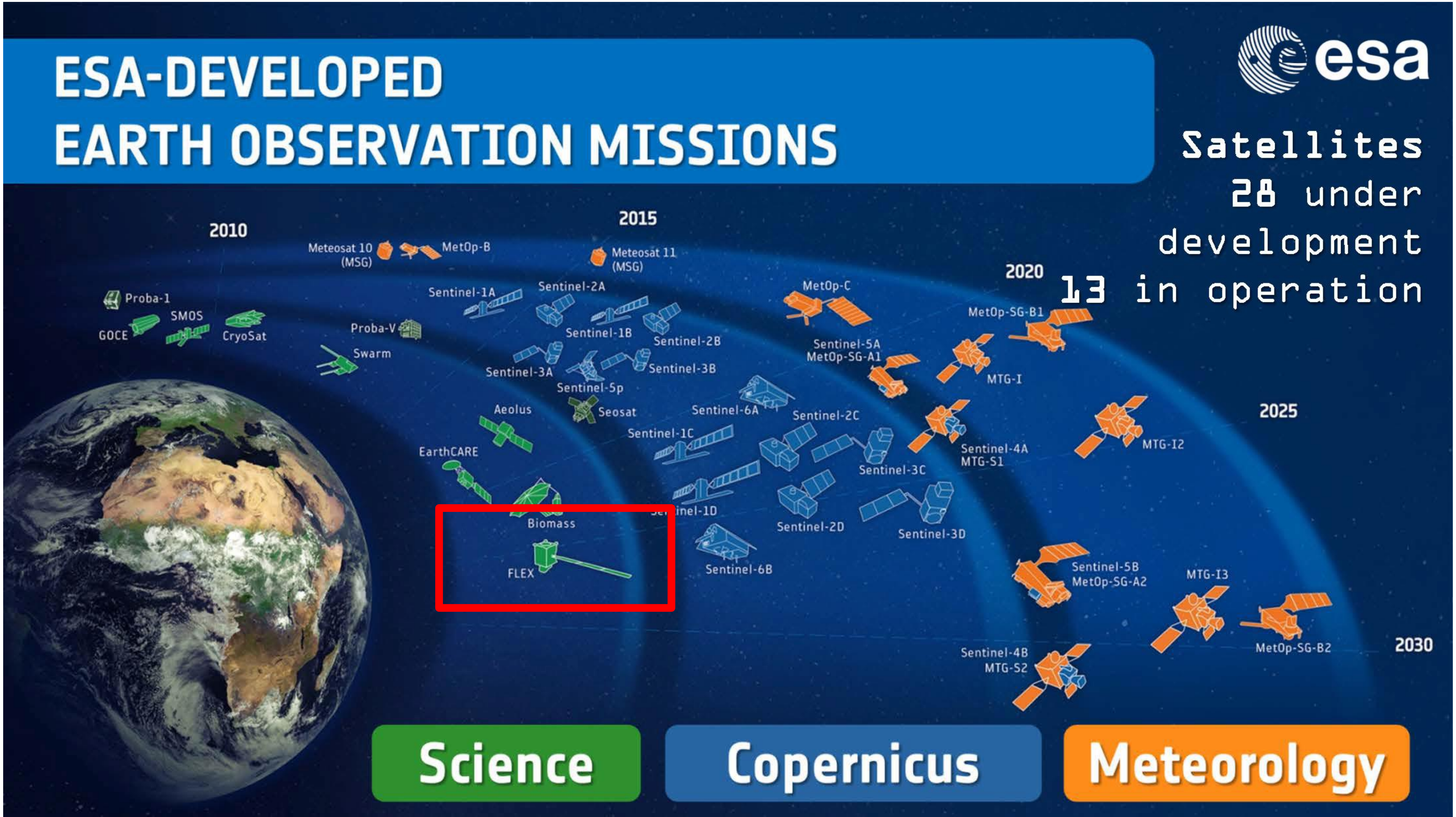
existing / past

future

Technical feasibility defines the possibility, scientific request define the balance between
(i) spatial resolution
(ii) number of spectral bands, and
(iii) revisiting time (return frequency)

