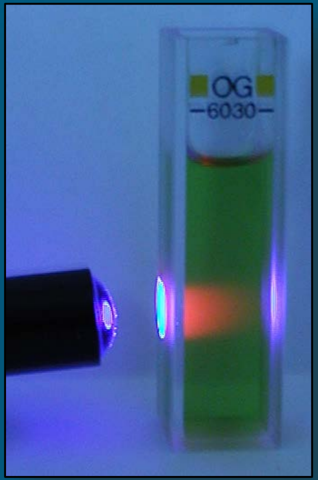
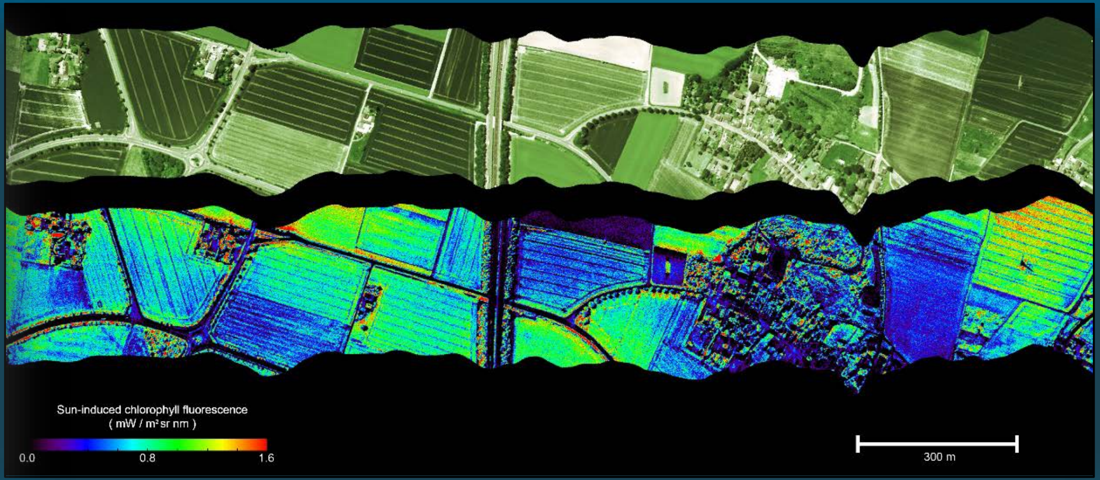
Mitglied der Helmholtz-Gemeinschaft

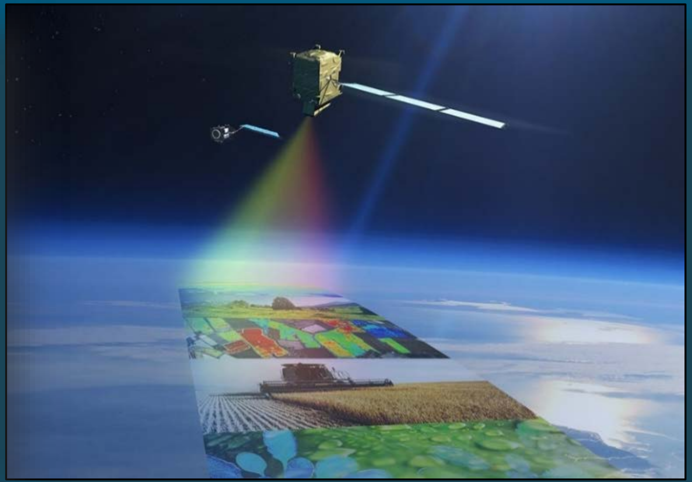
Institut für Bio- und Geowissenschaften
IBG-2: Pflanzenwissenschaften

Measuring and understanding solar-induced fluorescence across scales

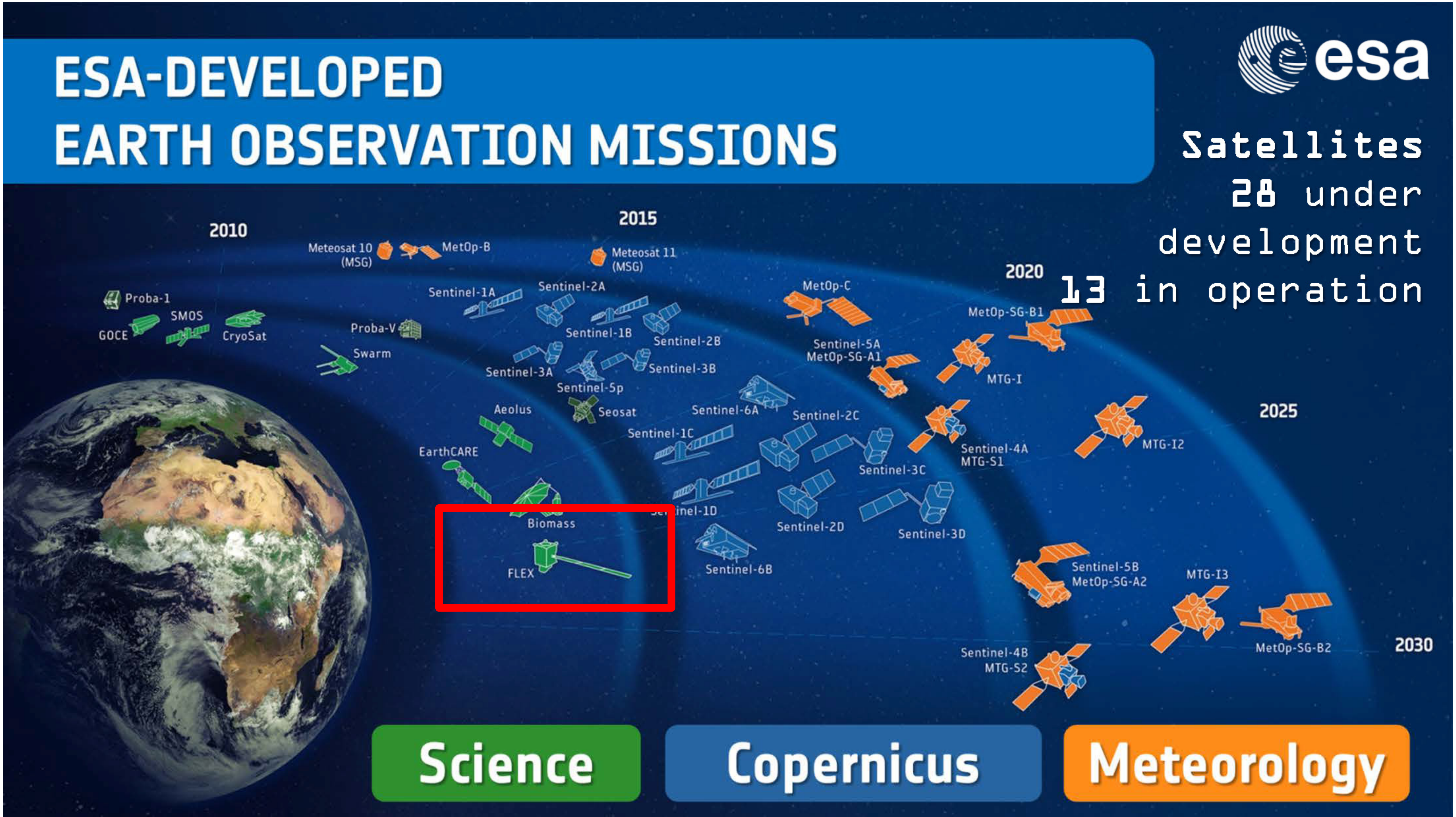
Uwe Rascher, A. Burkart, S. Cogliati, R. Colombo, A. Damm, D. Emin, J. Hanus, S. Heinemann, T. Julitta, L. Junker, V. Krieger, M. Matveeva, O. Muller, P. Näthe, P. Rademske, B. Siegmann, N. Wilke
* Forschungszentrum Jülich, Institute of Bio- and Geosciences, IBG-2: Plant Sciences, Germany







ESA’s Earth Observation satellites

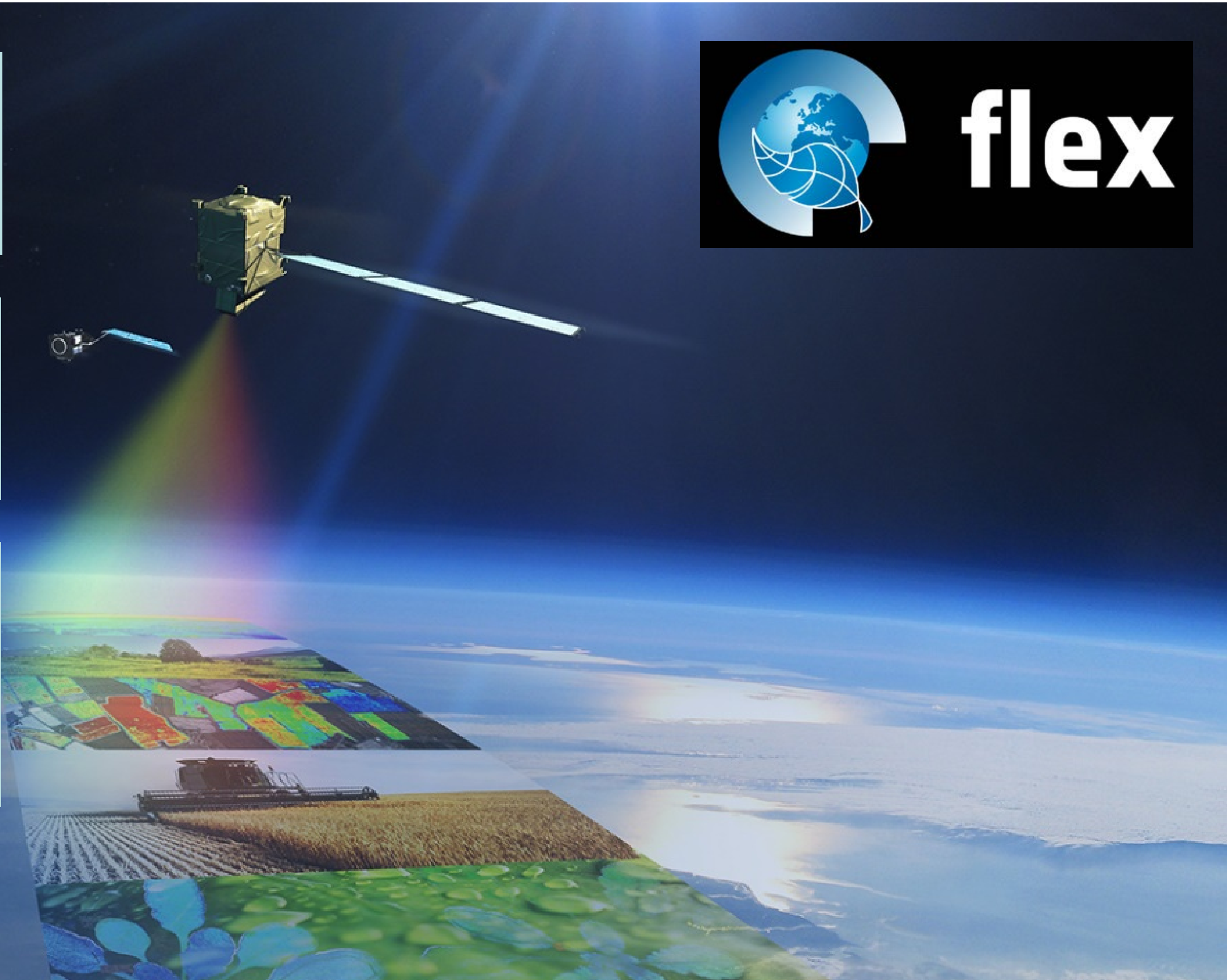


FLEX Satellite Mission will become the 8th Earth Explorer of ESA

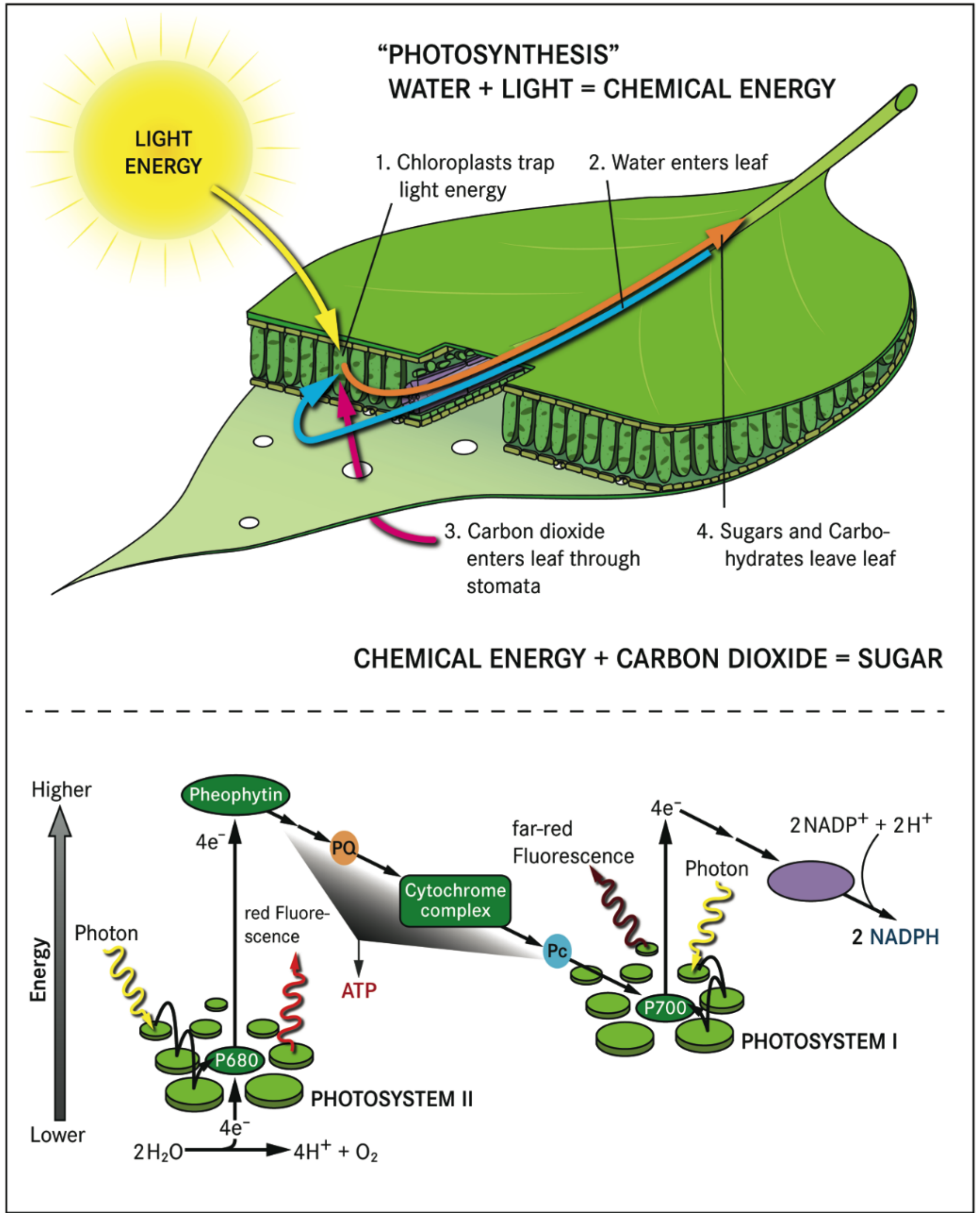
FLEX will quantify **actual photosynthetic activity** of terrestrial ecosystems

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

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



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

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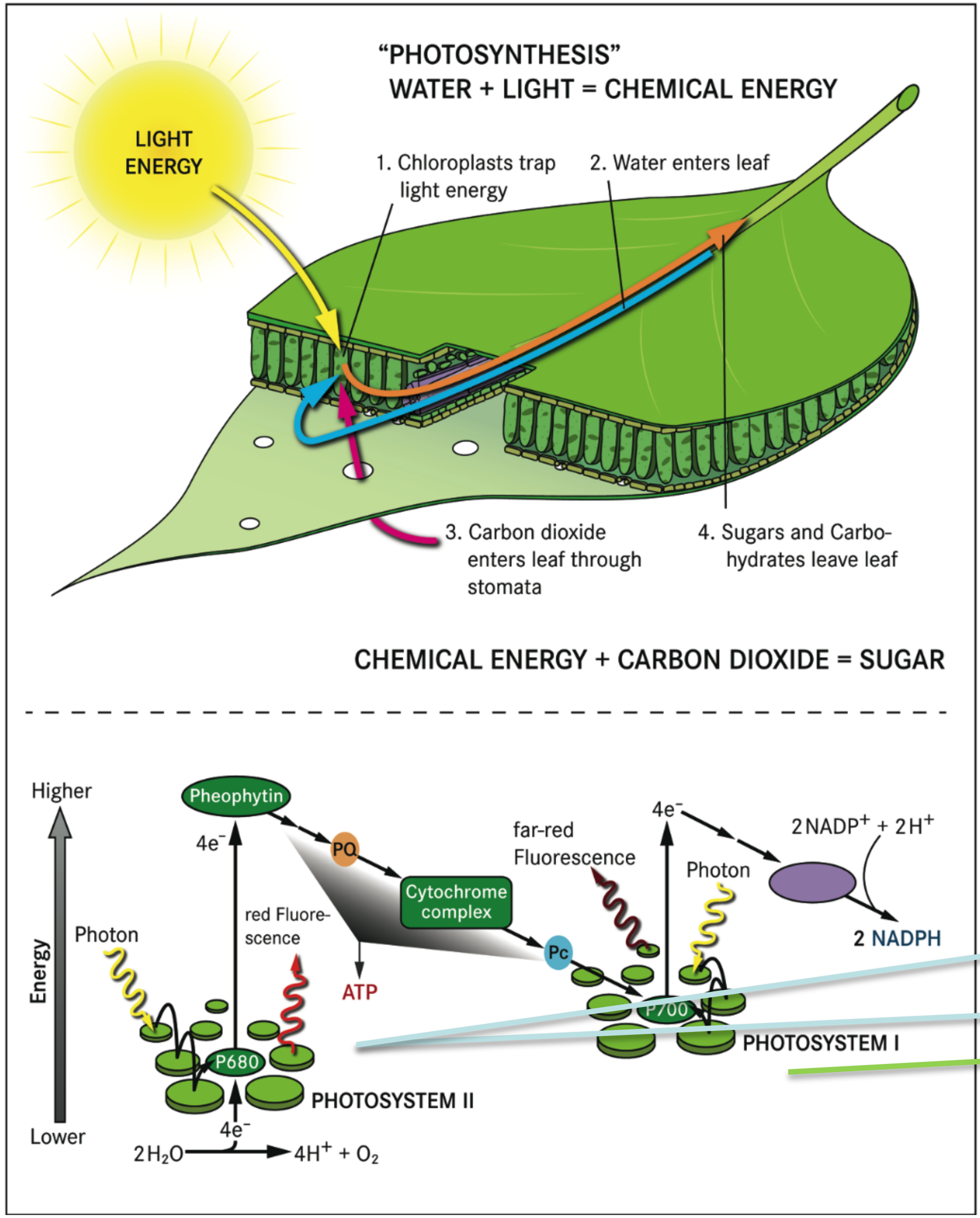