ESA’s Earth Observation satellites

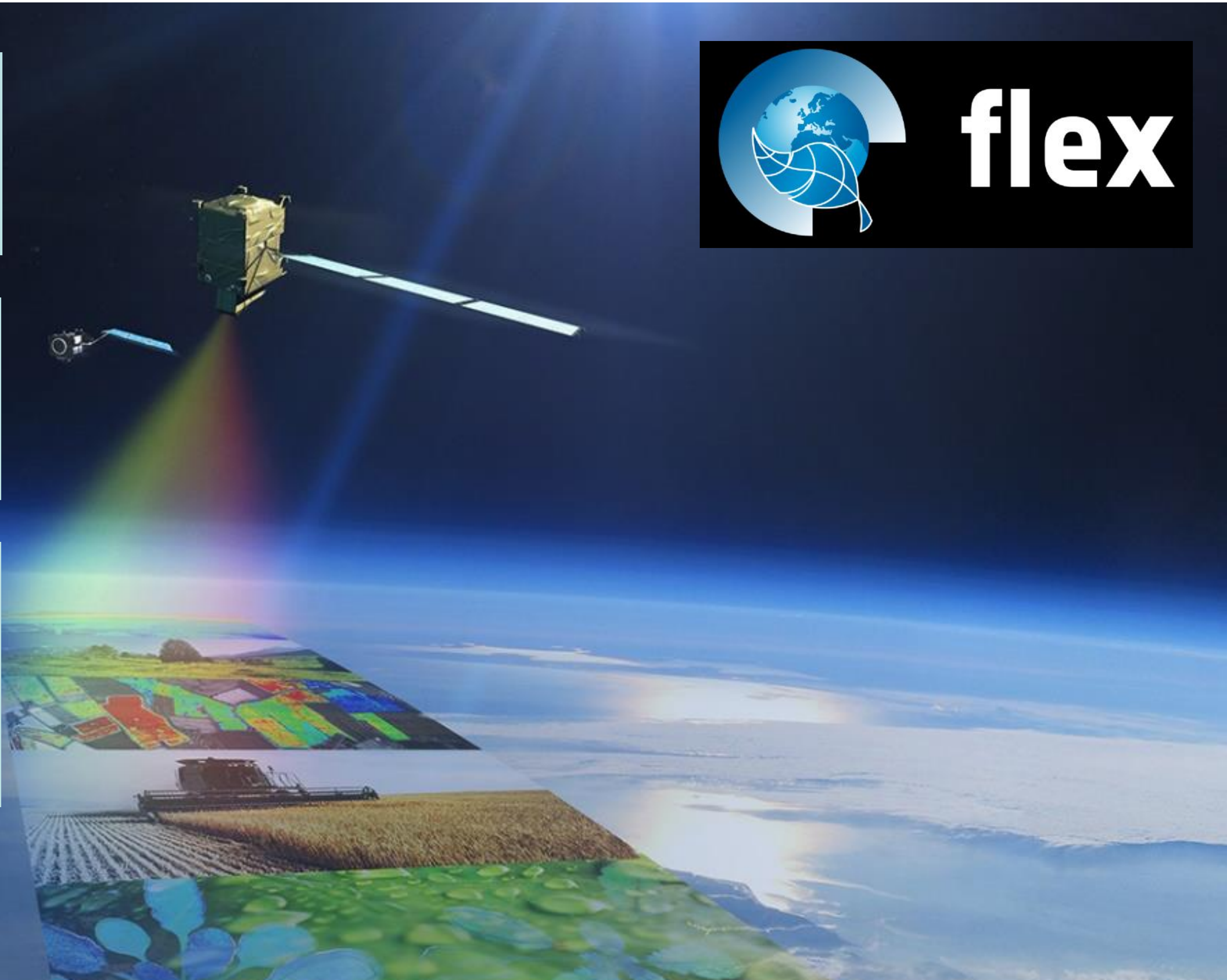


FLEX Satellite Mission will become the 8th Earth Explorer of ESA

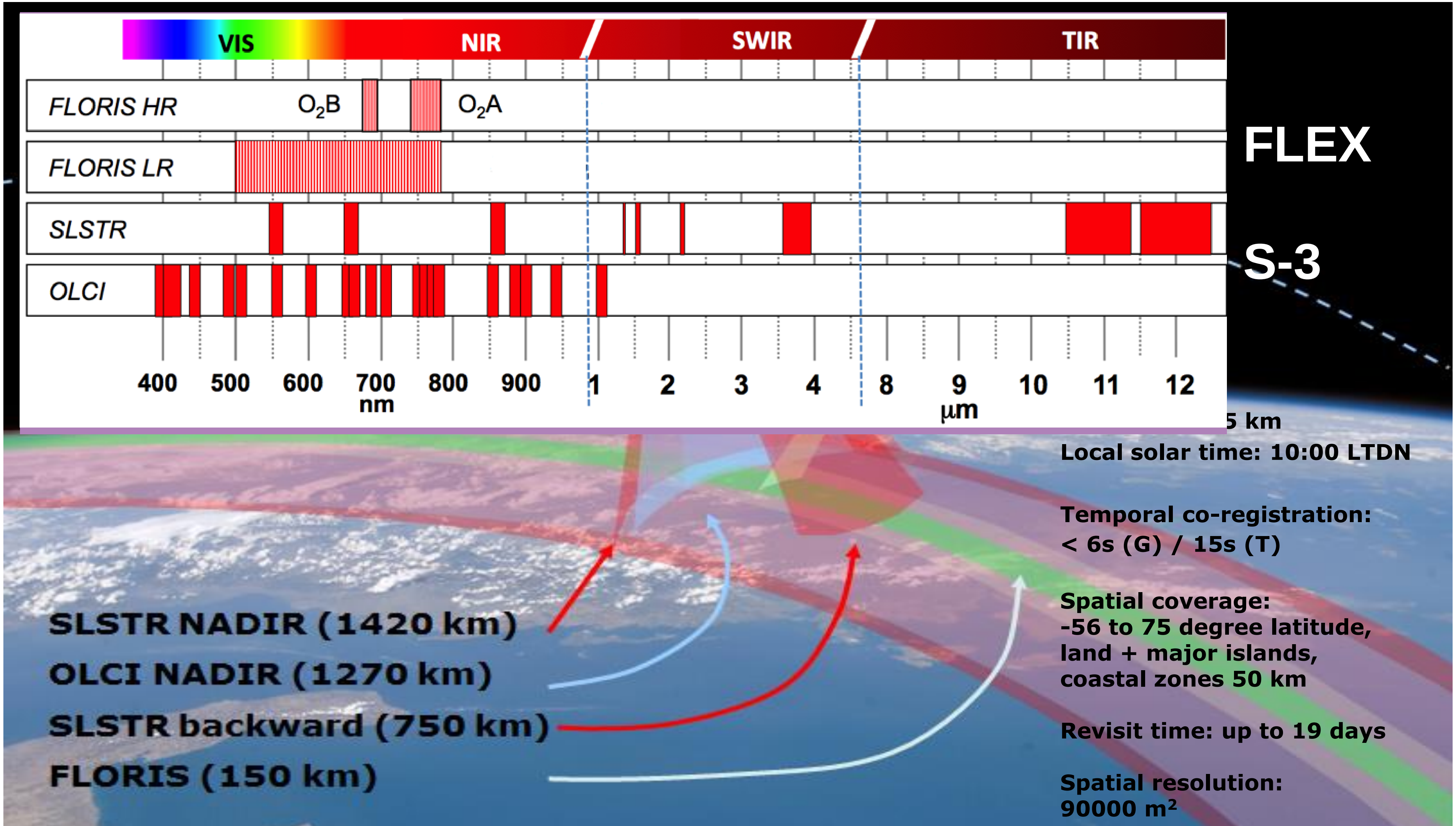
FLEX will quantify **actual photosynthetic activity** of terrestrial ecosystems

FLEX will provide **physiological indicators** for vegetation health status

by direct measurements of **vegetation fluorescence** at 300x300 meters every 10-25 days



FLEX Satellite Mission will be launched mid 2025 and become the 8th Earth Explorer of ESA



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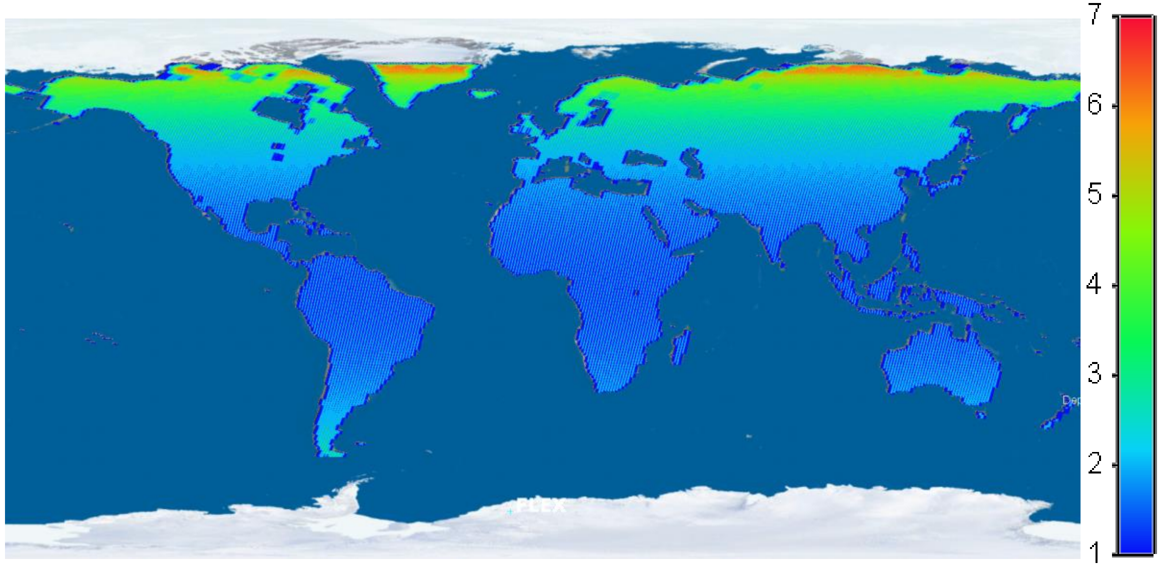
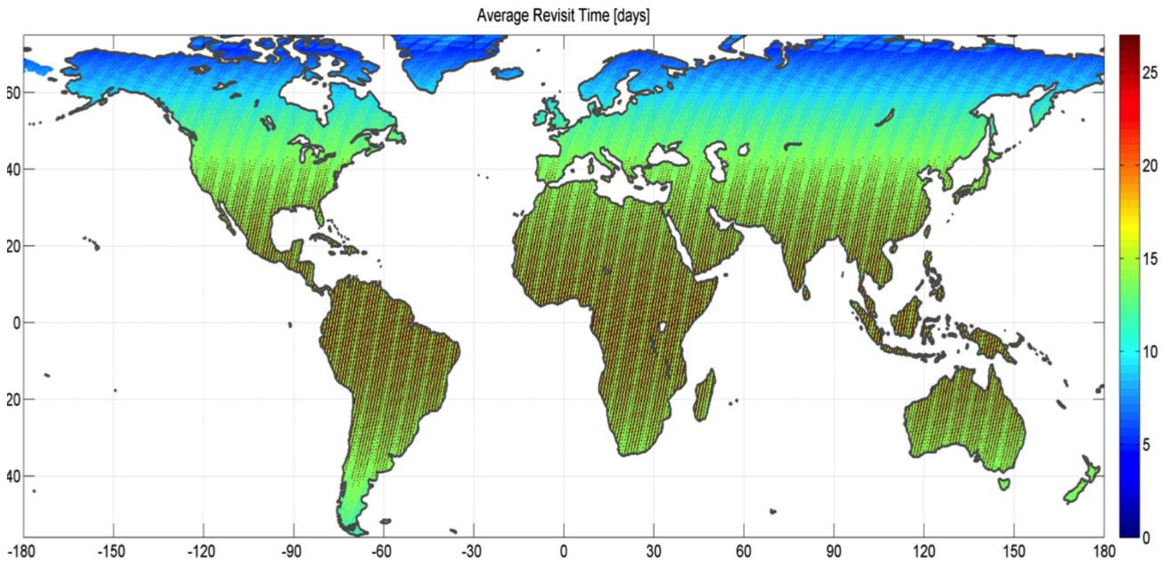
FLEX Satellite Mission – a tandem concept with Sentinel-3



Number of acquisitions within a repeat cycle

Average revisit time (days)

- FLEX will acquire images of all land between 56° S to 75° N, including major islands and coastal areas
- 300 x 300 meter pixels
- Launch is scheduled for 2023
- Full coverage every 27 days



Longitude

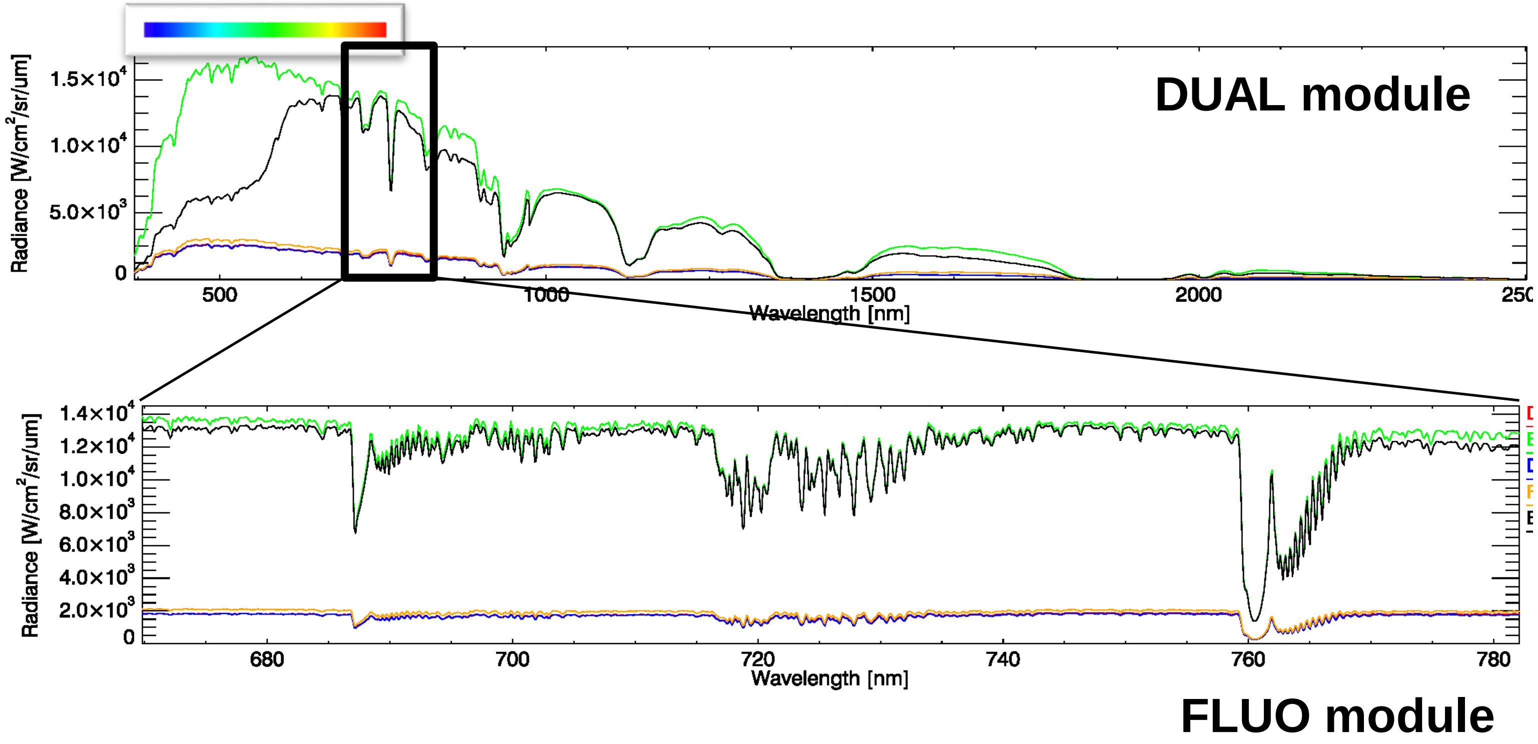
Average revisit time:

- 27 days at Equator
- ~ 20 days at Tropics
- ~ 10 to 15 days over Europe and Canada
- ~ 5 to 10 days over boreal forests

HyPlant: A high-resolution airborne imaging spectrometer with FLEX like measurement characteristics

Rascher et al. (2015) *Global Change Biology, 21*, 4673–4684

- **DUAL module** (380 – 2500 nm)
  VIS/NIR: 3-4 nm FWHM, 1.7 nm SSI, SNR > 510
  SWIR: 13 nm FWHM, 5.5 nm SSI, SNR > 1100
- **FLUO module** (670 – 780 nm)
  0.25 nm FWHM, 0.11 nm SSI, SNR > 250
- Various improvement and now consolidated version (HyPlant_3)



HyPlant complemented by thermal imager (TASI) and LIDAR system (since 2018 campaign)

TASI-600

- Hyperspectral thermal sensor (8 – 11.5 µm)
- Field of view alligned with HyPlant sensor
- Operated in synchrony with HyPlant

LIDAR (Riegl LMS-Q780)

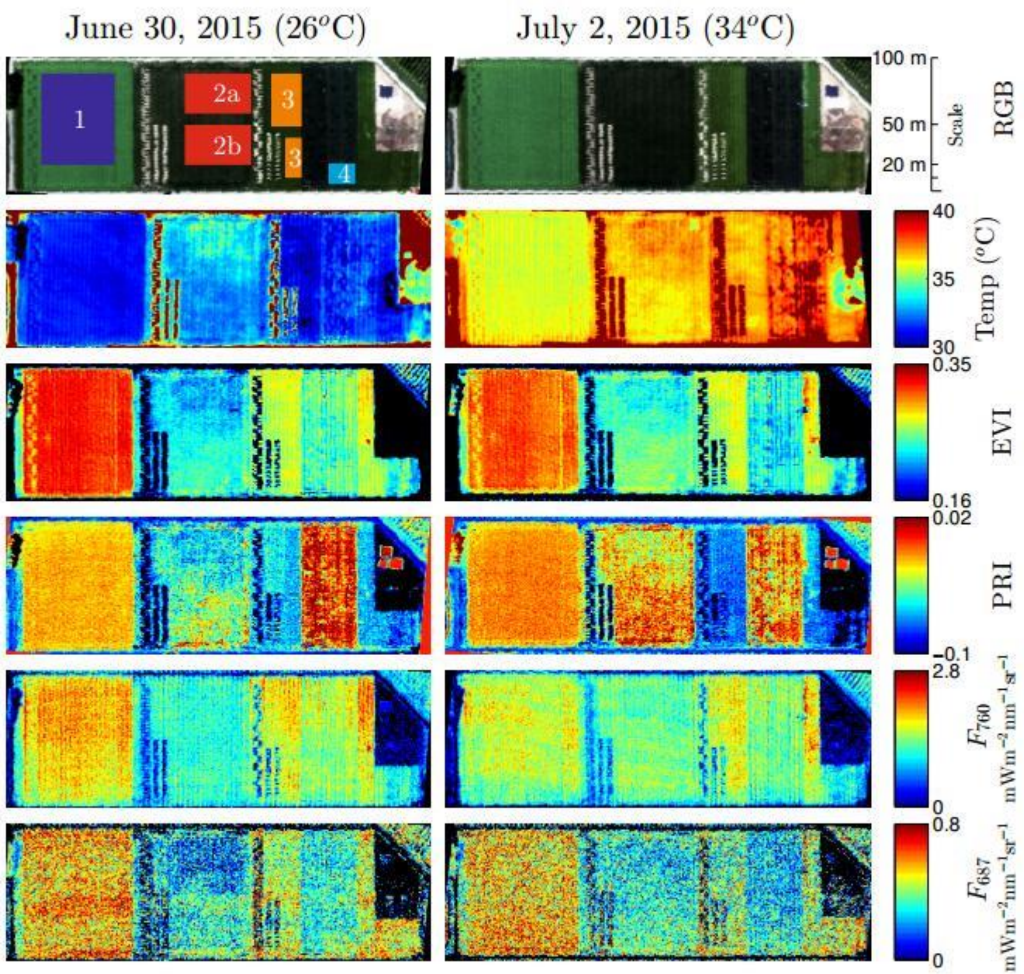
- Long range laser scanner
- Full-waveform echo digitalization and analysis