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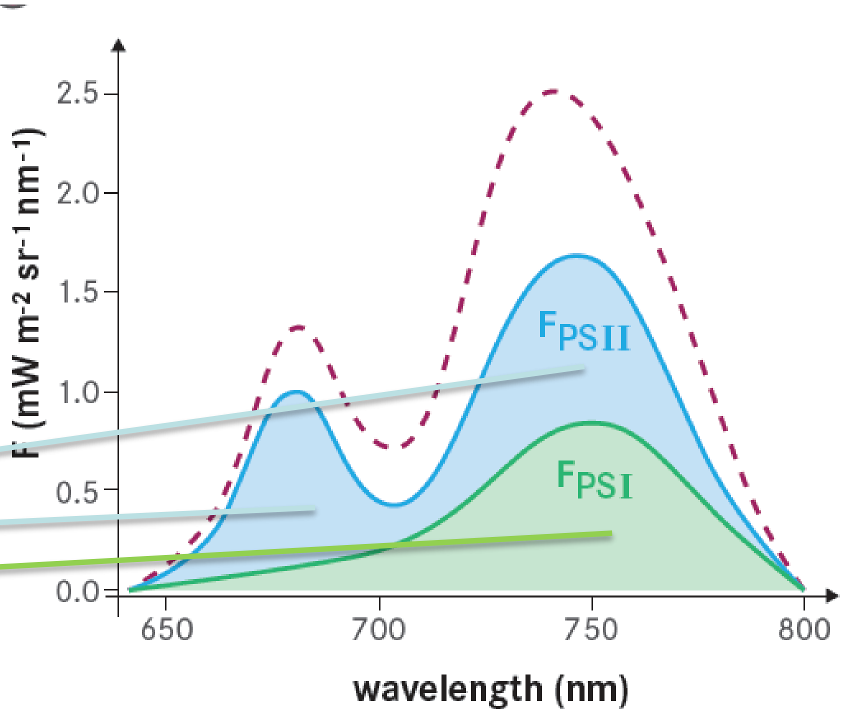

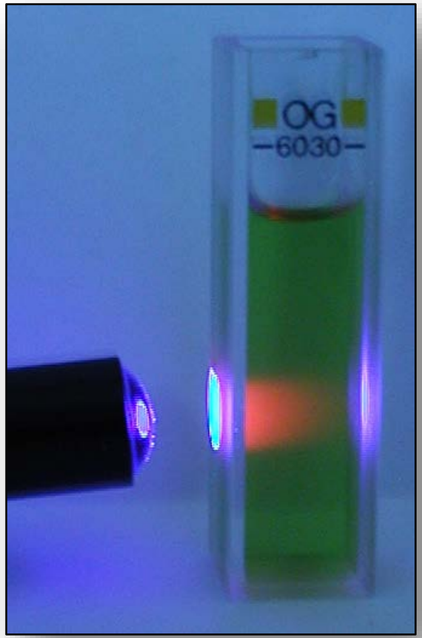

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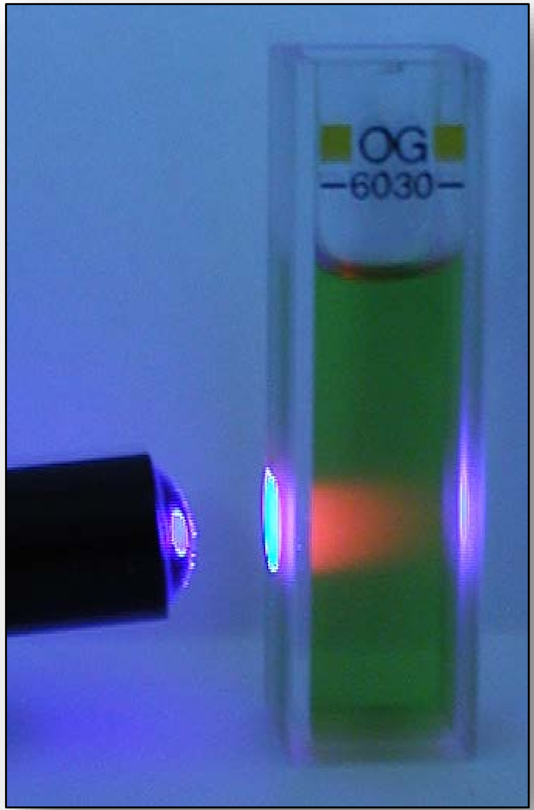
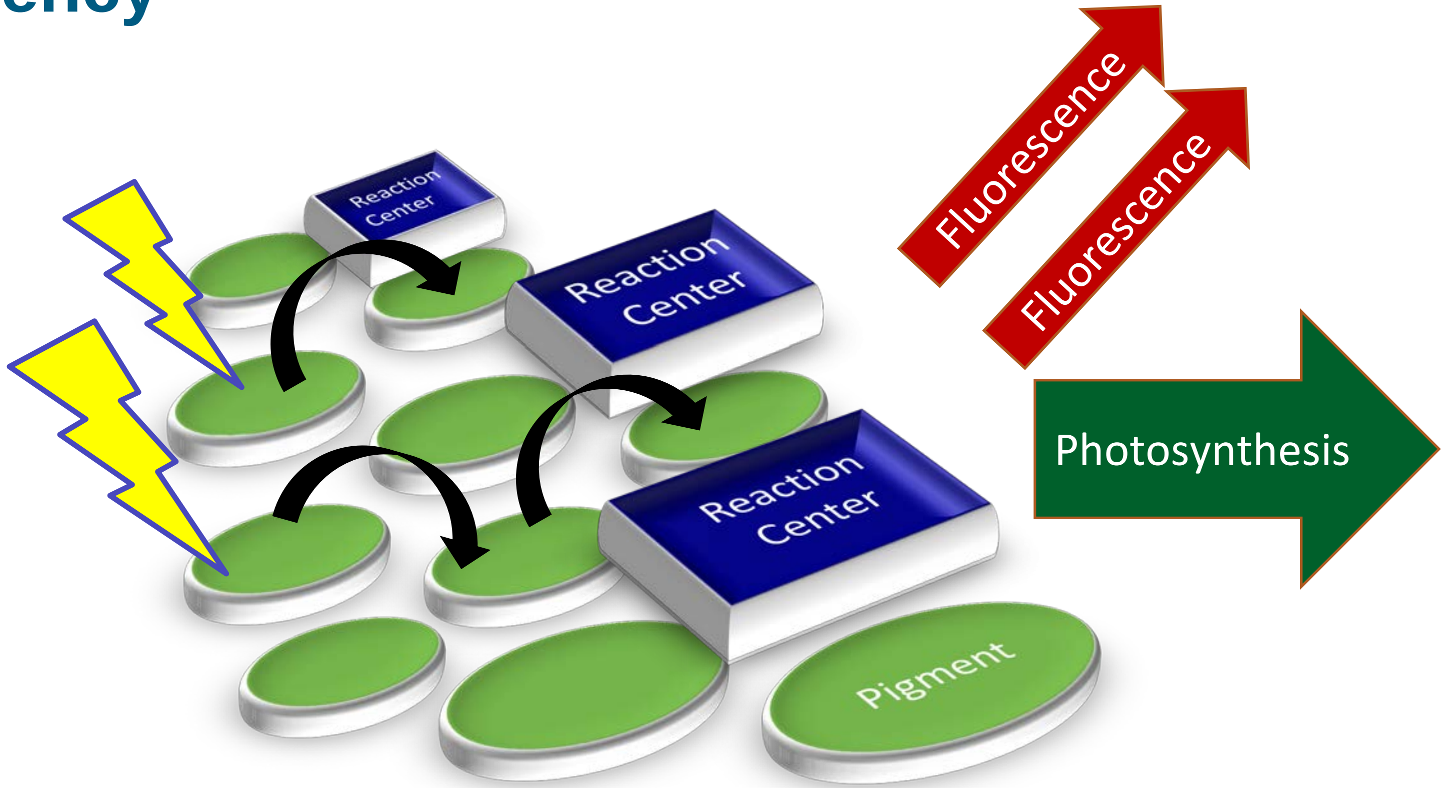
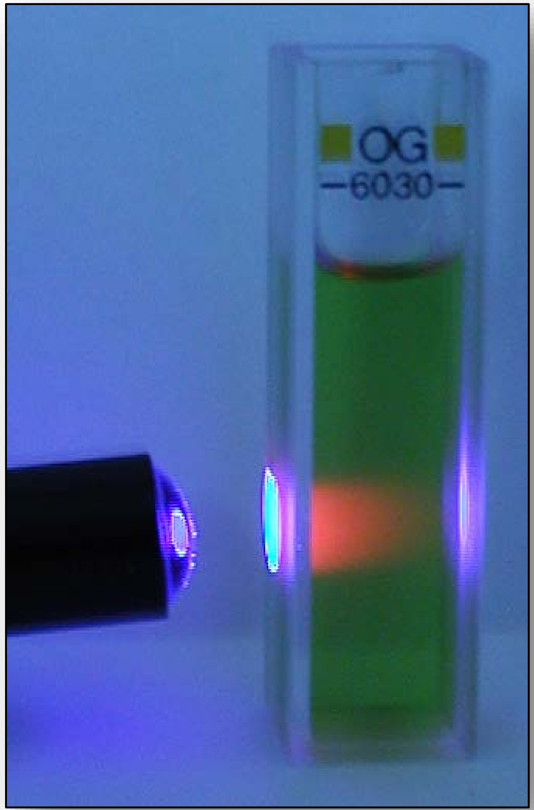




1. Chlorophyll molecules emit fluorescence. The intensity of the fluorescence signal is a function of light intensity and the concentration of chlorophyll
2. Additionally, the functional status of photosynthesis modulates the intensity of the fluorescence signal

Leaf fluorescence – two photosystems and two dynamically adapting signals



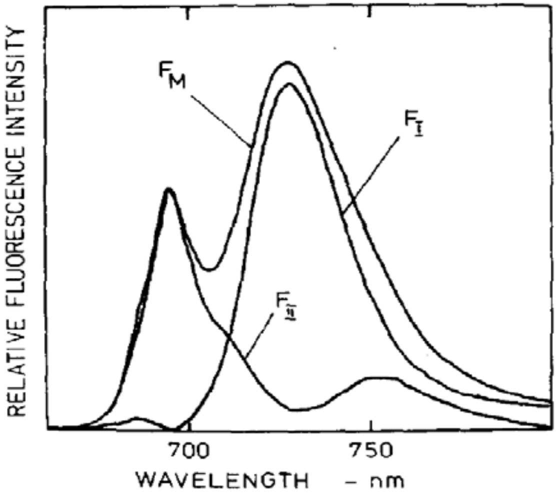
Biochimica et Biophysica Acta, 462 (1977) 307–313

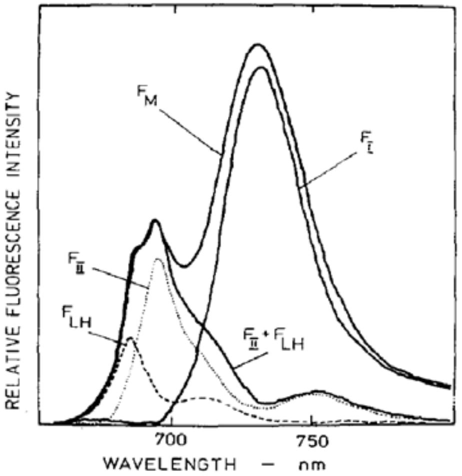
BBA 47380

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

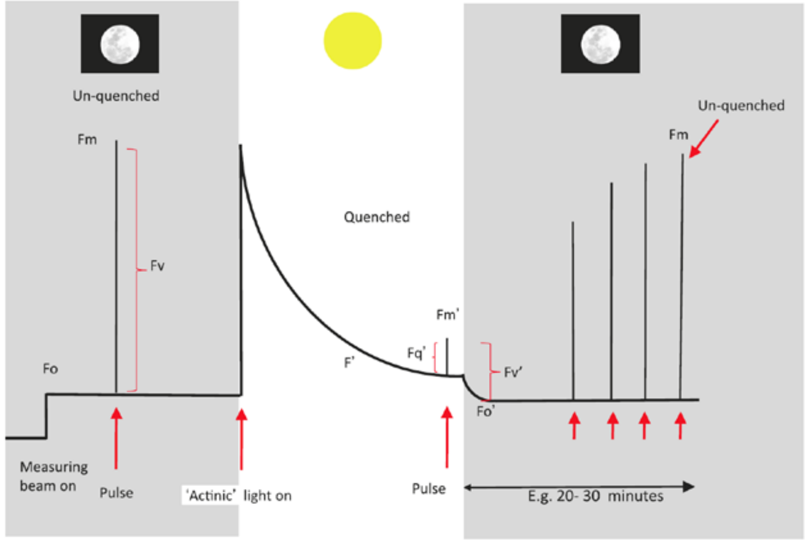
Department of Biology, University of California, San Diego, La Jolla, Calif. 92093 (U.S.A.)





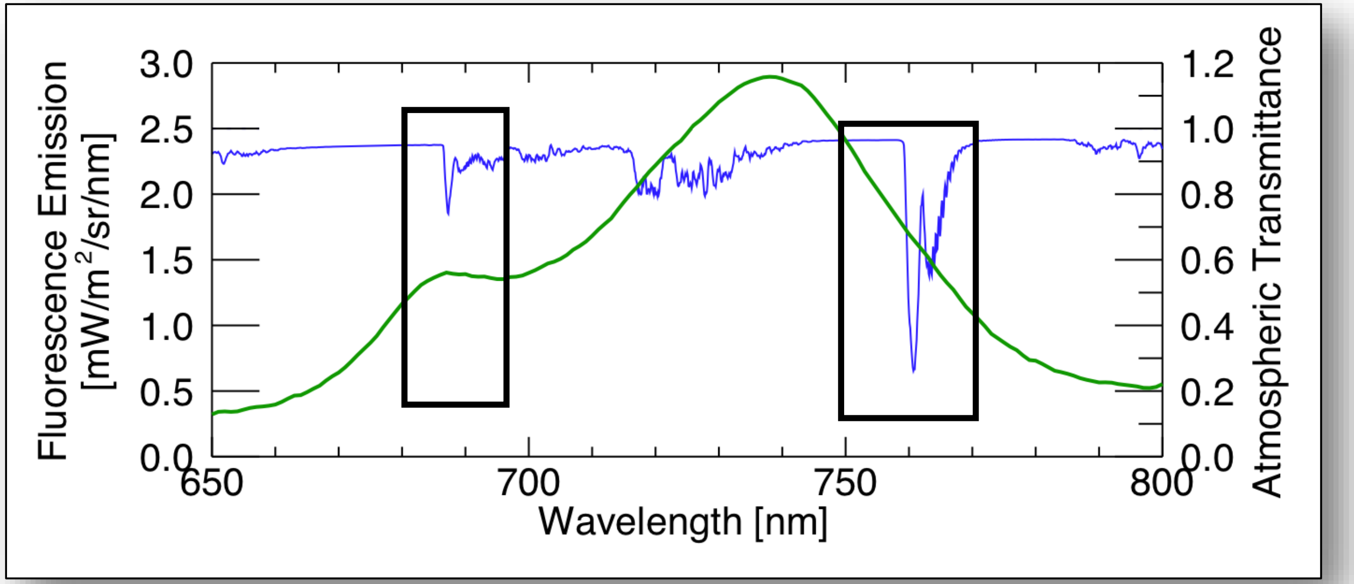
Fluorescence techniques are the most widely used approaches to investigate photosynthesis

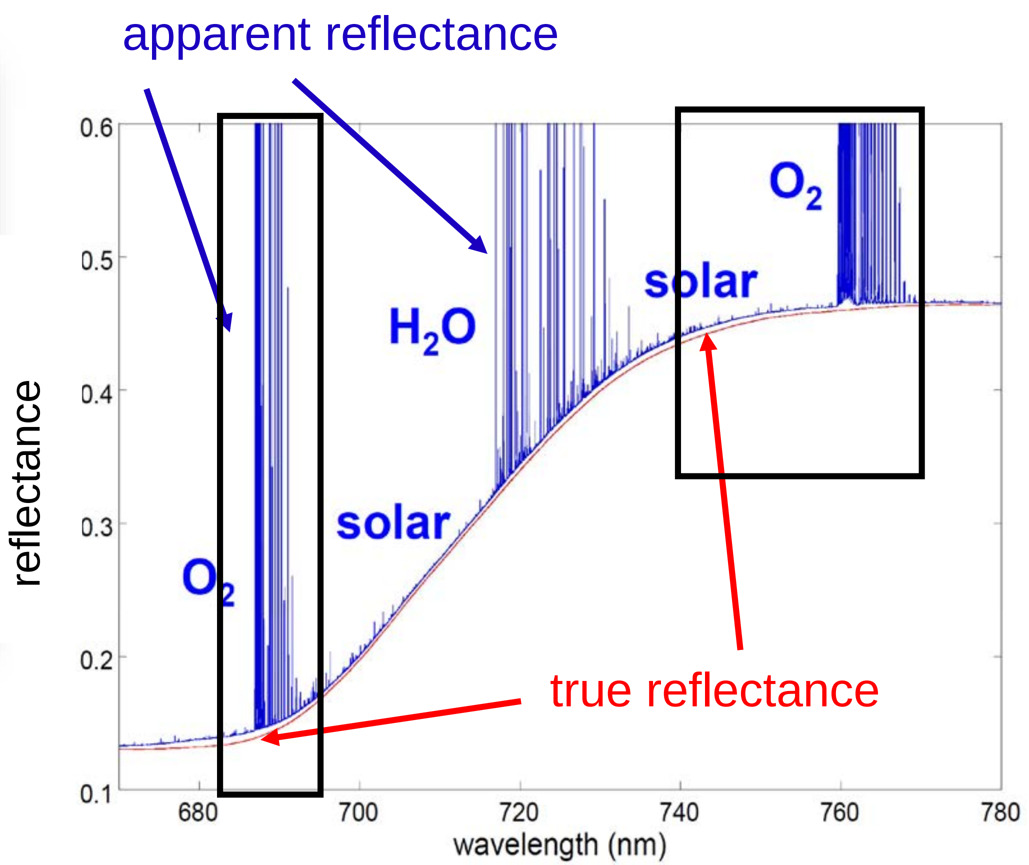
- Various leaf level instruments available and currently ~750 Papers published per year
- Most methods use active approaches, such as PAM, saturating light pulses or lasers induced fluorescence transients



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, doi: 0.1007/s11120-018-0594-9.