Sensor	**TASI-600**
Spectral Region	LWIR
Sensor Type	Pushbroom Hyperspectral TIR
Spectral Bands	32
Spectral Range [nm]	8 000 – 11 500
Number of Spatial Pixels	600
Max. Spectral Resolution [nm]	110
FOV [°]	40
IFOV [°]	0.07
Dynamic Range	14-bits (16384:1)
Burst Data Rate	5 Mpix/sec
NEDT	TASI-600/32: 0.11° C @ 100° C
Spectral Smile	TASI-600/32: < ±0.25 pixels
Keystone Distortion	TASI-600/32: < ±0.25 pixels

Sensor	**Riegl LMS-Q780**
Max. Pulse Repetition Rate [kHz]	400
Max. Operating Altitude [m]	5800
Wavelength [nm]	1064
Max. Laser Beam Divergence [mrad]	0.25
FOV [°]	60
Eye Safety Class	Laser Class 3B
Min. Operating Altitude	50m

HyPlant campaigns: Measuring and understanding the spatial dynamics of solar-induced fluorescence

- ➢ Vegetation stress during summer heat wave
  [Yang et al (2019) Rem. Sens. Environ., doi: 10.1016/j.rse.2018.11.039]



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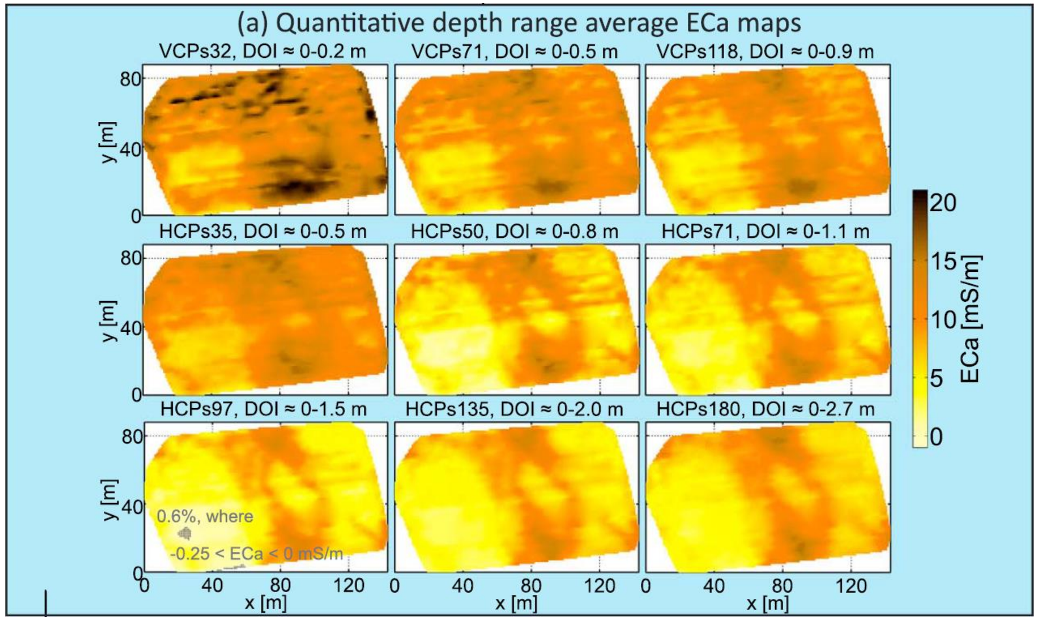

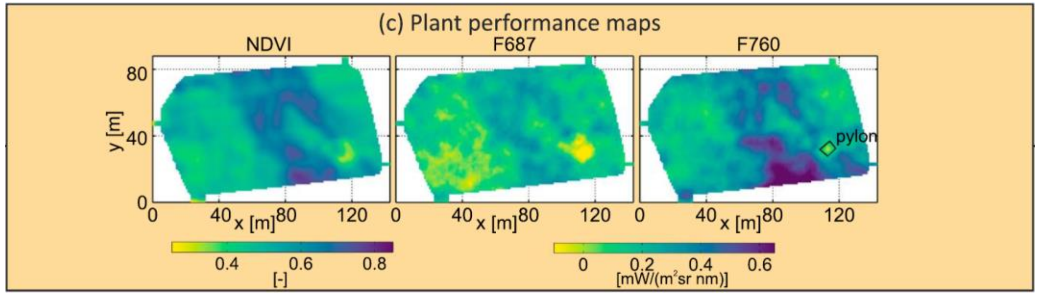

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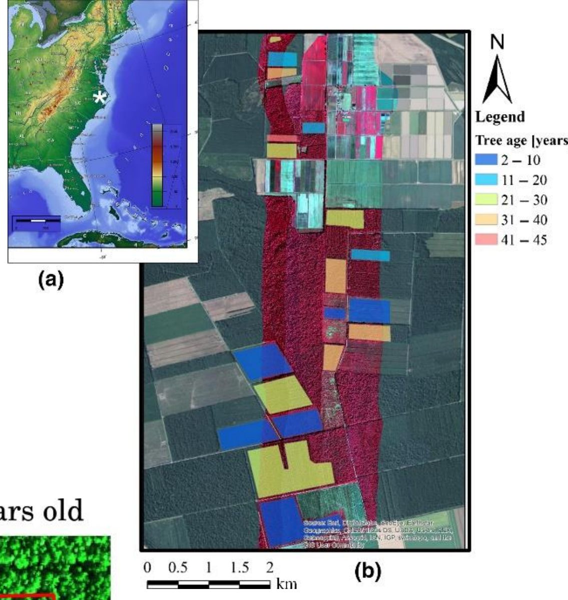