Sun-induced fluorescence can be measured in the solar and atmospheric absorption lines





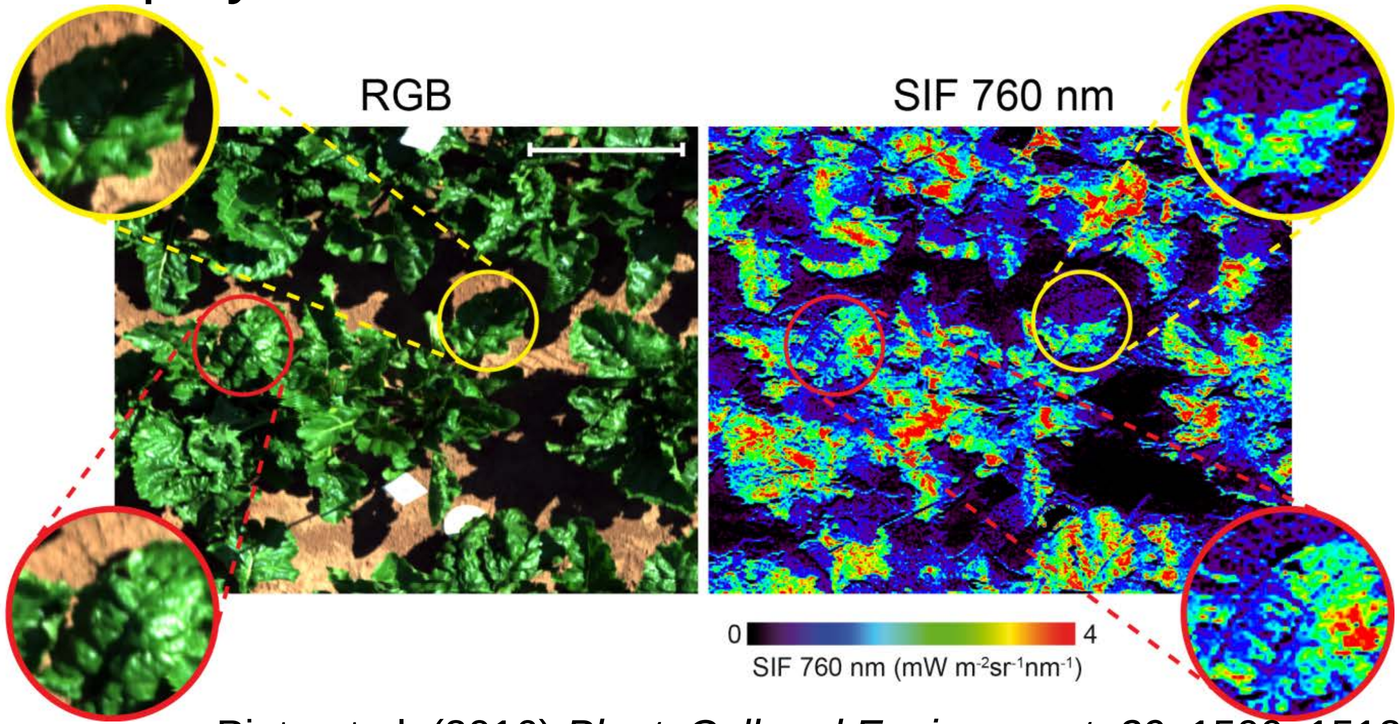
Atmospheric oxygen and solar absorption lines facilitate the retrieval of the weak fluorescence signal from the surface reflectance

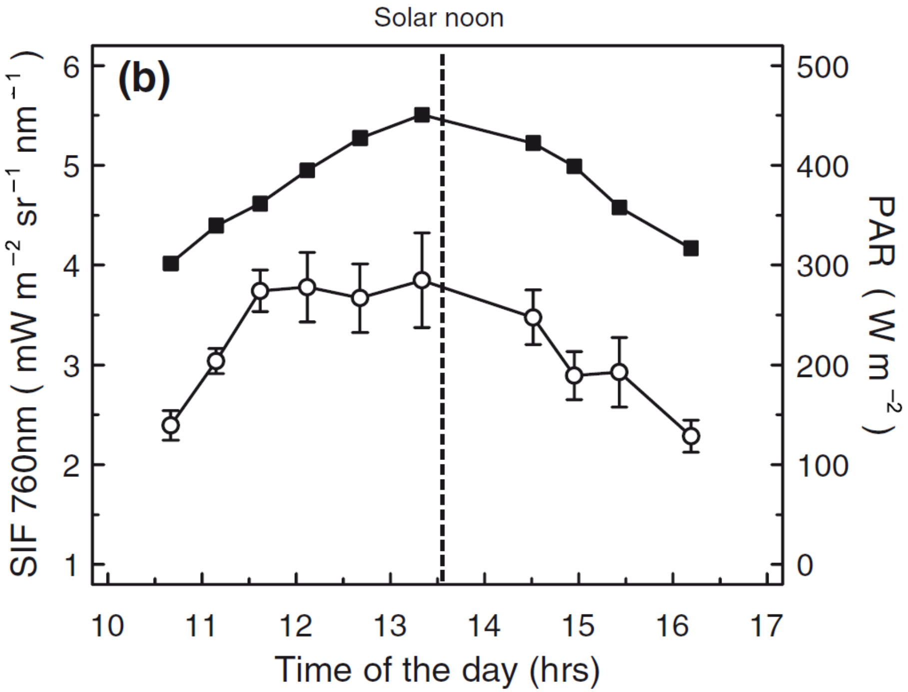
Plascyk (1975) *Optical Engineering 14*, 339–346
Carter et al. (1996) Remote Sensing of Environment 55, 89–92
Moya et al. (2004) Remote Sensing of Environment 91, 186–197
Meroni et al. (2009) *Remote Sensing of Environment, 113*, 2037-2051
Cogliati et al. (2015) *Remote Sensing of Environment, 164*, 270-281
Cogliati et al. (2019) Remote Sensing, doi: 10.3390/rs11161840

Steady-state fluorescence and photosynthetic efficiency are non-linearly related – leaf/canopy level

- Mapping of sun-induced fluorescence on the ground to understand interplay of the variations of light intensity within natural canopies and the three dimensional leaf display

Diurnal course of sun-lit leaves of upper canopy





Pinto et al. (2016) *Plant, Cell and Environment, 39*, 1500–1512

Pinto et al. (2017) *Remote Sensing, 9, 415, doi: 10.3390/rs9050415*

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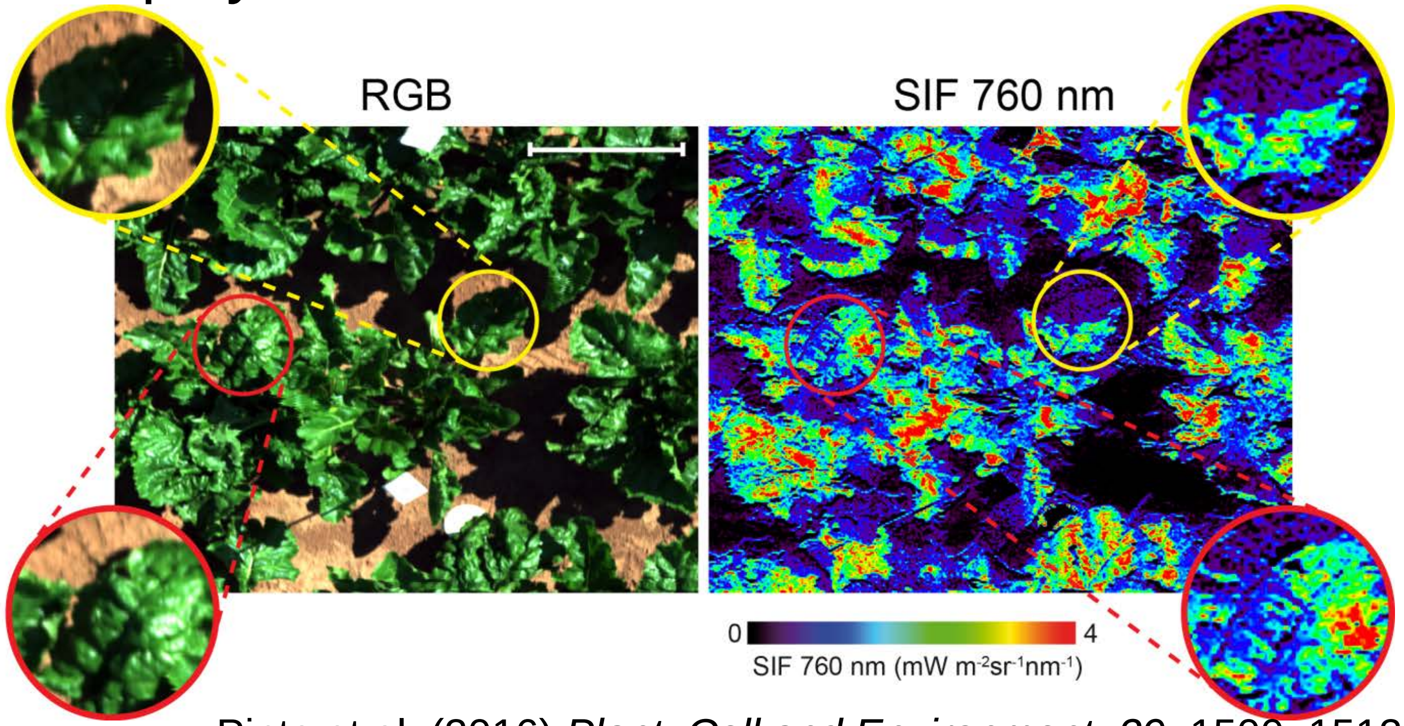

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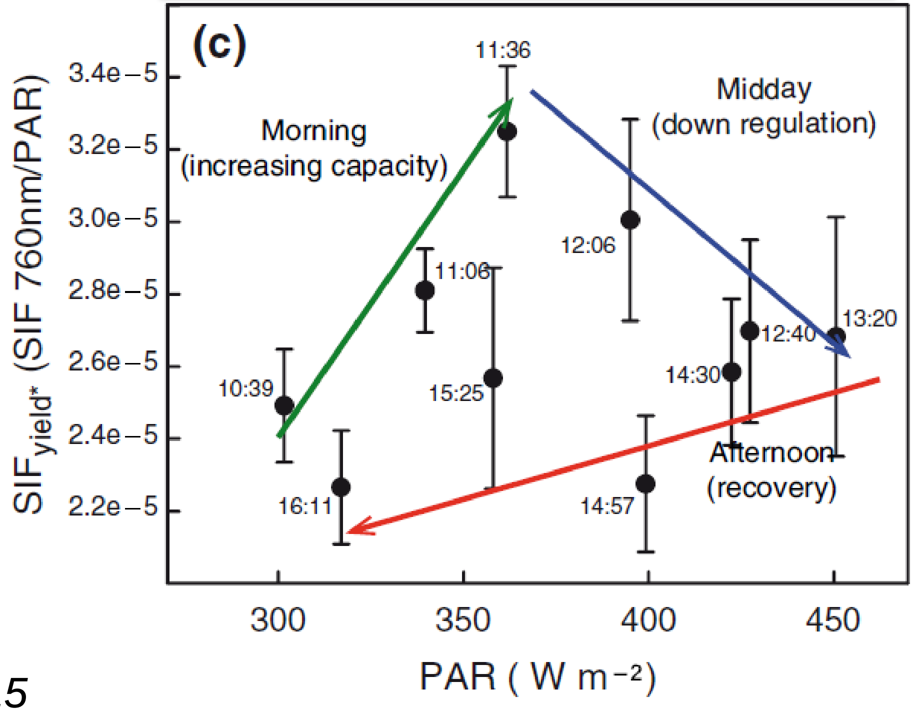

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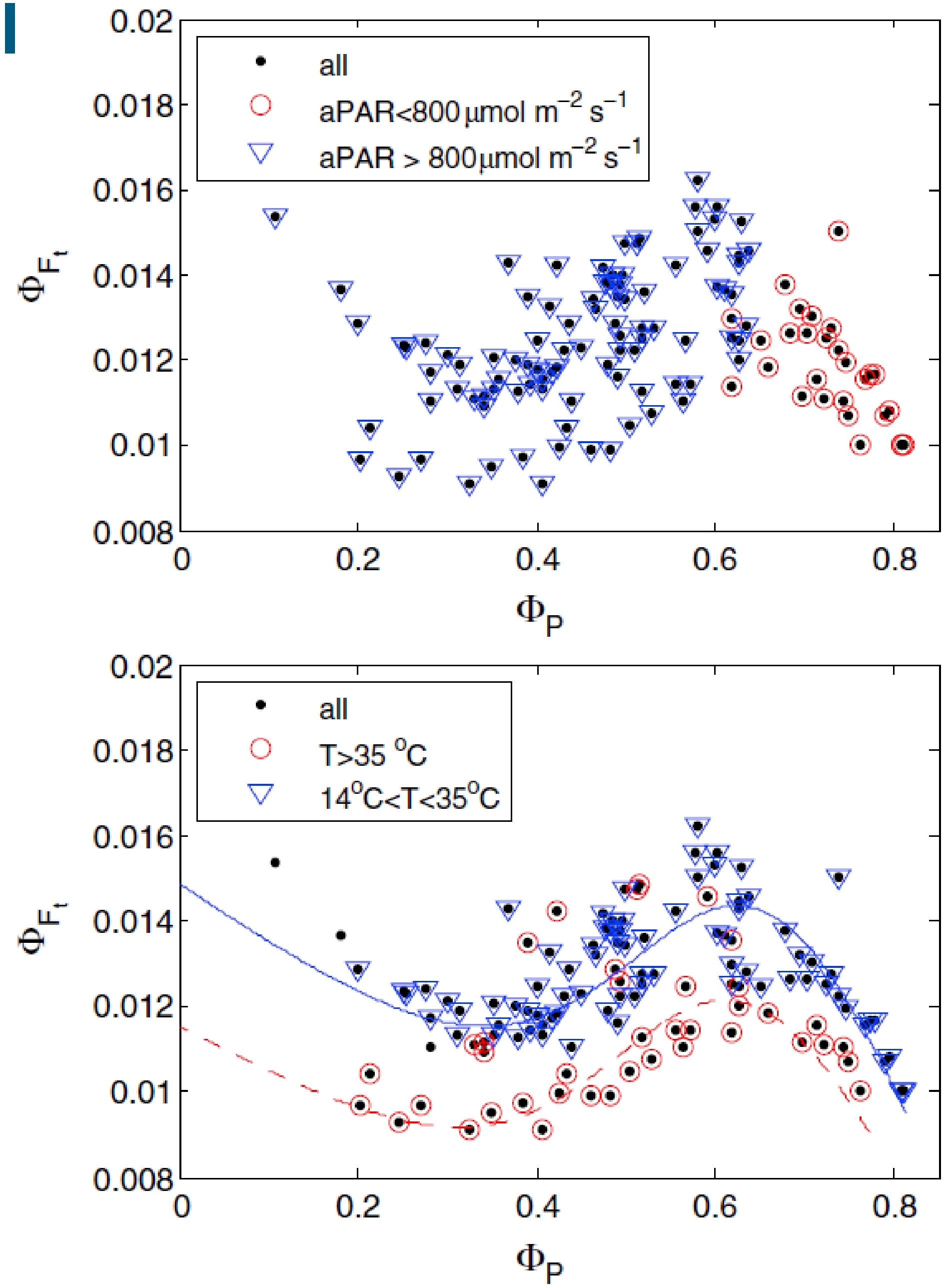
Steady-state fluorescence and photosynthetic efficiency are non-linearly related – leaf level

- The relationship between solar-induced fluorescence and efficiency of photosynthesis is not linear



van der Tol C., Berry J.A., Campbell P.K.E. & **Rascher U.** (2014) Models of fluorescence and photosynthesis for interpreting measurements of solar-induced chlorophyll fluorescence. *Journal of Geophysical Research - Biogeosciences*, *119*, 2312-2327.