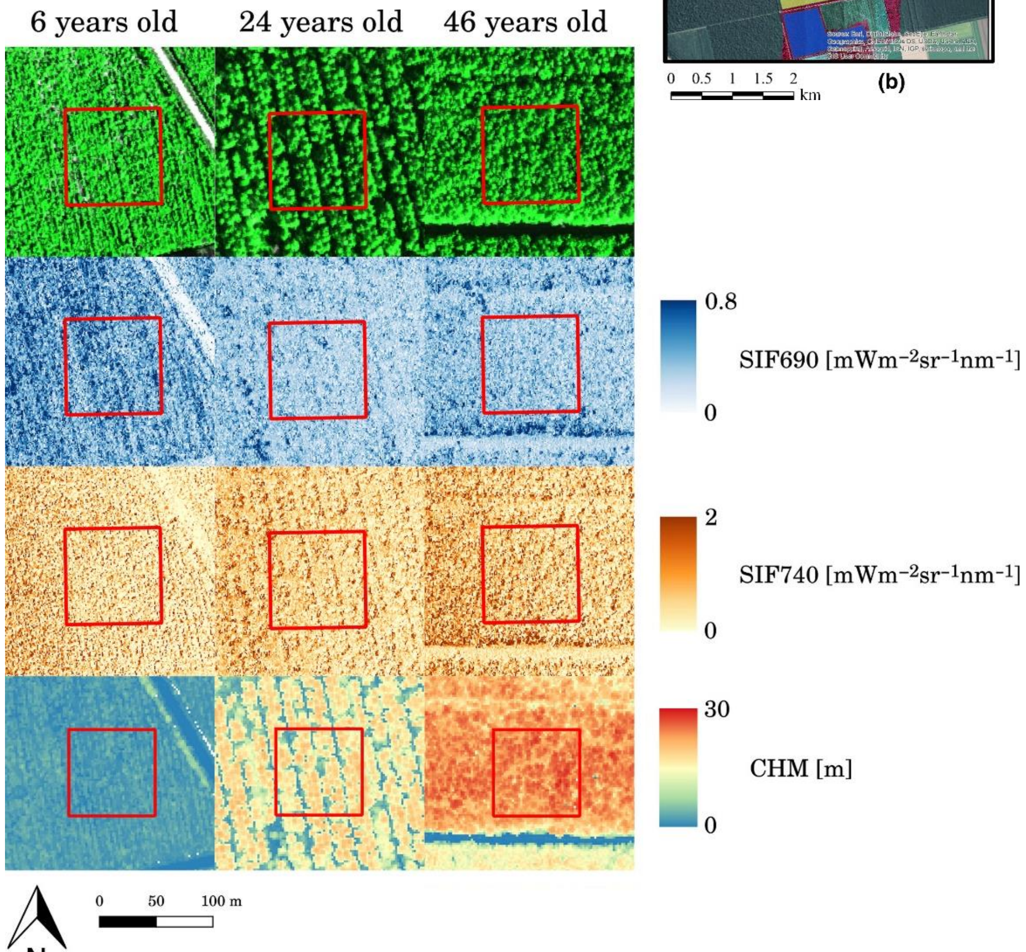

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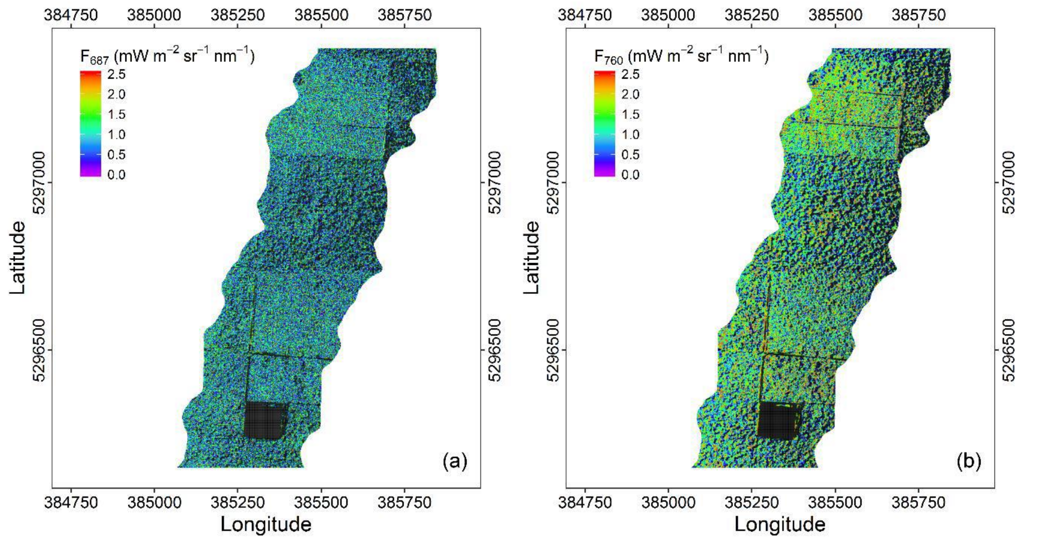
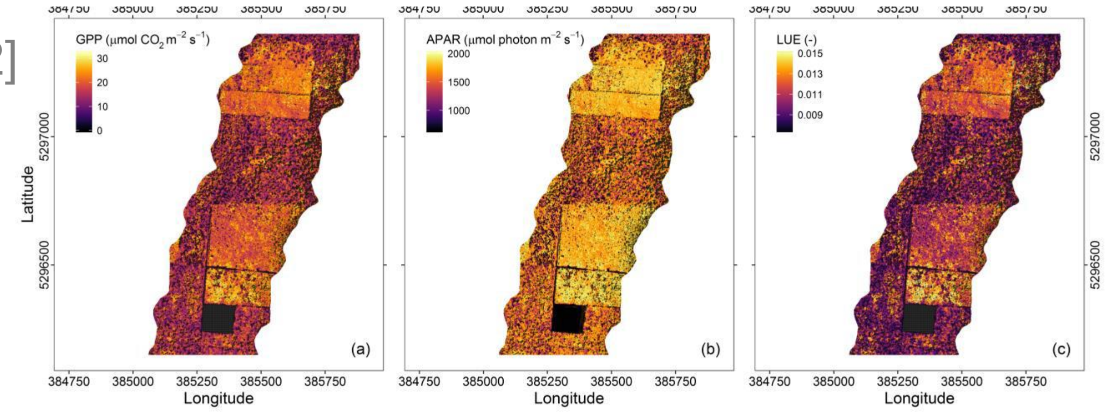
- F_{687} is not related with GPP and APAR; F_{760} is positively, but nonlinearly related to GPP and APAR in the spatial domain.
  [Tagliabue et al. (2019) Rem. Sens. Environ., 231, article no. 111272]