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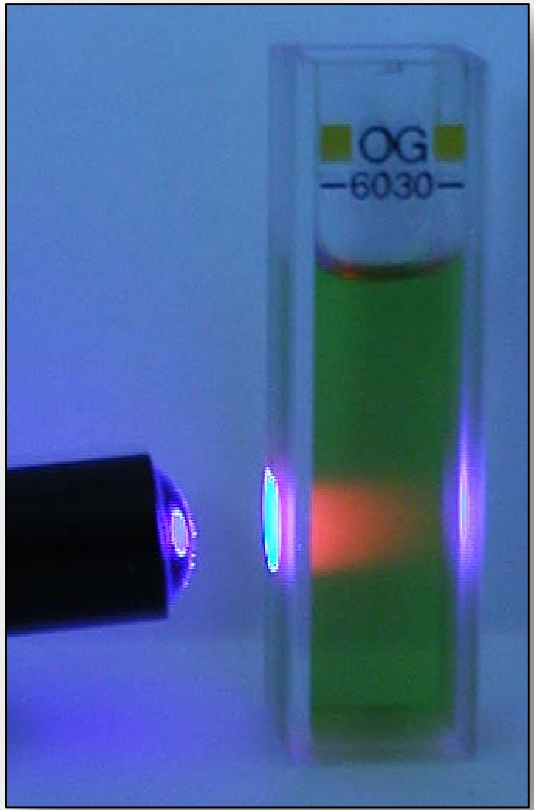

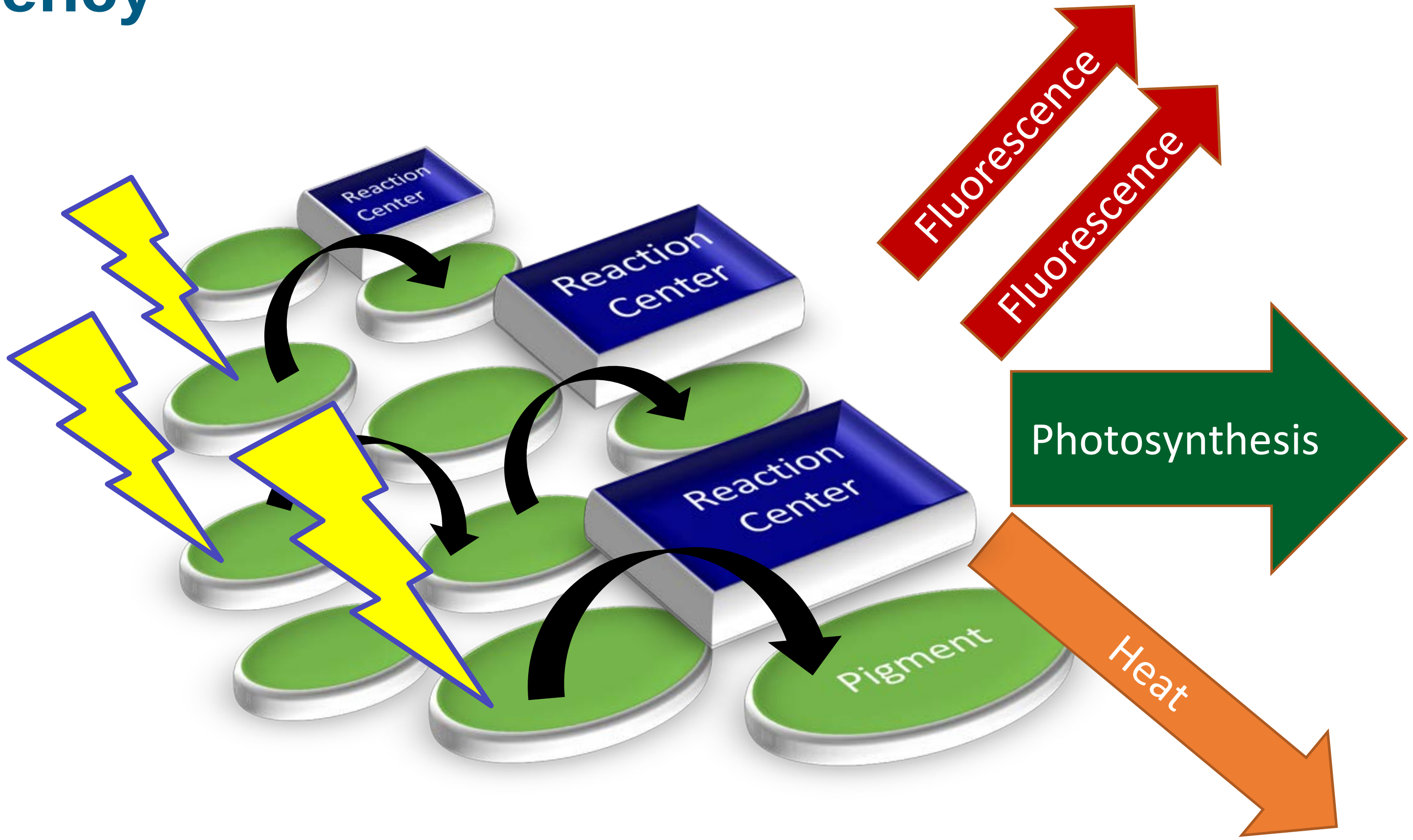

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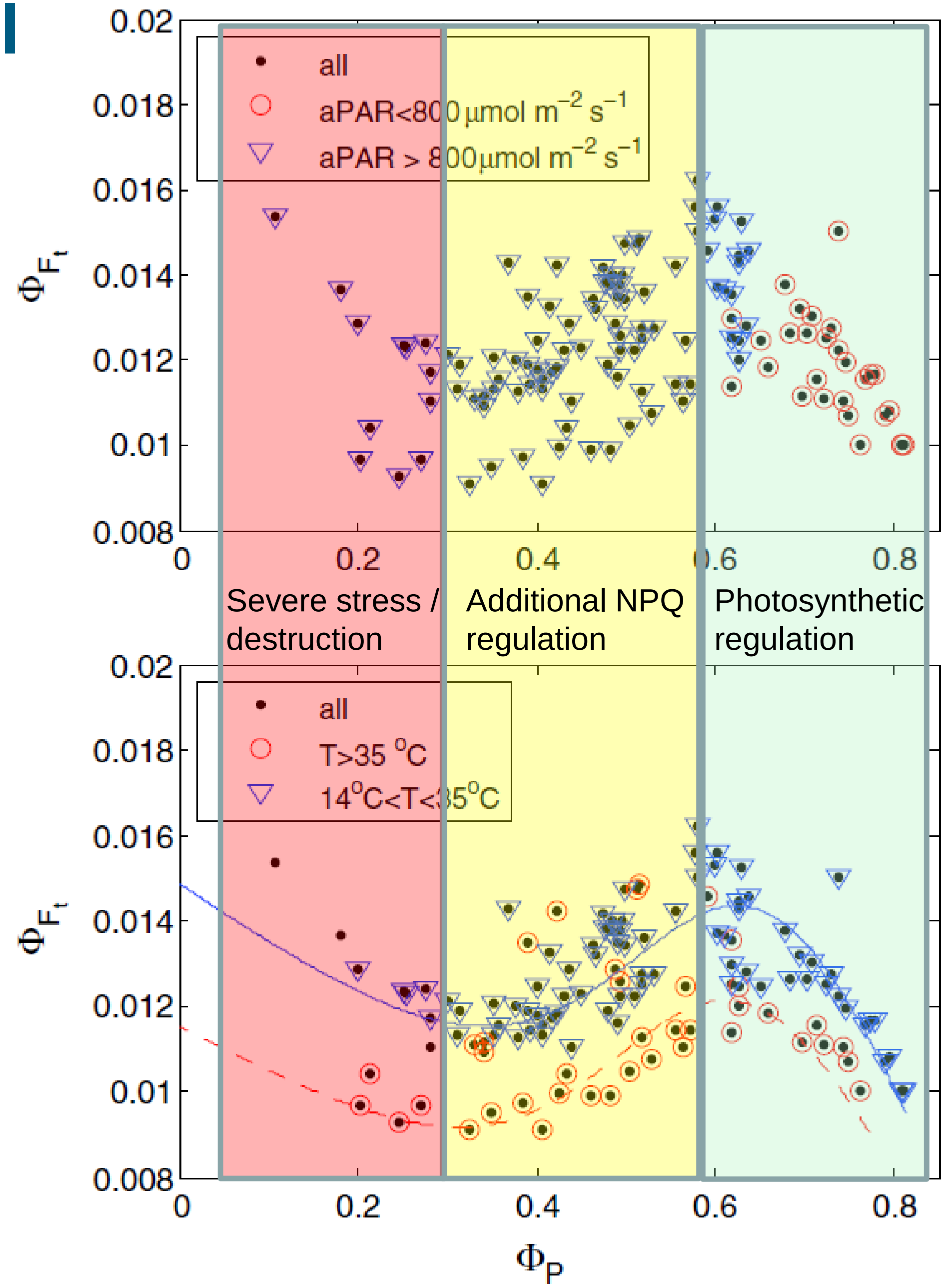
Steady-state fluorescence and photosynthetic efficiency are non-linearly related – leaf level

- The relationship between solar-induced fluorescence and efficiency of photosynthesis is not linear
- Light intensity, temperature and the degree of non-photochemical energy dissipation influence the relation between solar-induced fluorescence and photosynthesis



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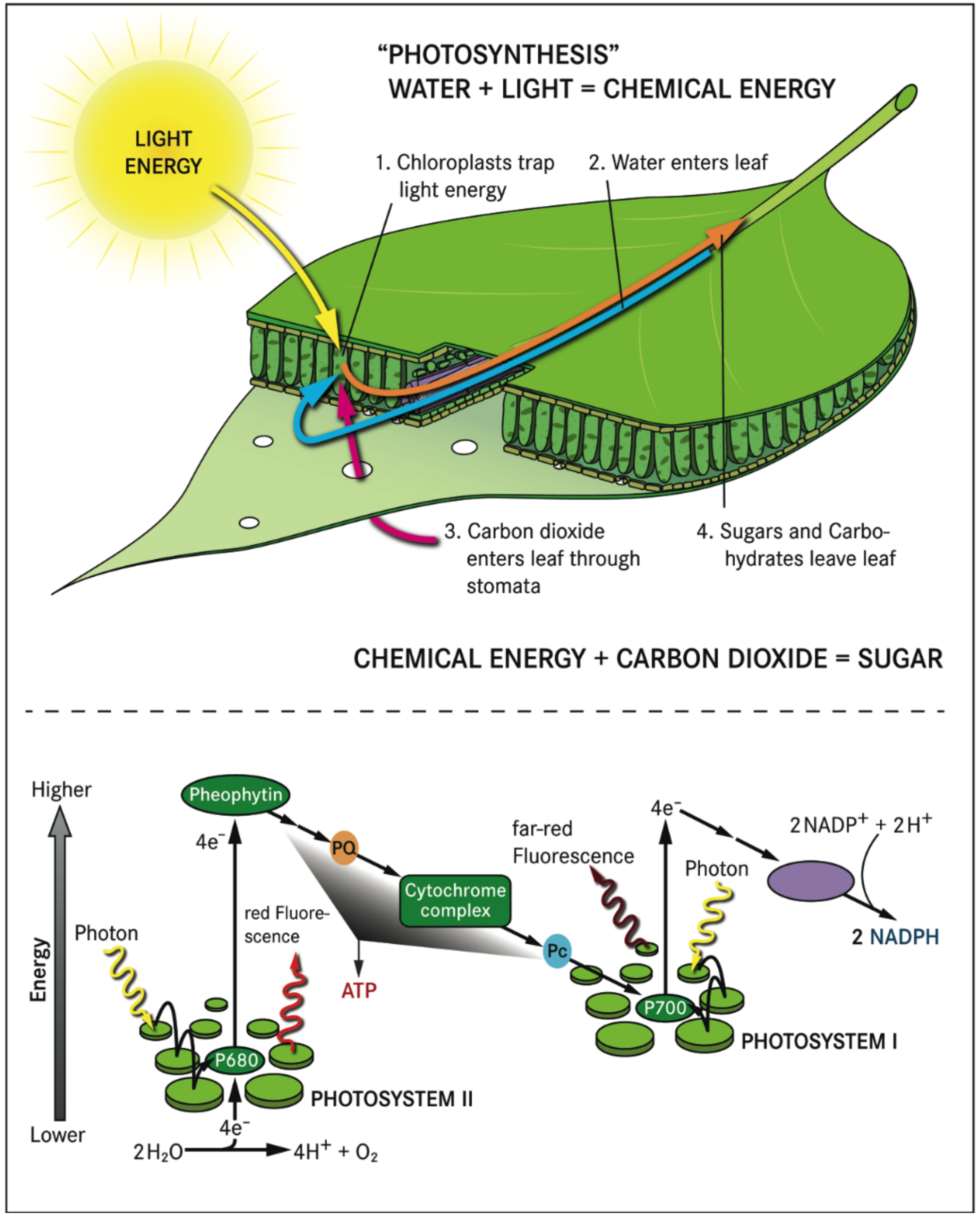

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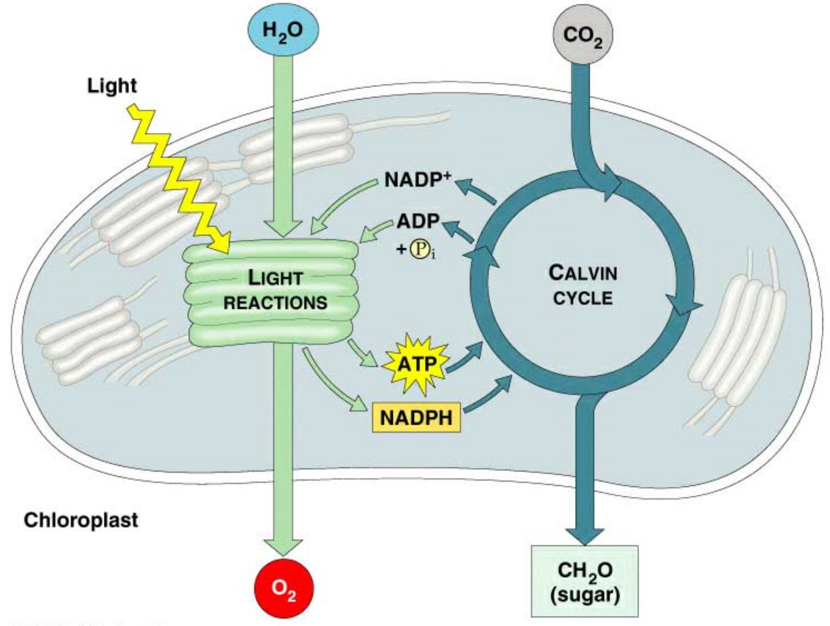

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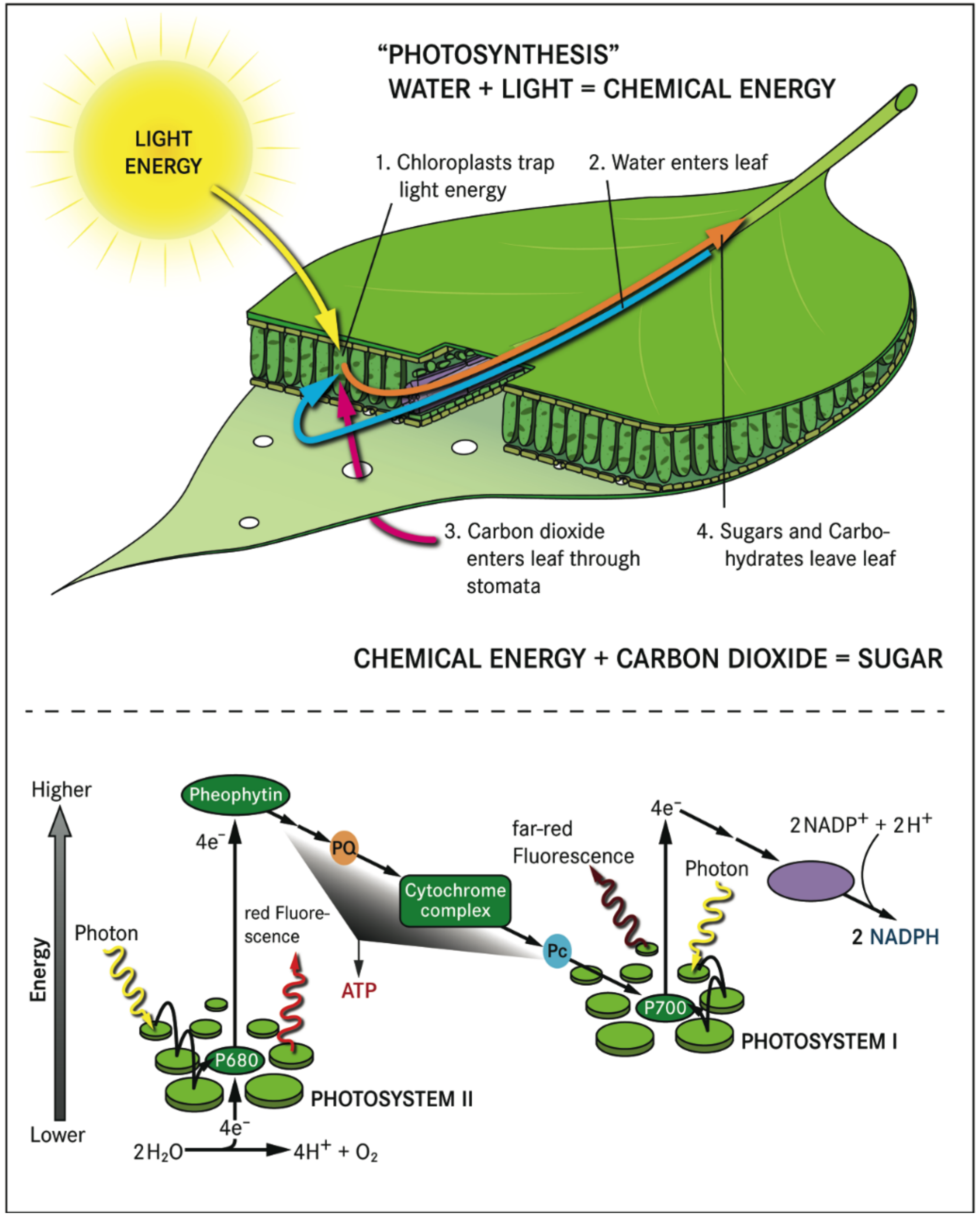

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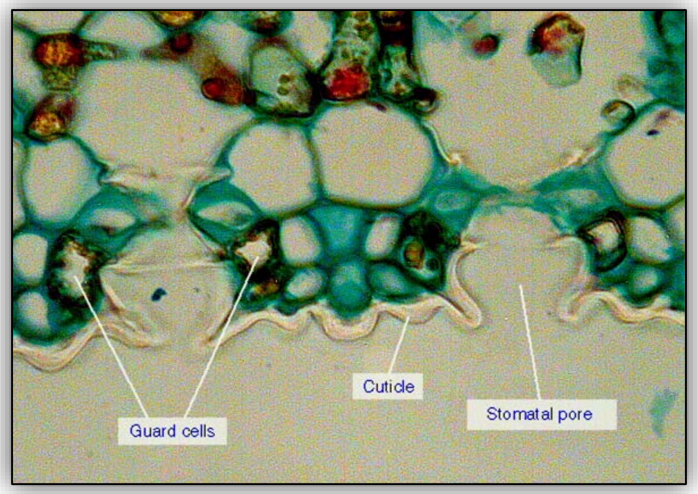
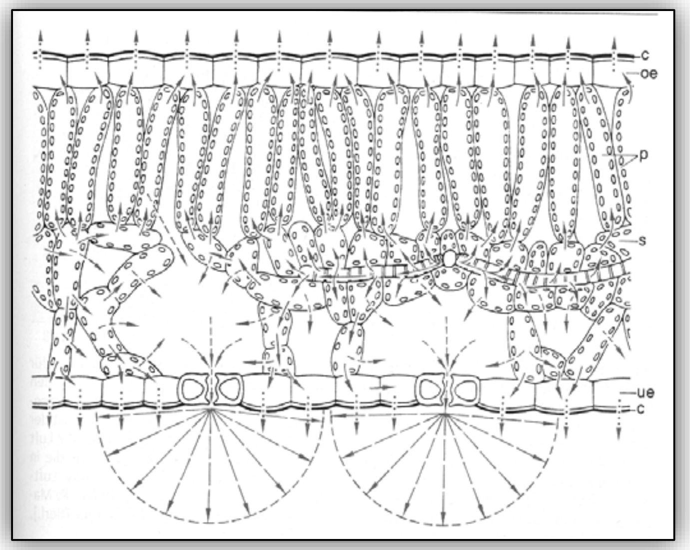
- And there are stomata… the maybe ‚most important cells on earth'





Preparing for a network of ground reference stations

- Technical development of ground reference instruments has progressed
- Currently three different instruments are available, with FloxBox (JB Hyperspectral) currently being the most widely used (covering ~ 20 sites worldwide)
- FloxBox also included in various ESA campaigns and basis for ground segment and Cal / Val plan




Migliavacca et al. (2017) *New Phytologist, 214*, 1078-1092, doi: 10.1111/nph.14437.

Wieneke et al. (2018) Remote Sensing of Environment, 219, 247-258, doi: 10.1016/j.rse.2018.10.019

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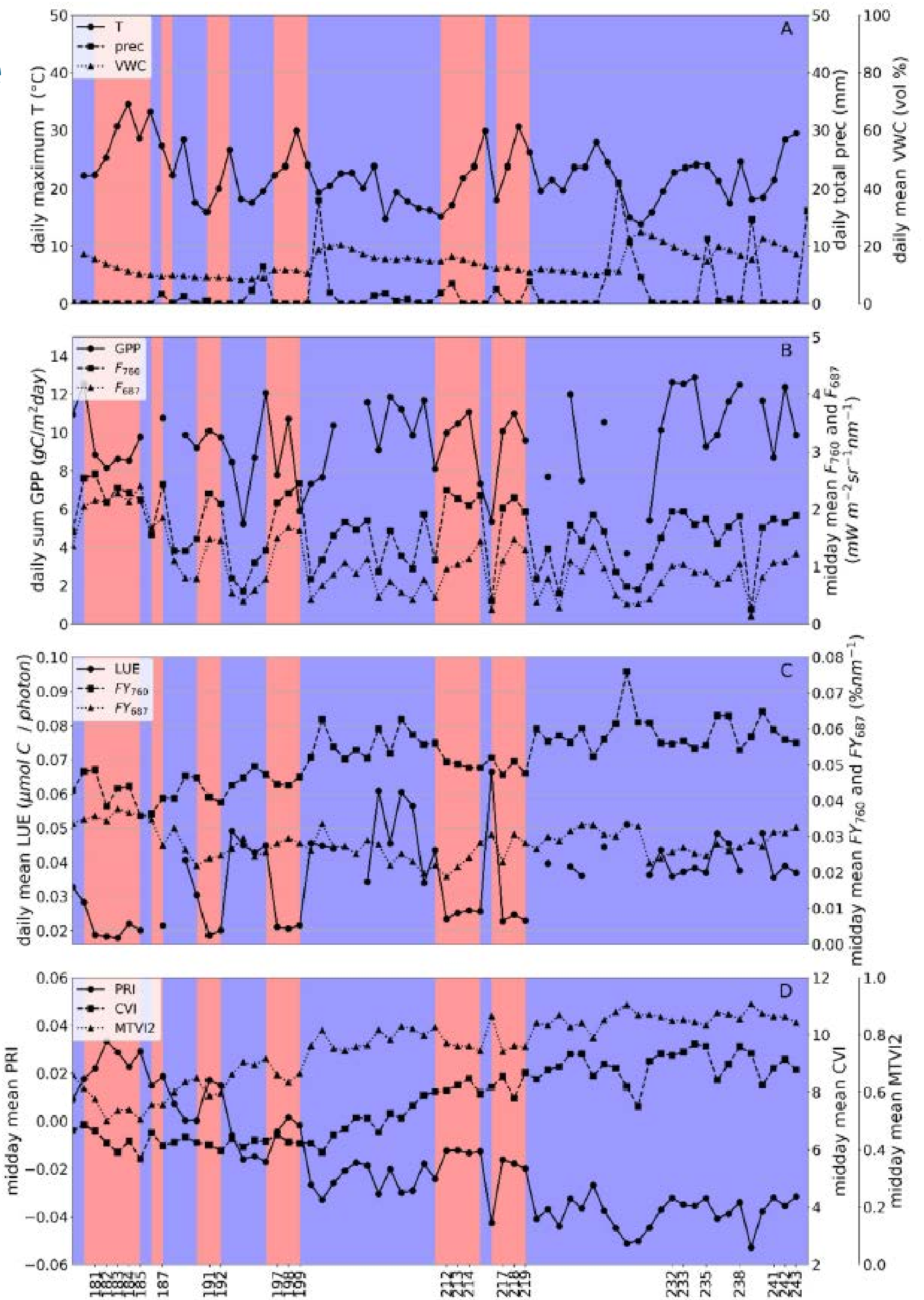

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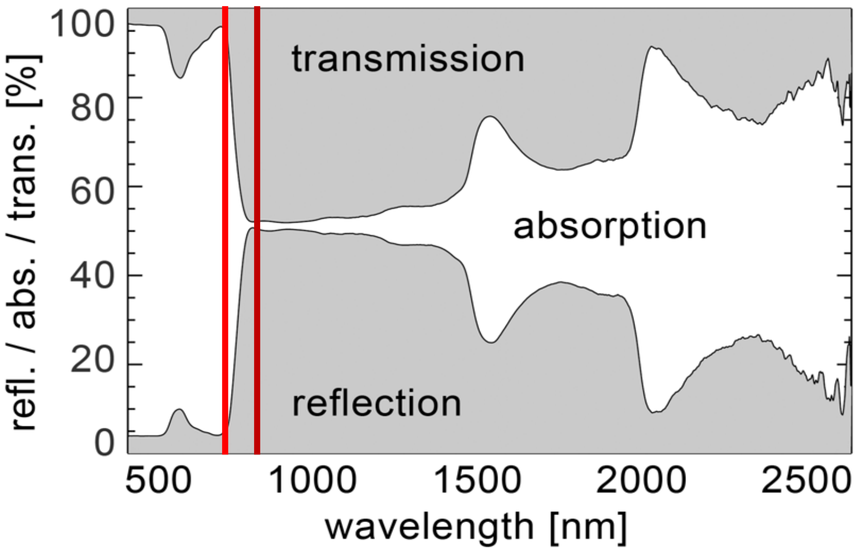
Two peak feature of fluorescence is affected by reabsorption in the leaf and the canopy



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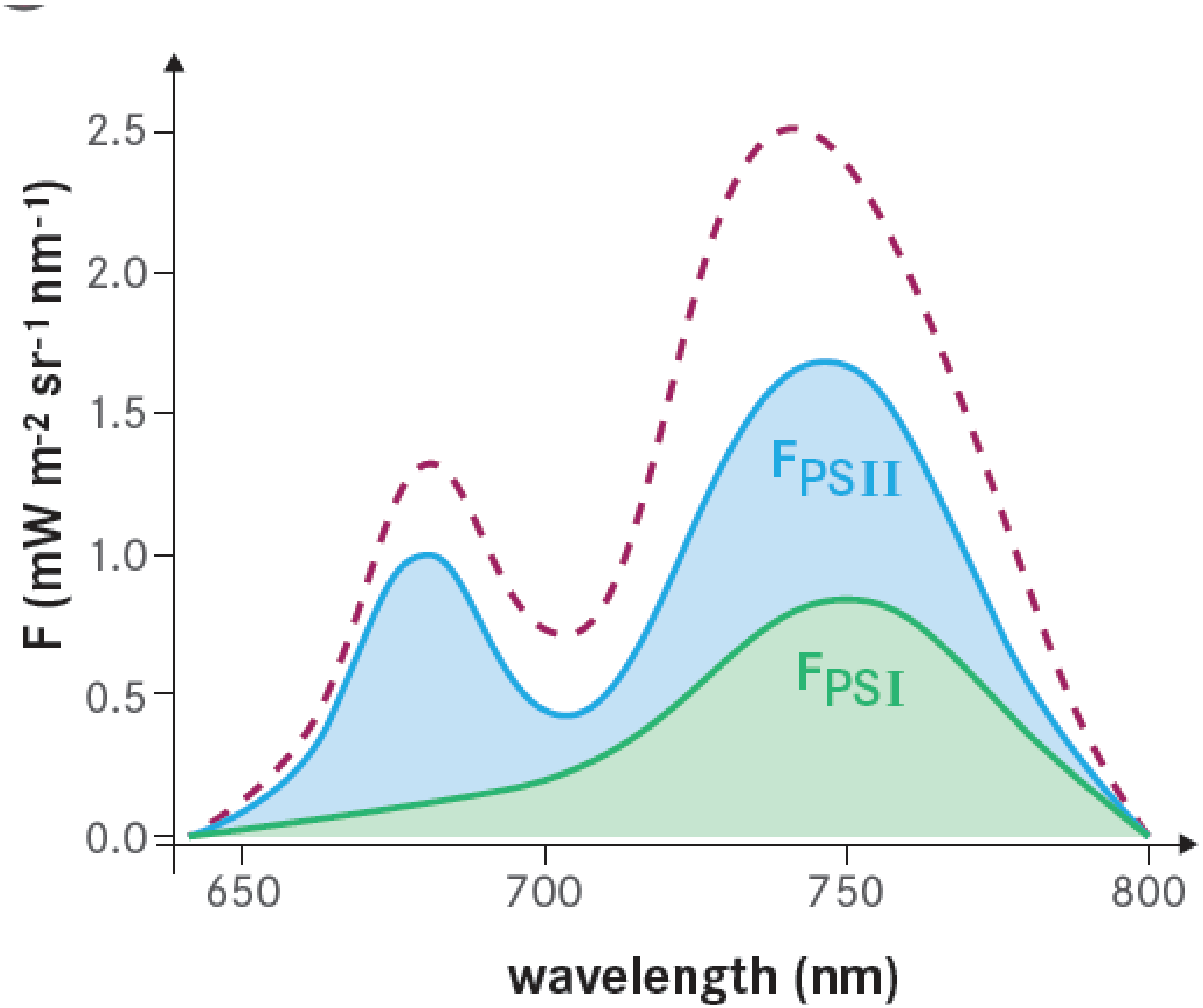
Strong absorption of the red peak, weak absorption of the far-red peak



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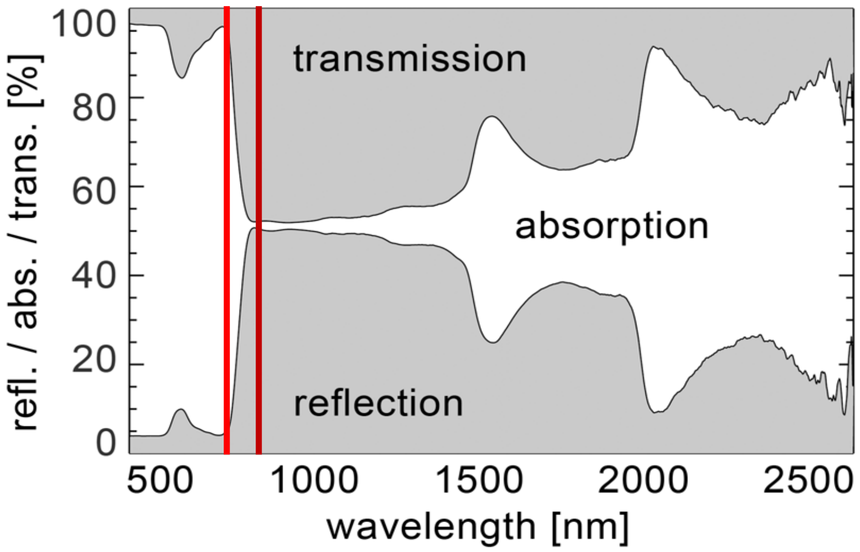

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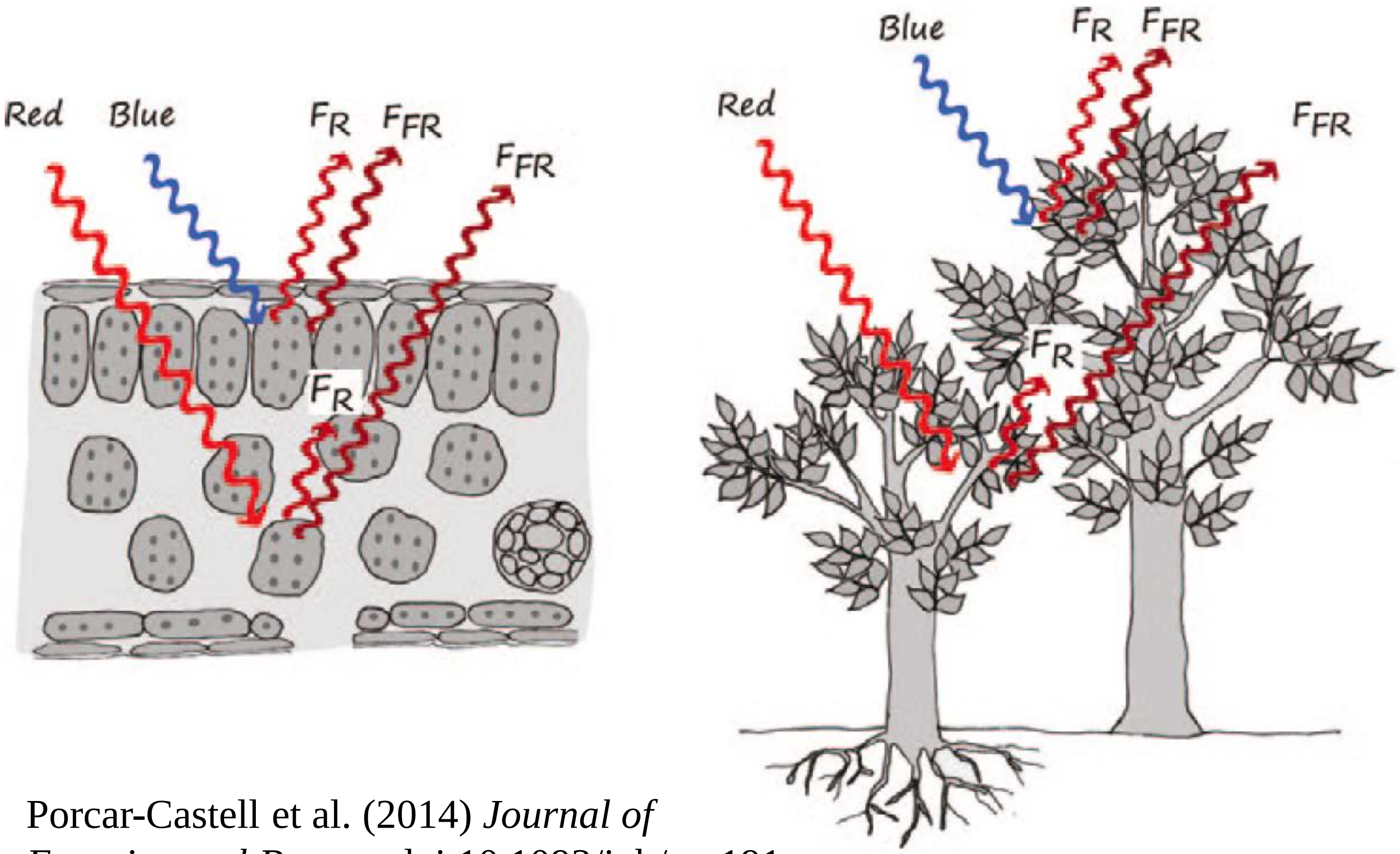