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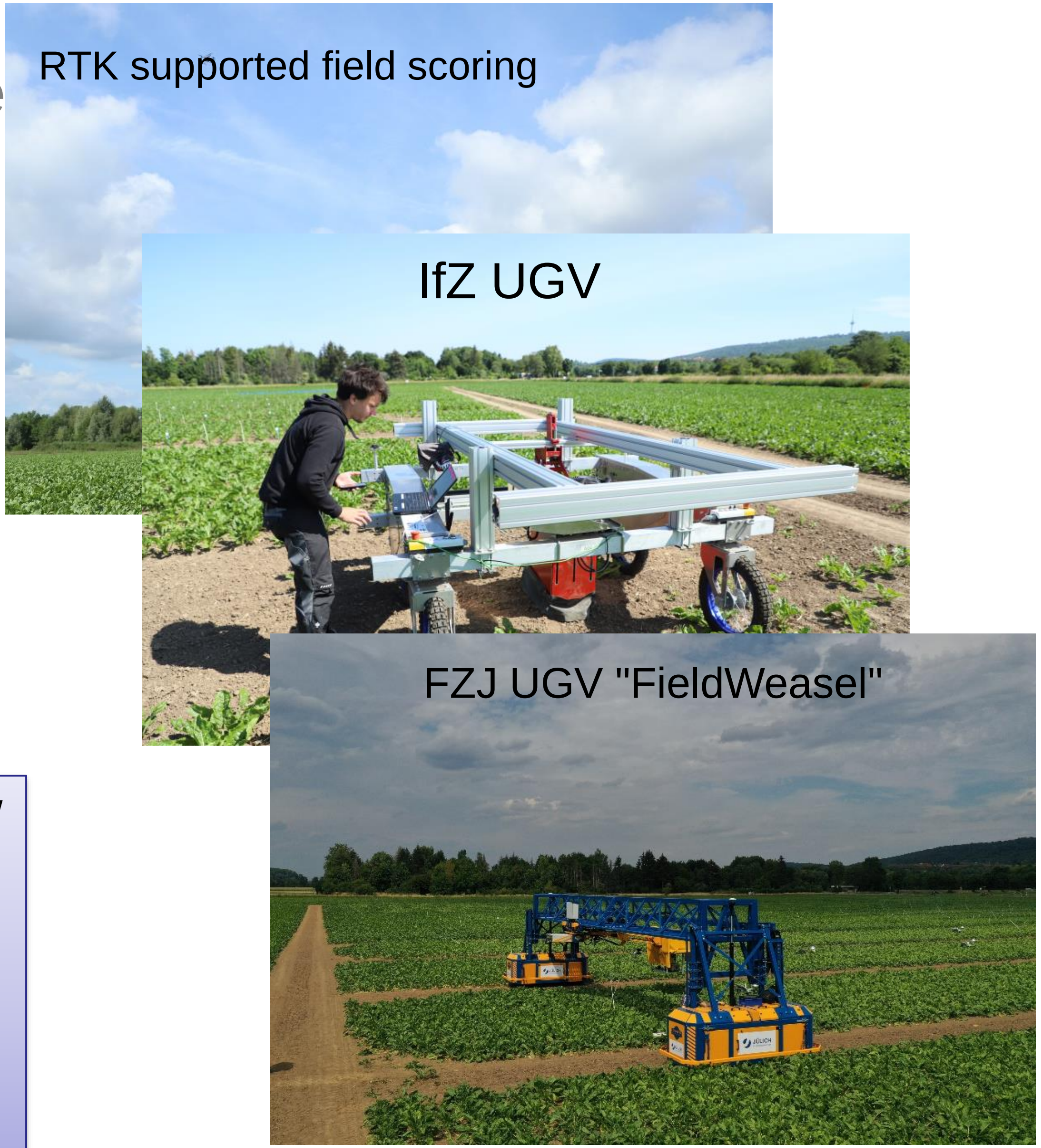
- No dedicated disease mapping / detection / identification campaigns or projects, yet.
- We are just preparing for first data acquisition over a disease field trail in Göttingen (cooperation with A. Mahlein)



On the potential to early and specifically map diseases from ground-, air-, and spaceborne plattforms

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- Proximity sensing: Advanced technologies (sensors and data processing techniques) nowadays open the possibility for reliable disease detection
- But we
  - need to get beyond vegetation indices, i.e. use the full information, which we have available from novel sensors
  - Be clear what are direct signals emerging from the disease and what are correlated effects that obscure the disease signal

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Current Opinion in Plant Biology

Quantitative and qualitative phenotyping of disease resistance of crops by hyperspectral sensors: seamless interlocking of phytopathology, sensors, and machine learning is needed!

Anne-Katrin Mahlein[1,2], Matheus Thomas Kuska[2], Stefan Thomas[2], Mirwaes Wahabzada[2], Jan Behmann[2], Uwe Rascher[3] and Kristian Kersting[4]

Check for updates

On the potential to early and specifically map diseases from ground-, air-, and spaceborne plattforms

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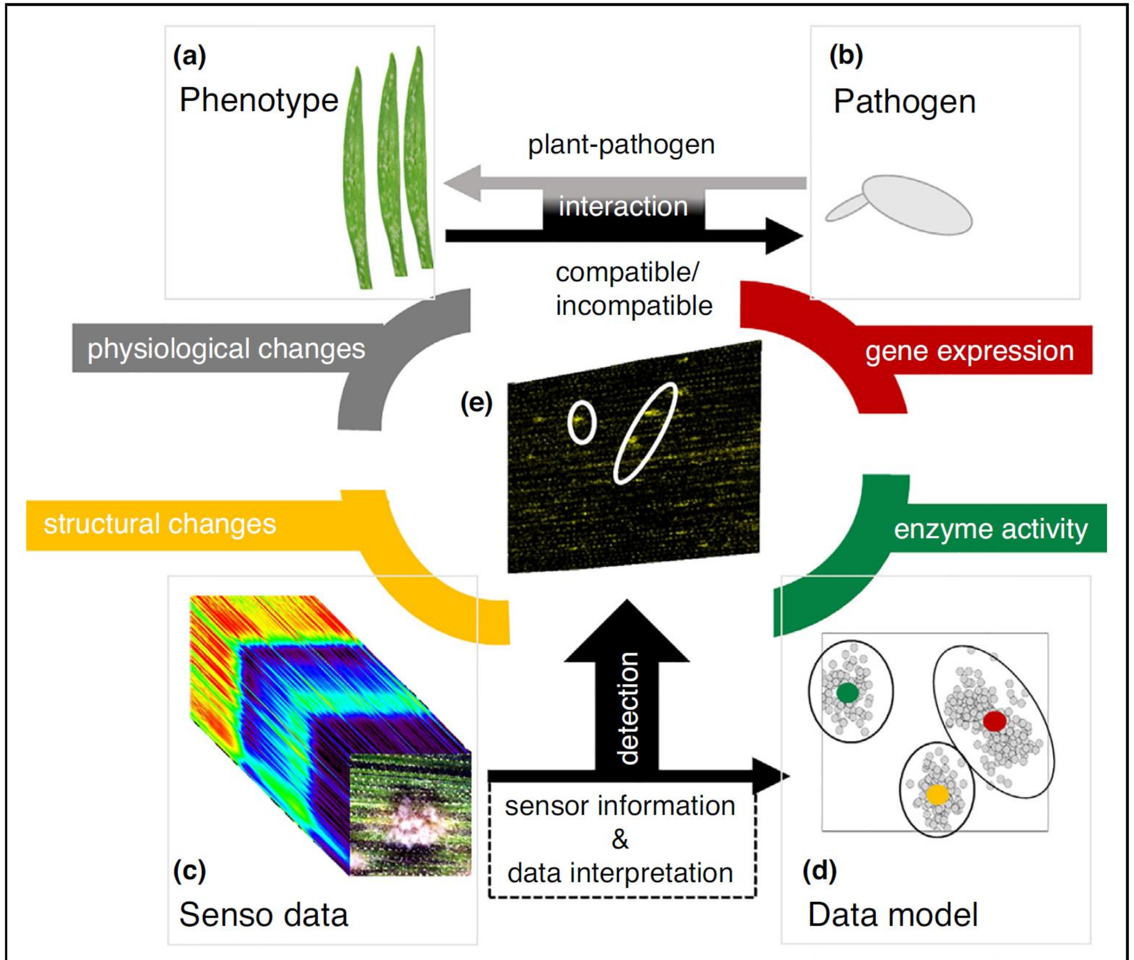
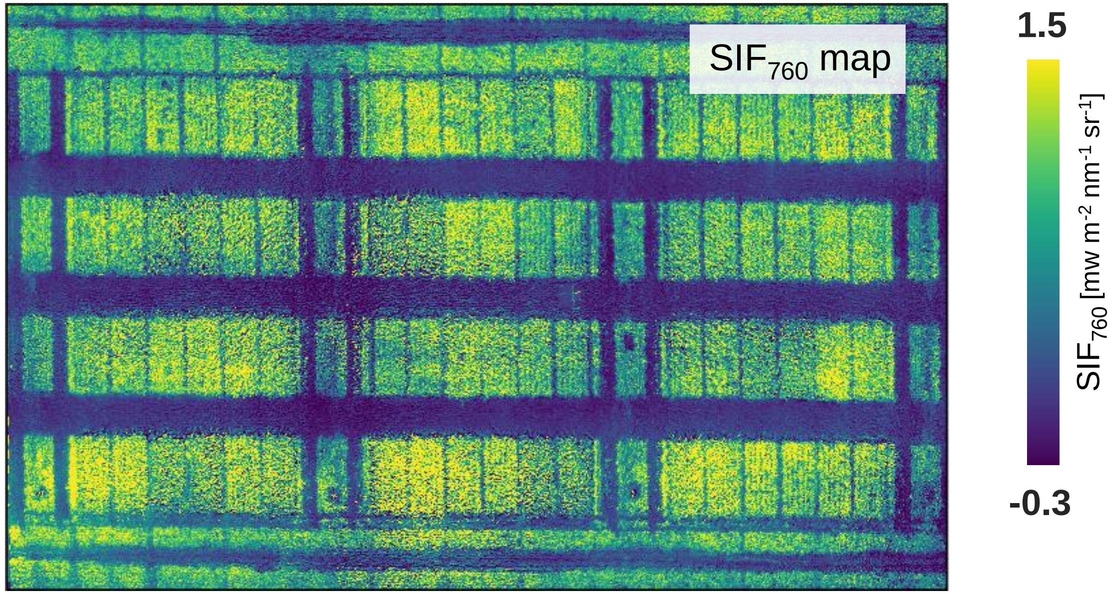