Porcar-Castell et al. (2014) *Journal of Experimental Botany*, doi:10.1093/jxb/eru191

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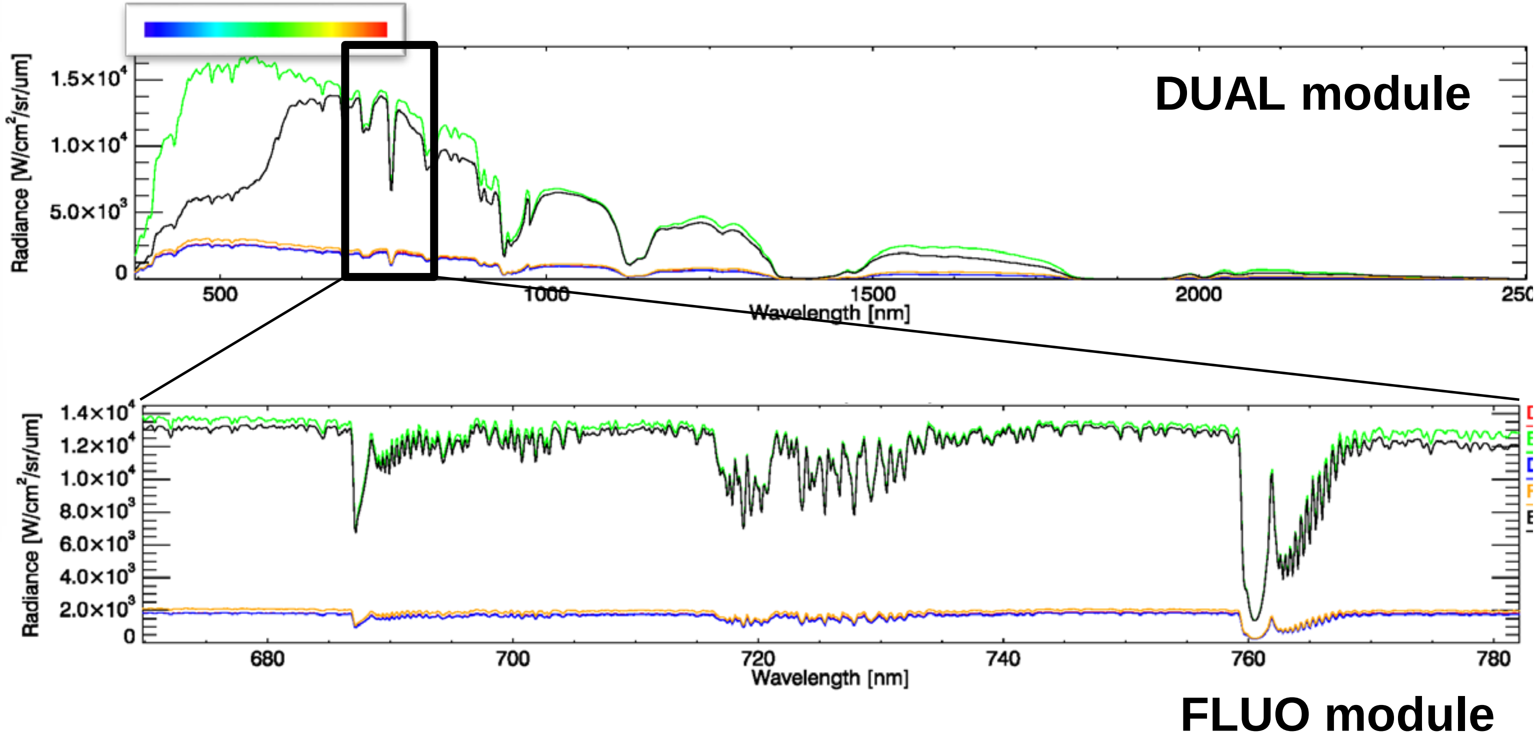
HyPlant: A high-resolution airborne imaging spectrometer with FLEX like measurement characteristics

JÜLICH
FORSCHUNGSZENTRUM

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

- Used to demonstrate the uncoupling of ‘greenness’ and fluorescence
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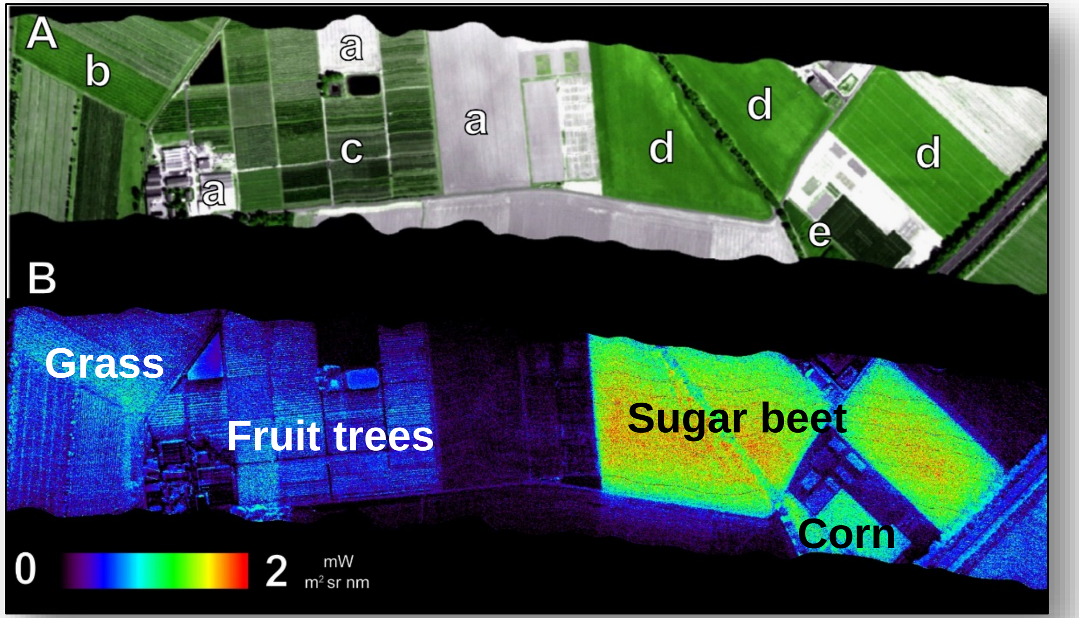

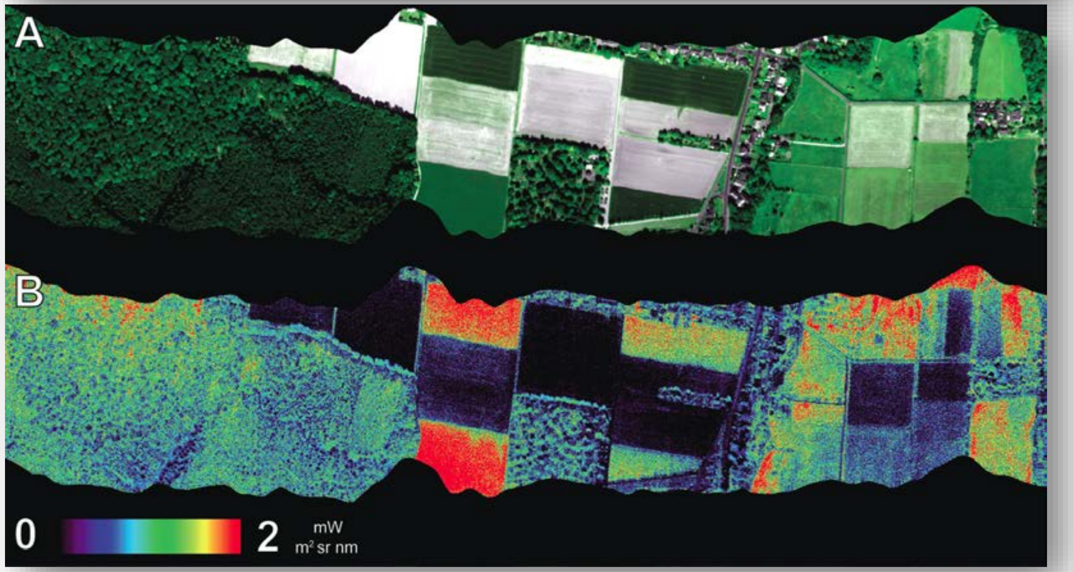

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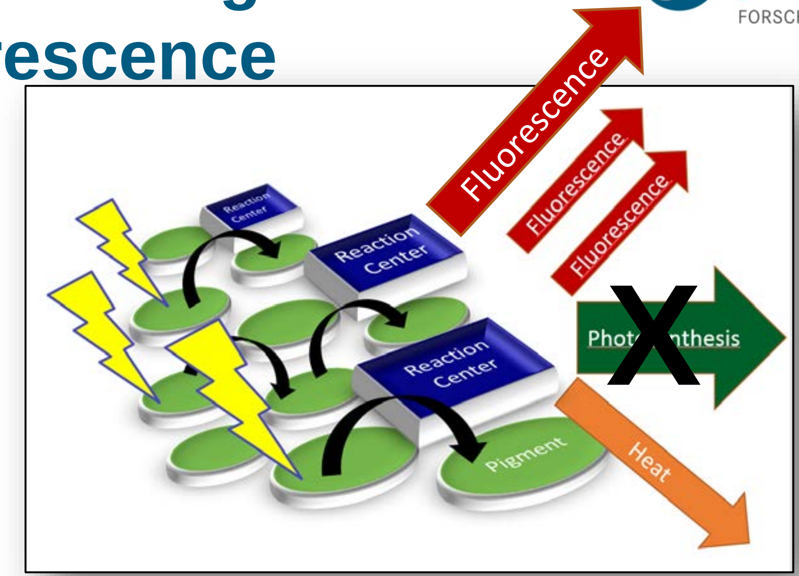

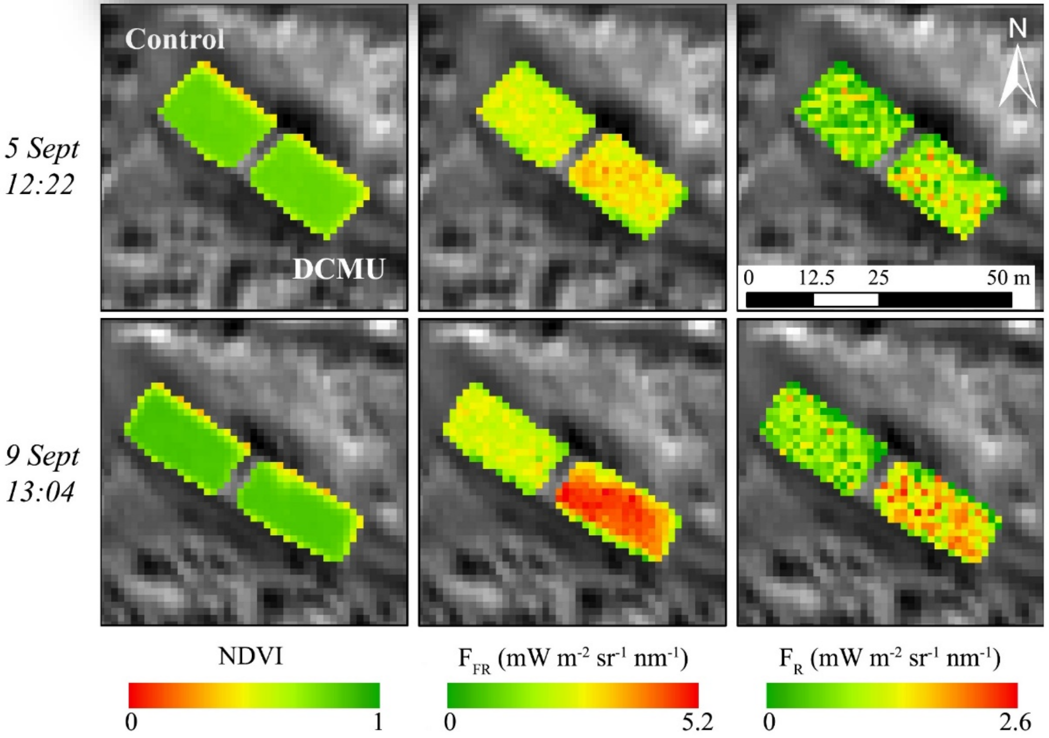

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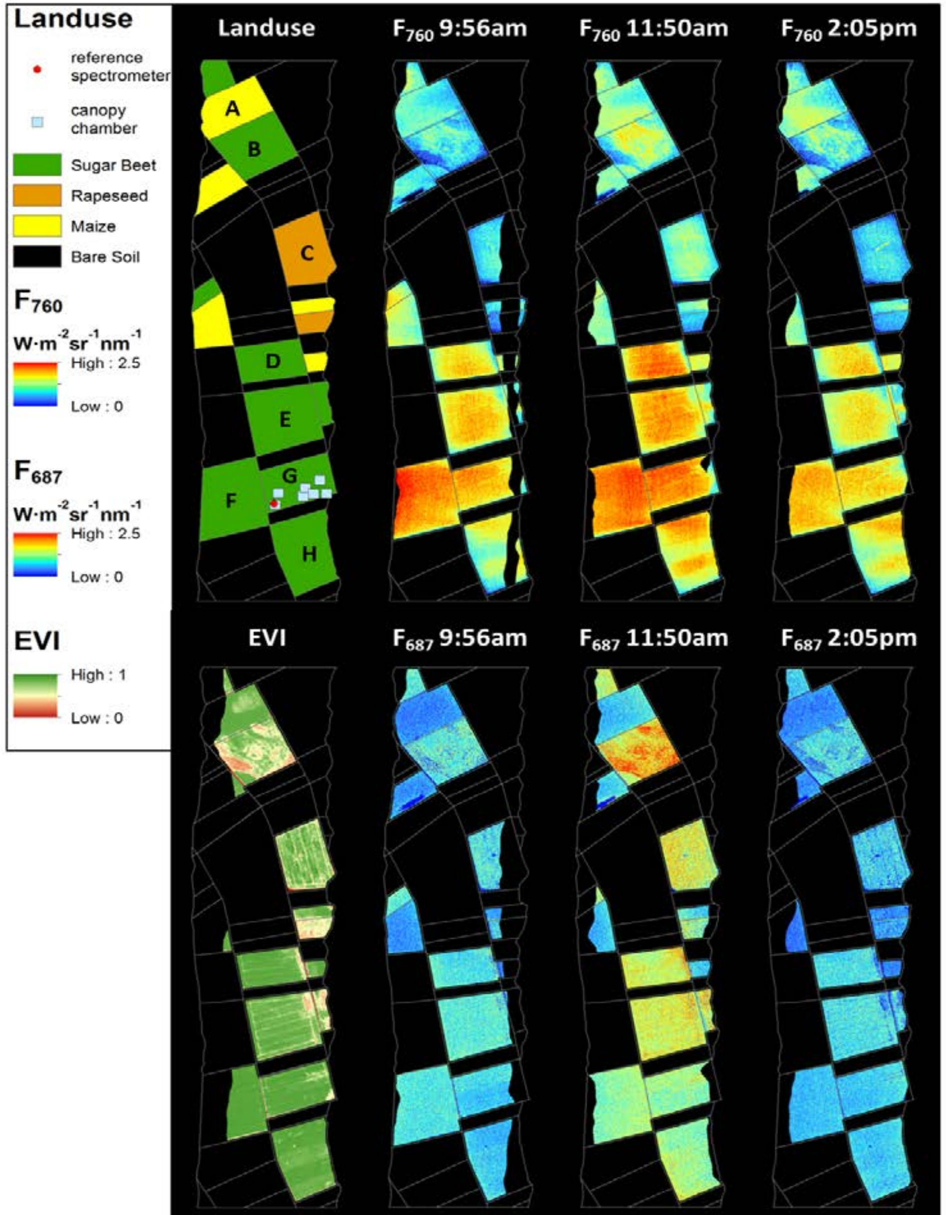