Current Opinion in Plant Biology

On the potential to early and specifically map diseases from ground-, air-, and spaceborne plattforms

- Airborne sensing: UAV-based are booming, while airborne sensors are on the decline.

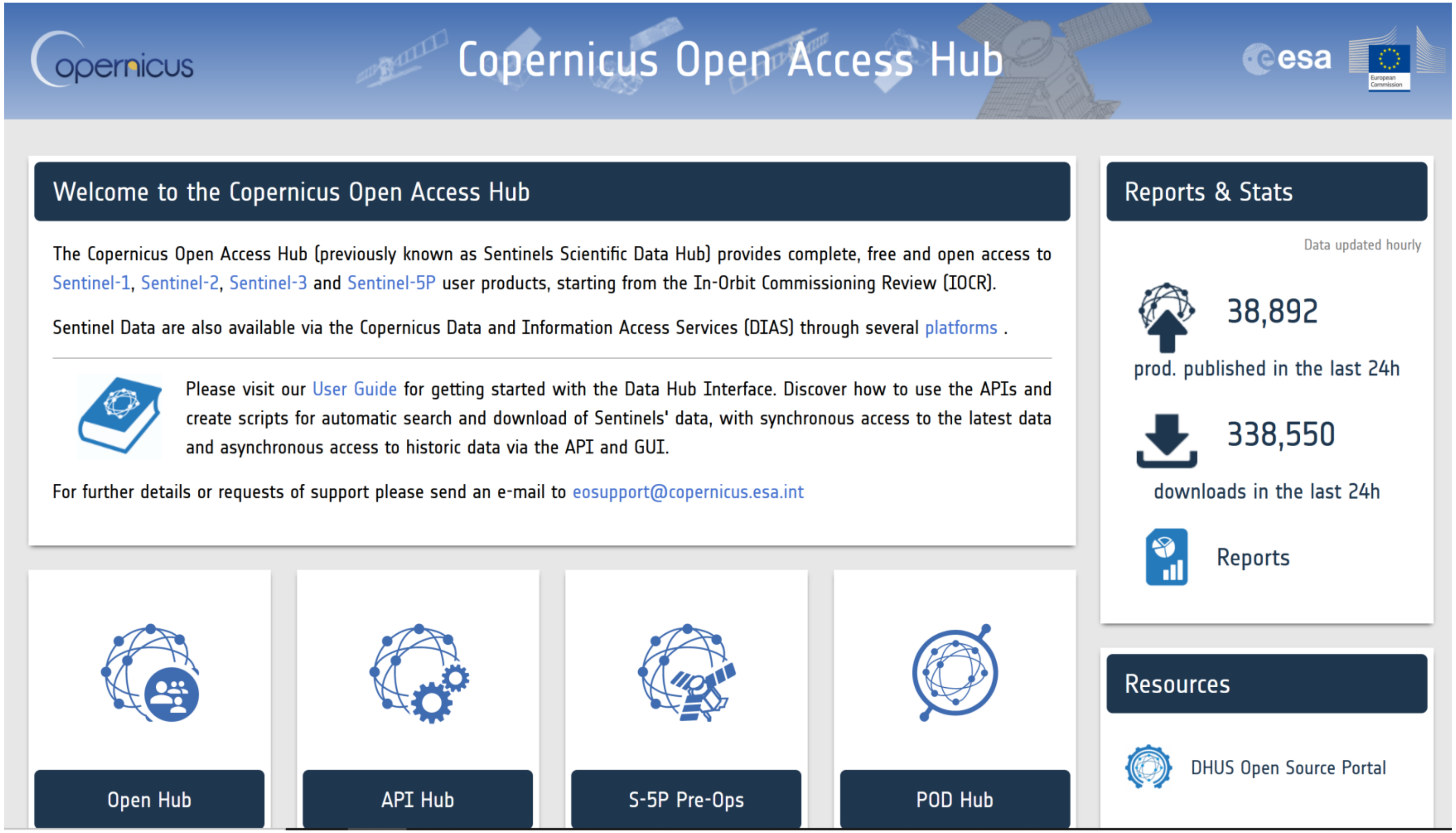
- Same considerations as before, additionally
  - Data quality of UAV based sensors is often limiting
  - Often naïve use of e.g. machine learning
  - Airborne sensors are important to close the gap to satellites
  - New measurement options which potential for disease detection may still be explored



Kneer et al (2023) A snapshot imaging system for the measurement of solar-induced chlorophyll fluorescence – addressing the challenges of high-performance spectral imaging for mapping SIF. *IEEE – Sensors, online first;* 10.1109/JSEN.2023.3297054

On the potential to early and specifically map diseases from ground-, air-, and spaceborne plattforms

- Satellite sensing: Satellite data are nowadays of high quality and easy to use. But still a trade-off between spectral performance spatial resolution and revisiting time