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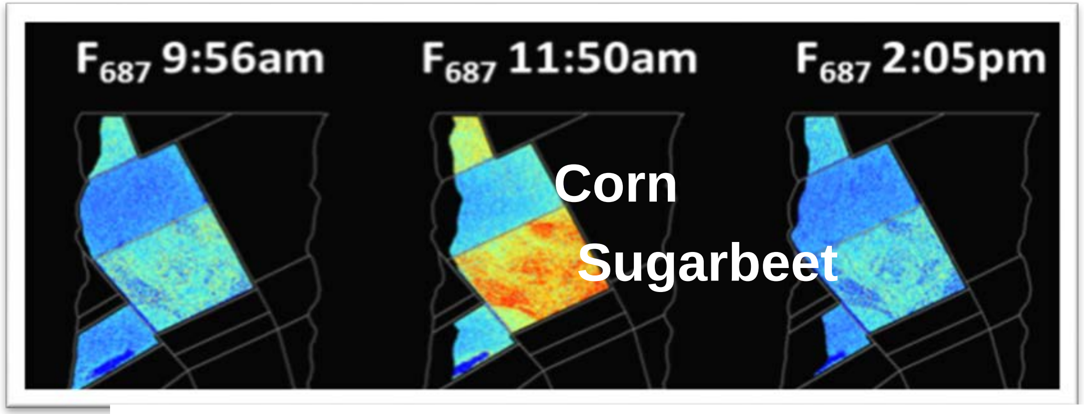

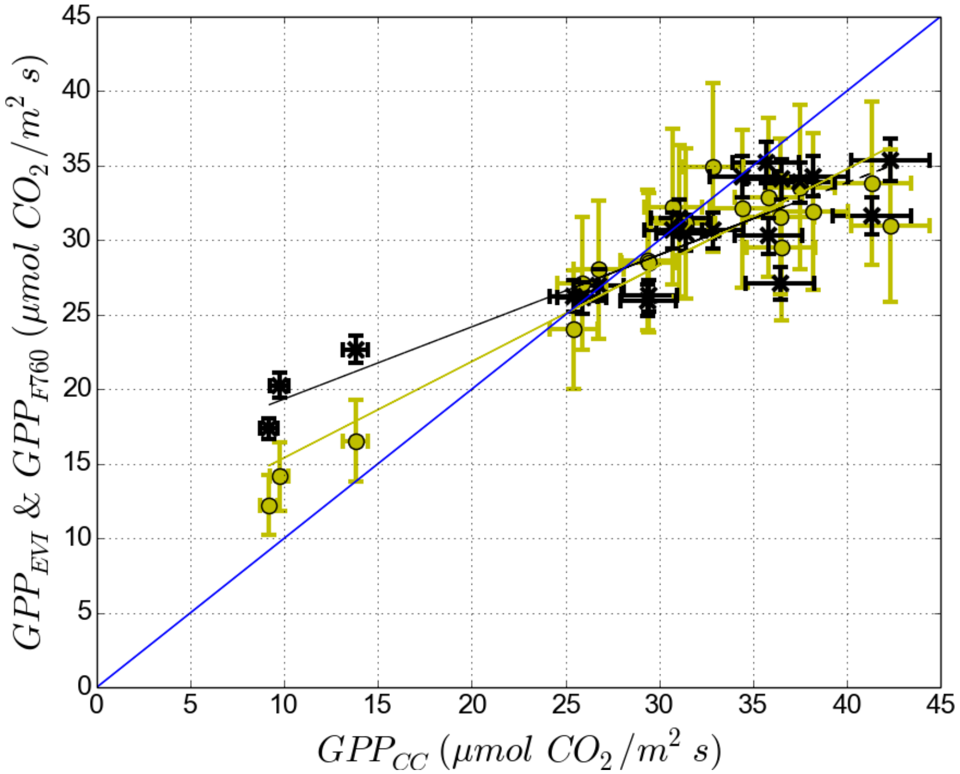

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JÜLICH FORSCHUNGSZENTRUM

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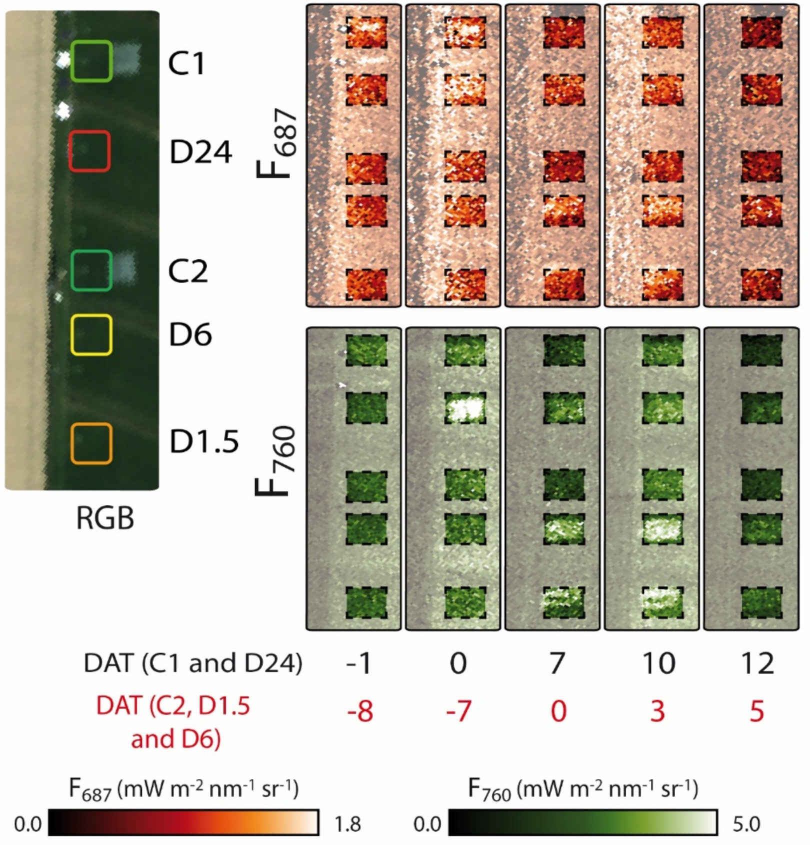
- Experimental studies to better understand the mechanisms of photosynthetic regulation on the canopy scale
  [Celesti et al (2018) Rem. Sens. Environ., 215, 97-108]
  [Sakowska et al (2018) Plant, Cell Environ., 41, 1427-1437]



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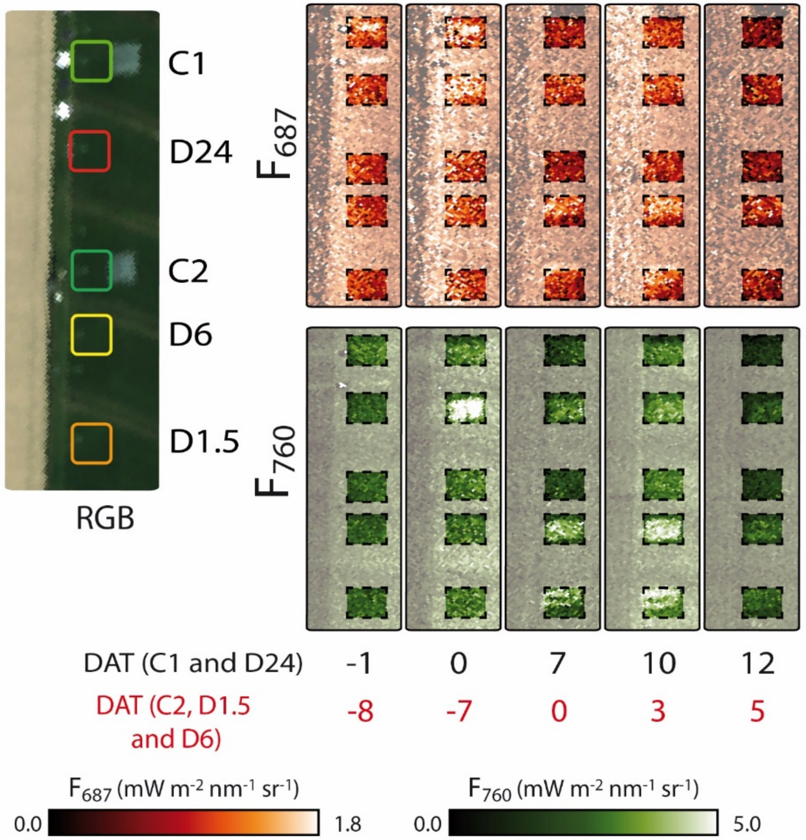
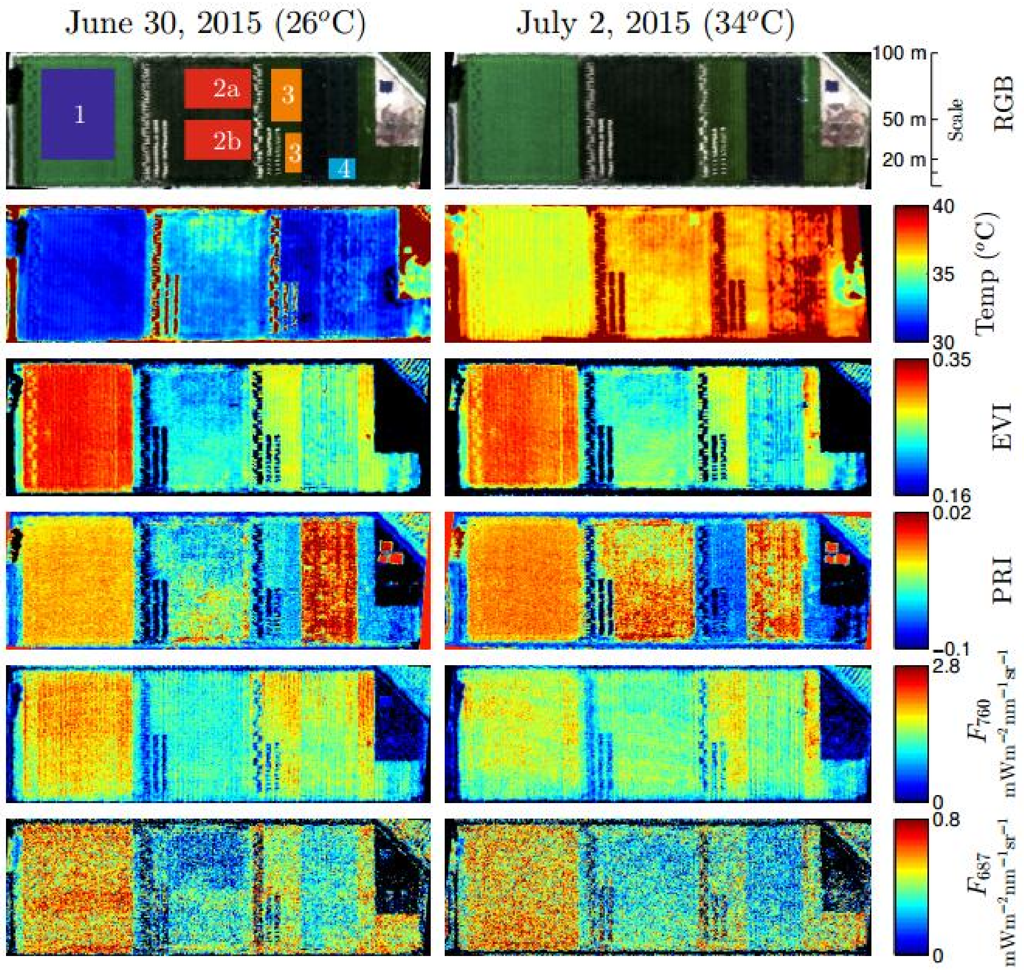
- Used to demonstrate the uncoupling of ‘greenness’ and fluorescence
  [Rascher et al (2015) Global Change Biol., 21, 4673-4684]
  [Simmer et al (2015) BAMS – Bulletin of the American Meteorological Society, 96, 1765-1787]
- Demonstration that functional blockage of photosynthesis can be mapped from aircraft
  [Rossini et al (2015) Geophys. Res. Lett., 42, 1632-1639]
- Fluorescence (F_{760}) improves modelling of diurnal changes in GPP
  [Wieneke et al (2016) Rem Sens Environ, 184, 654-667]
- Experimental studies to better understand the mechanisms of photosynthetic regulation on the canopy scale
  [Celesti et al (2018) Rem. Sens. Environ., 215, 97-108]
  [Sakowska et al (2018) Plant, Cell Environ., 41, 1427-1437]



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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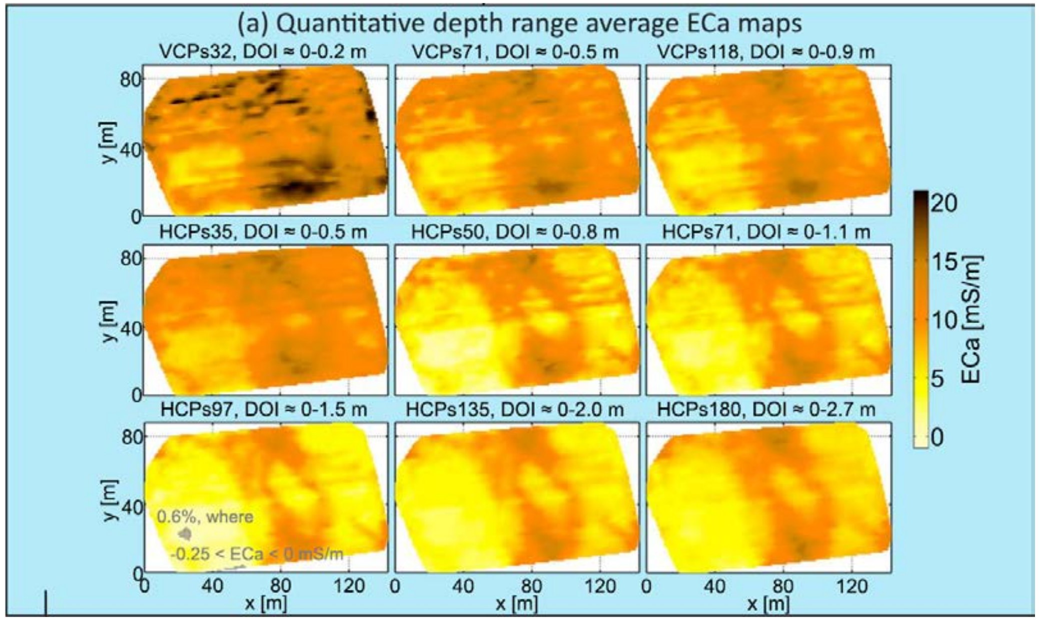
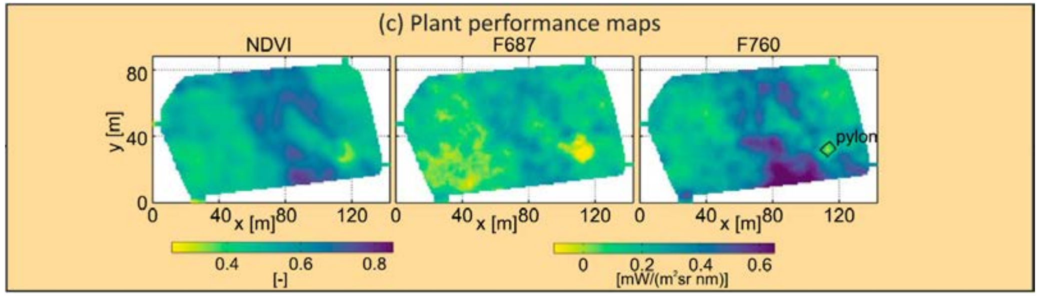
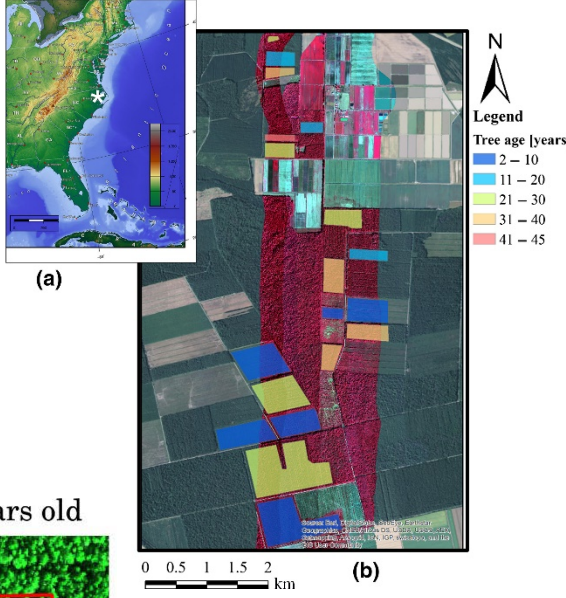




HyPlant campaigns: Measuring and understanding the spatial dynamics of solar-induced fluorescence