https://scihub.copernicus.eu/

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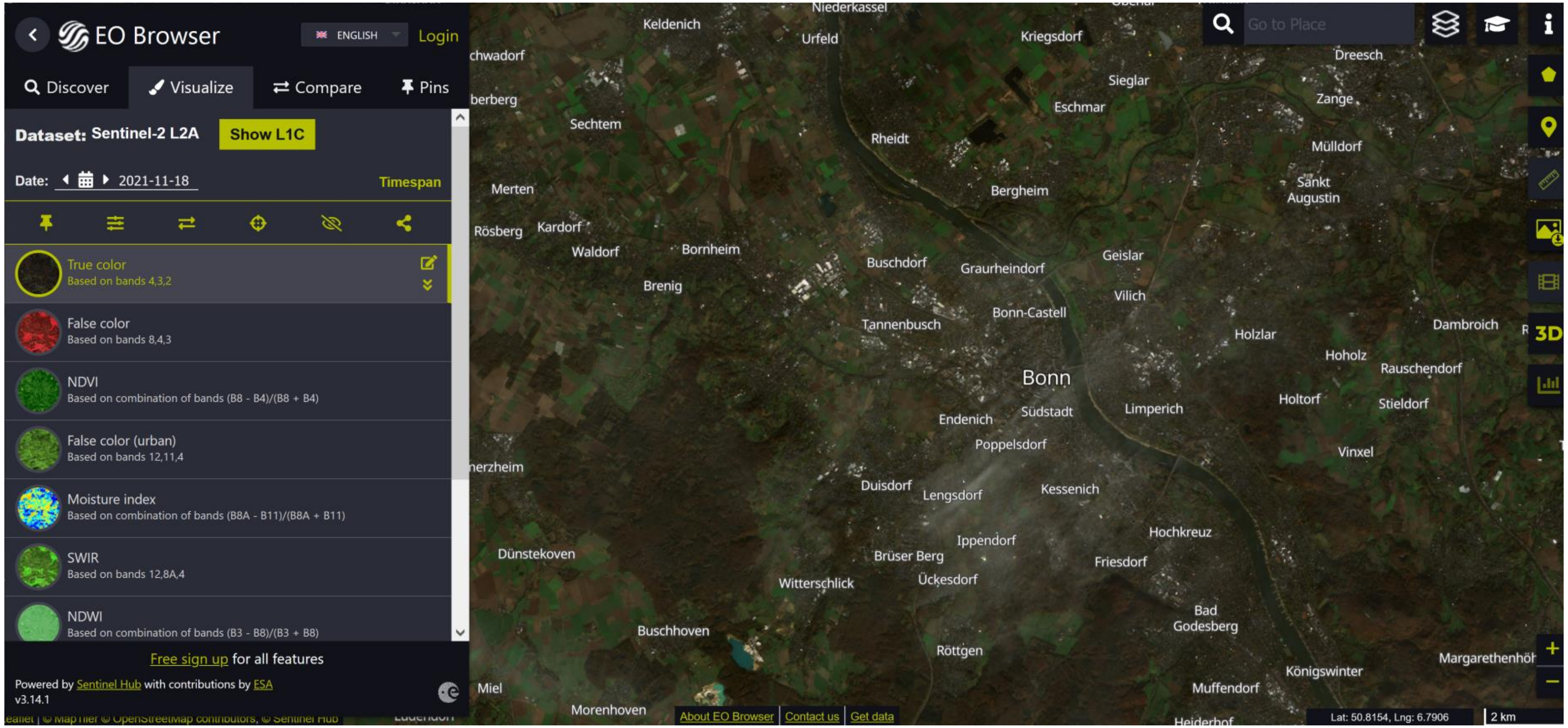
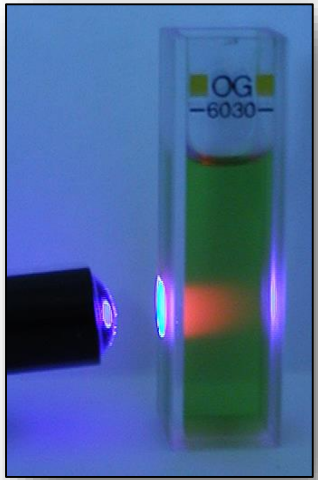


https://apps.sentinel-hub.com/eo-browser/

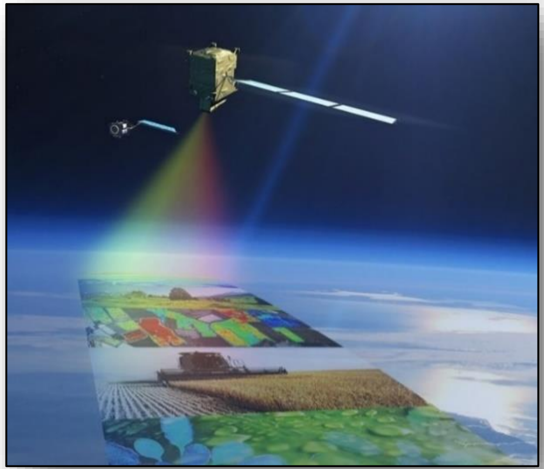
Summary – u.rascher@fz-juelich.de / 0170-2219199

- Disease symptoms are complex and already at the close range (proximity sensing) a meaningful combination of spectrally resolved data, covering the right range and advanced data processing is needed
- Small scale symptoms are often obscured on the larger scale and hidden correlations may hamper diseases detection from the distance
- Combination of spectrally resolved reflectance, fluorescence and thermal approaches shall be further exploited
- Combination of ground based systems (high temporal resolution and specifity) with airborne & satellite data (large coverage) is needed

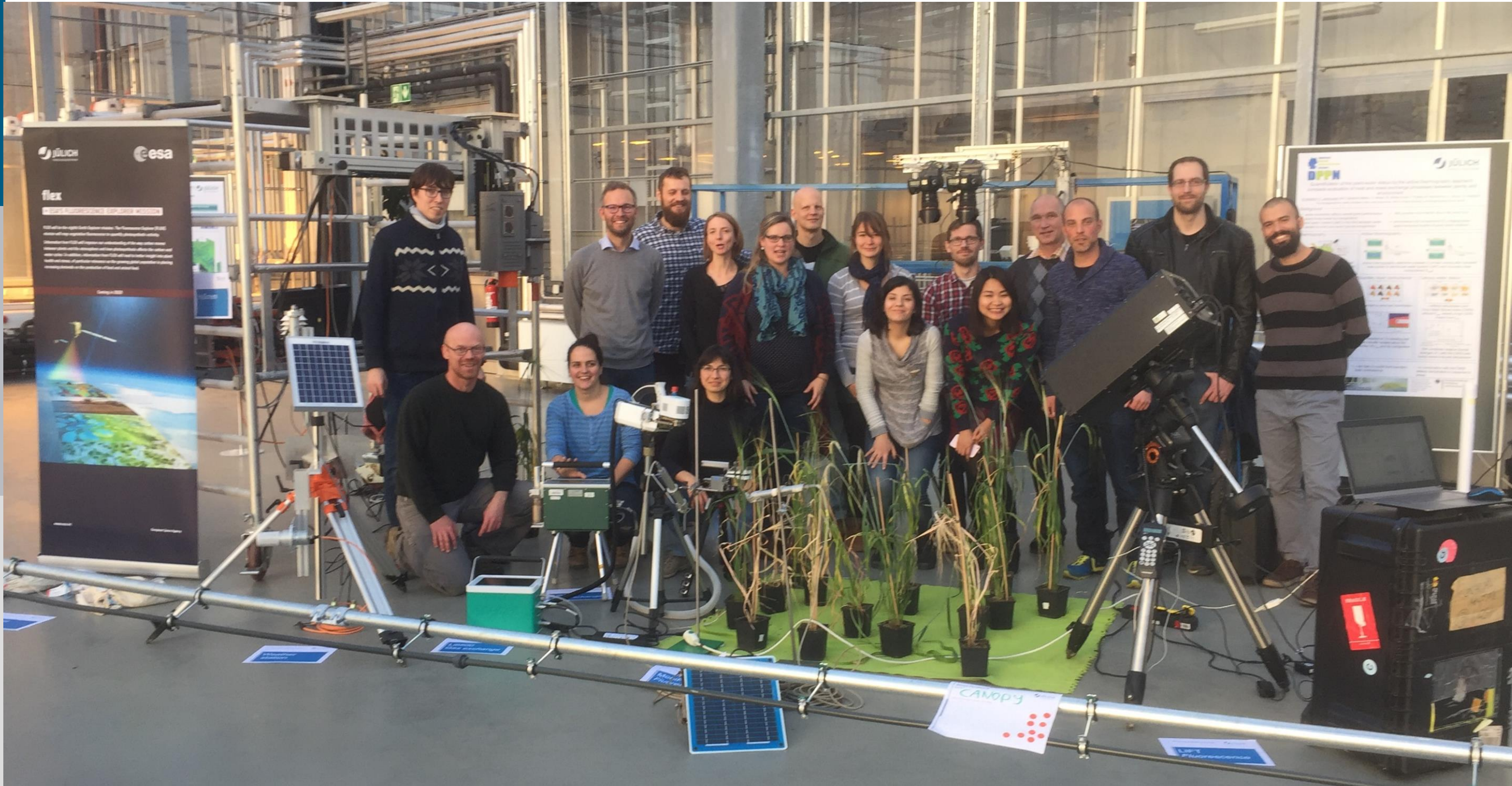








Many thanks to my group



Many thanks to the numerous partners

University of Zurich UZH

Consiglio Nazionale delle Ricerche

University of Cologne

universität bonn

Deutsche Forschungsgemeinschaft DFG

Centre de Recherche Public Gabriel Lippmann

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