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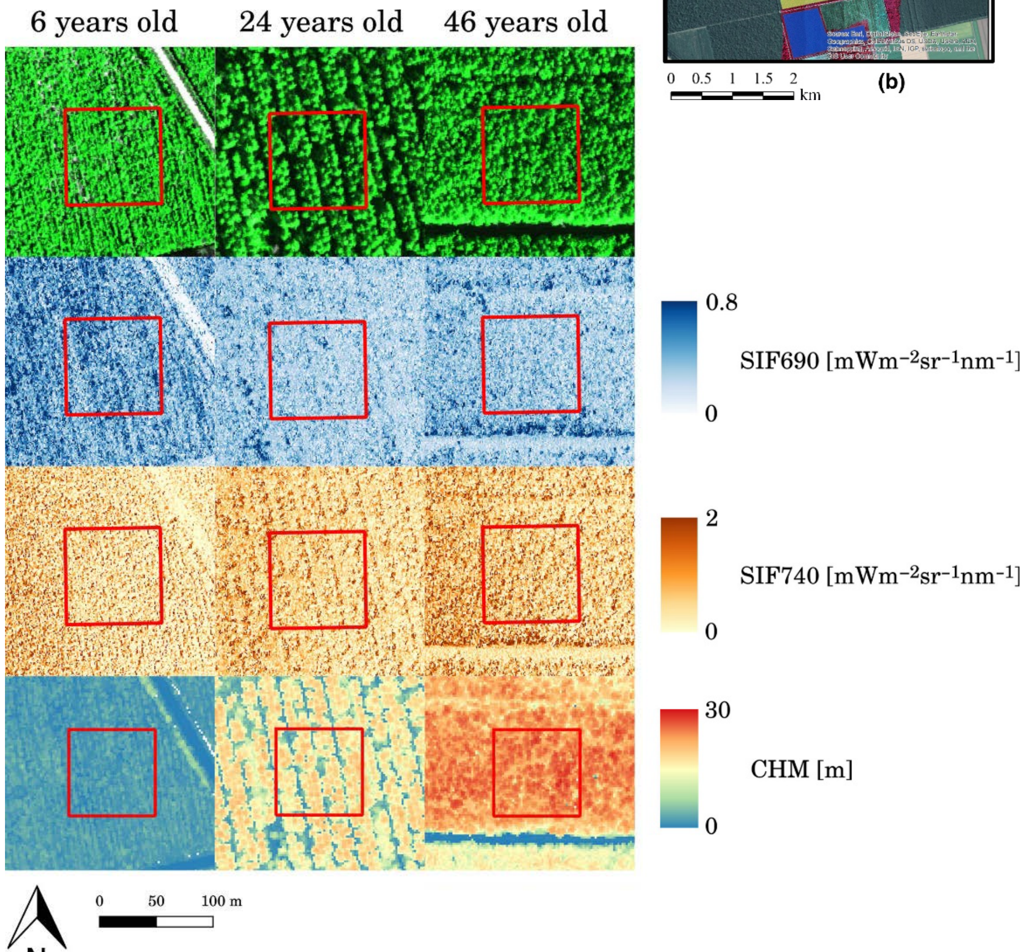

HyPlant campaigns: Measuring and understanding the spatial dynamics of solar-induced fluorescence

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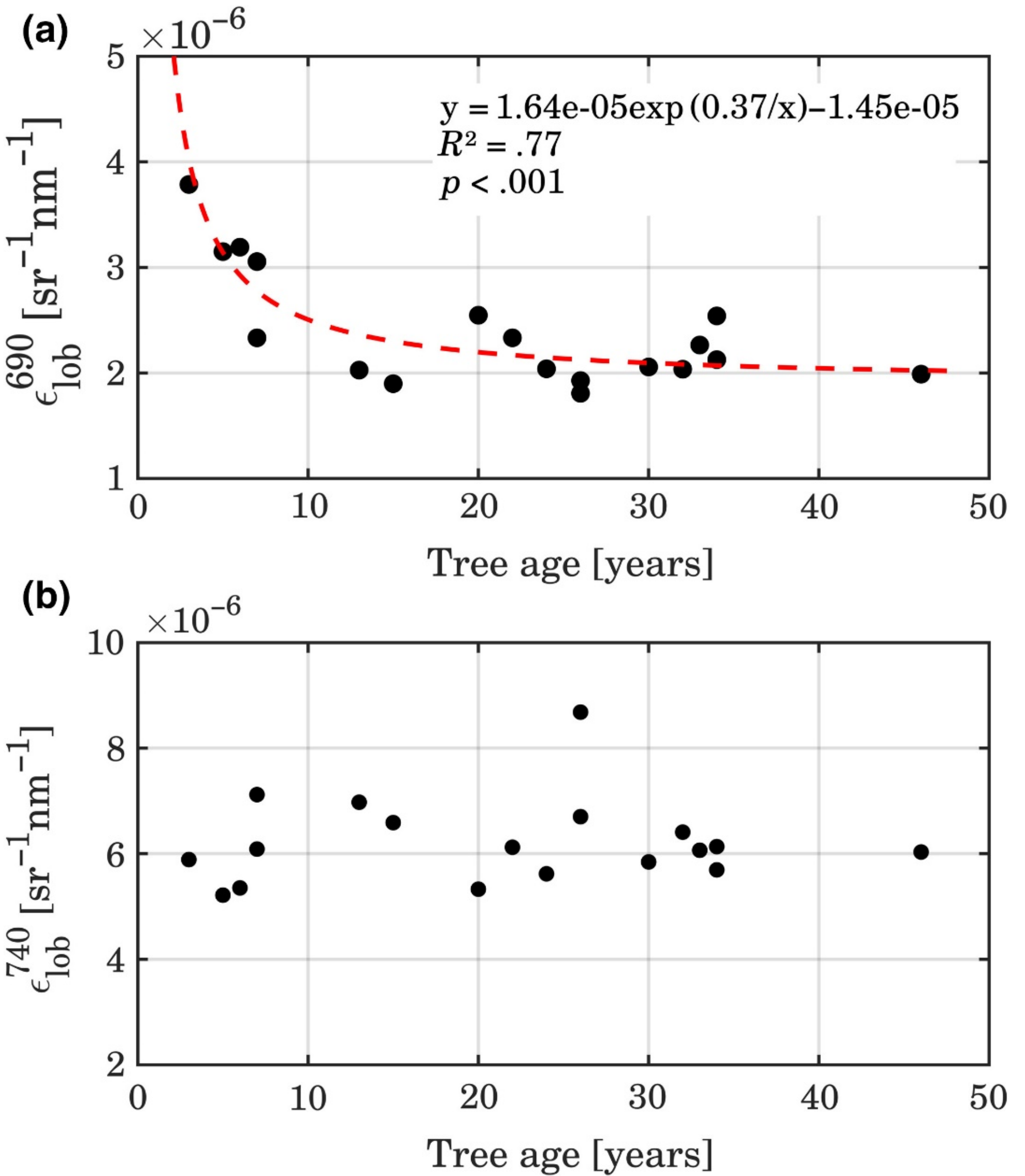

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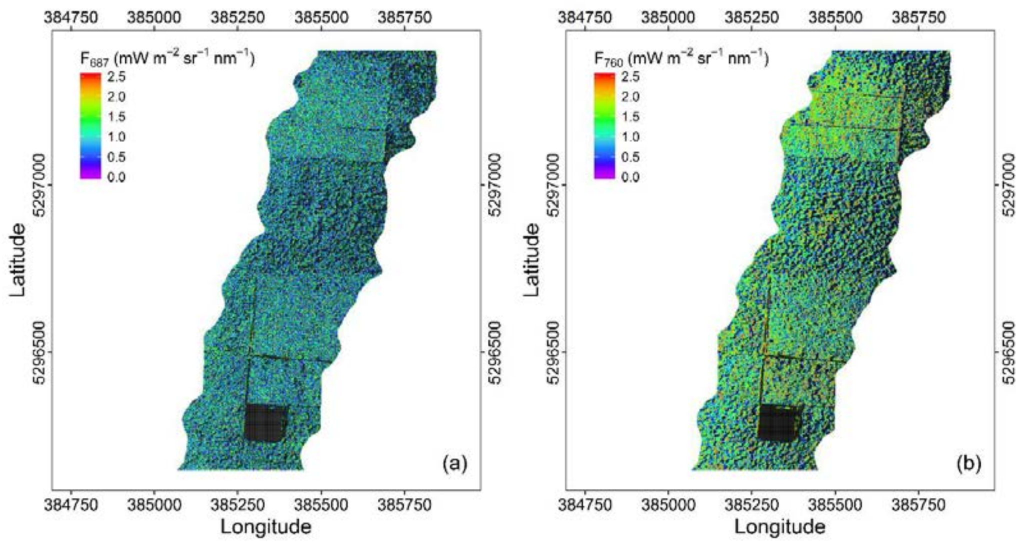

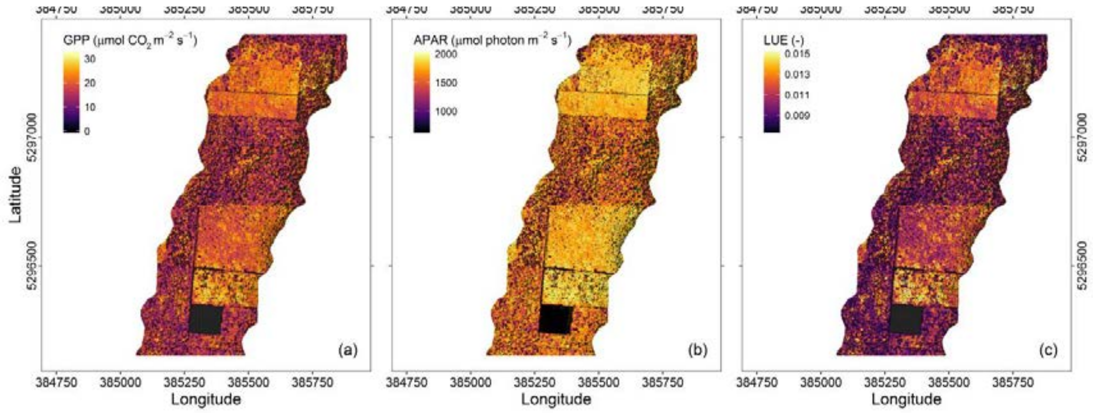

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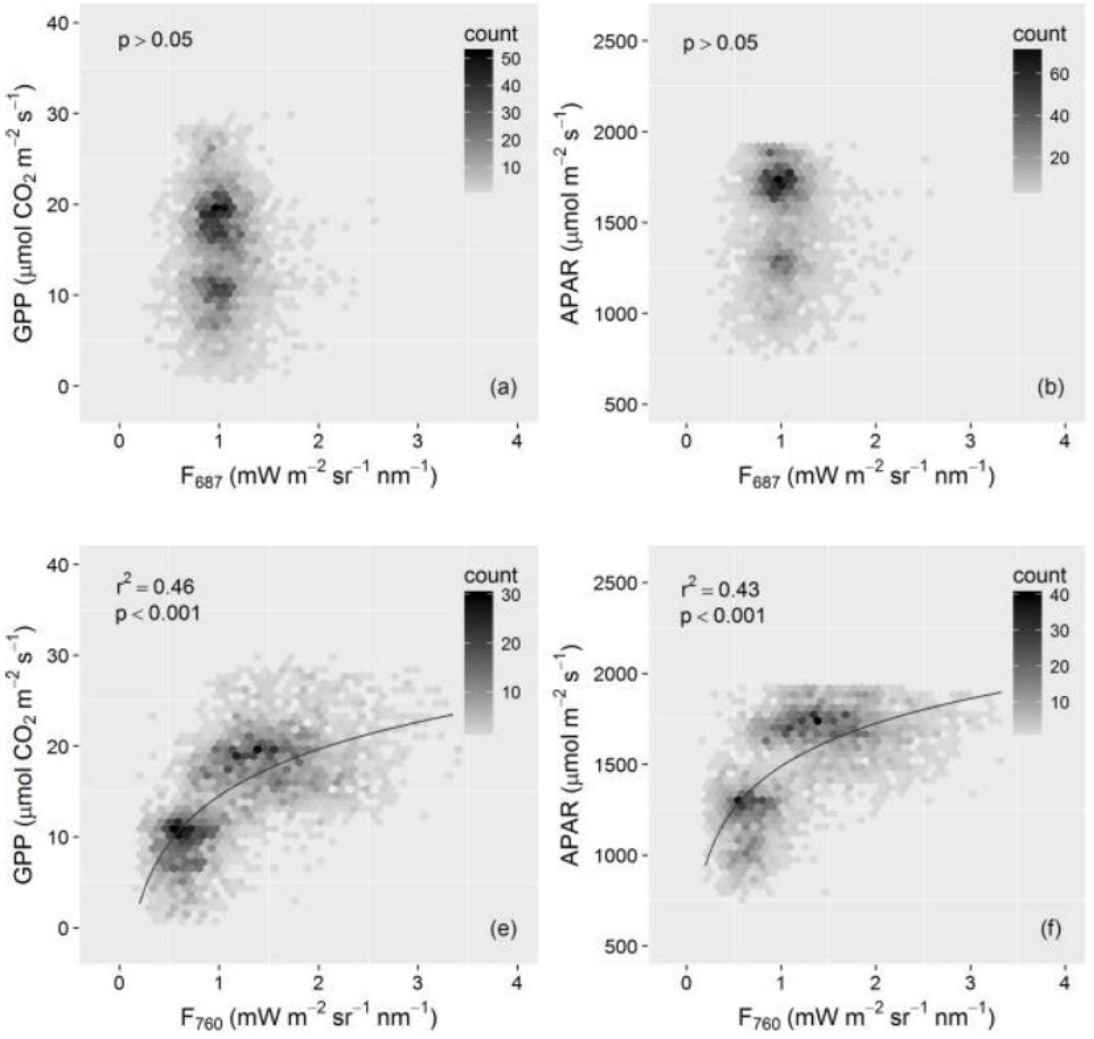
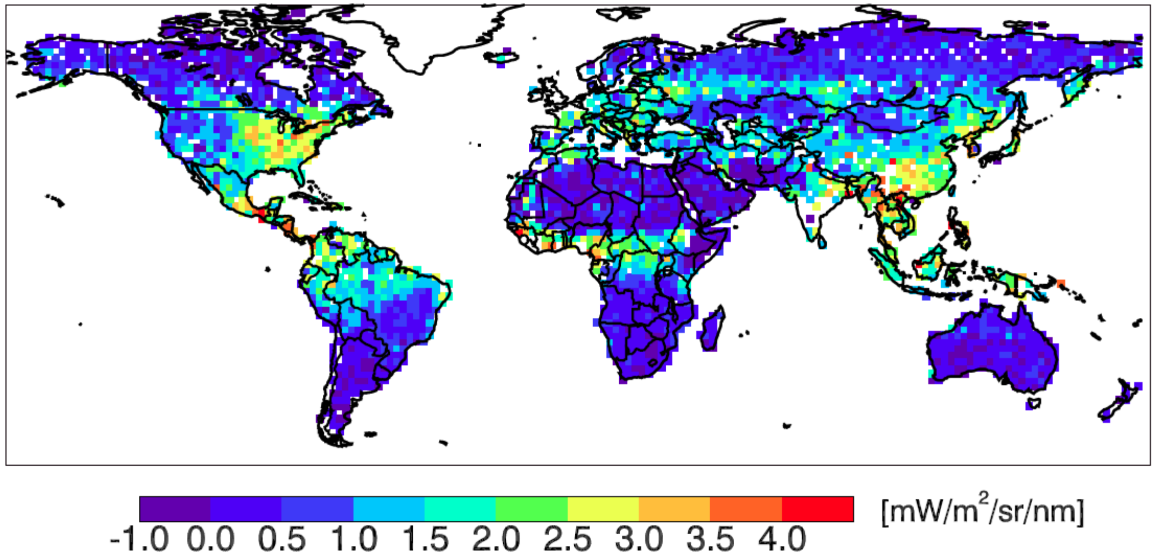


Mapping solar-induced fluorescence globally

- First demonstration that solar-induced fluorescence can be monitored from space (GOSAT aggregated data)
  [Joiner et al (2011) Biogeosciences, 8, 637-651]



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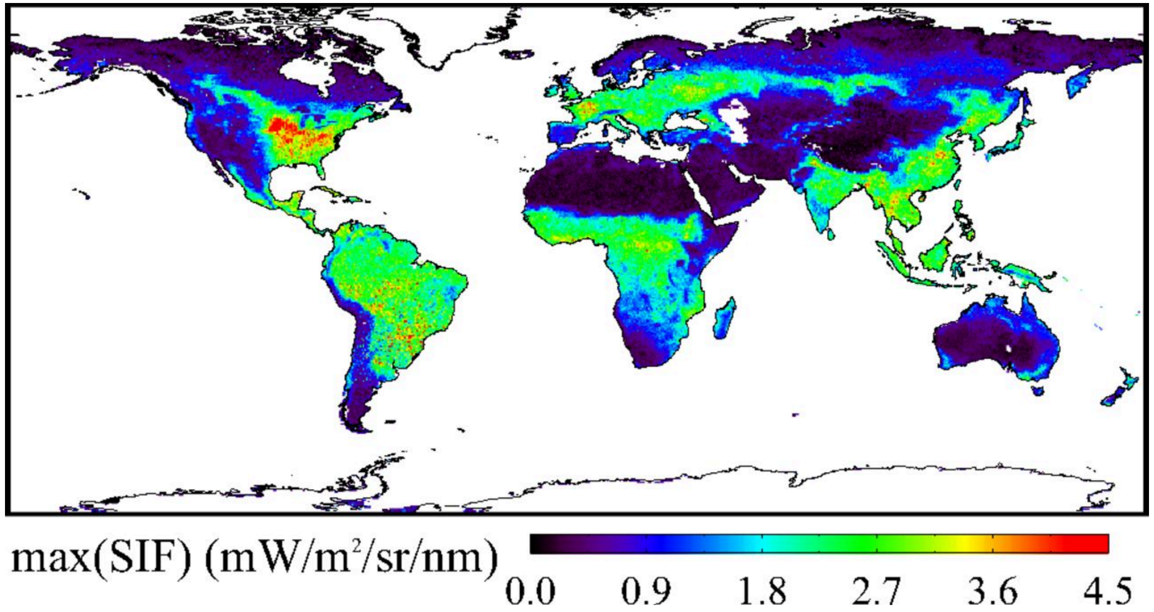

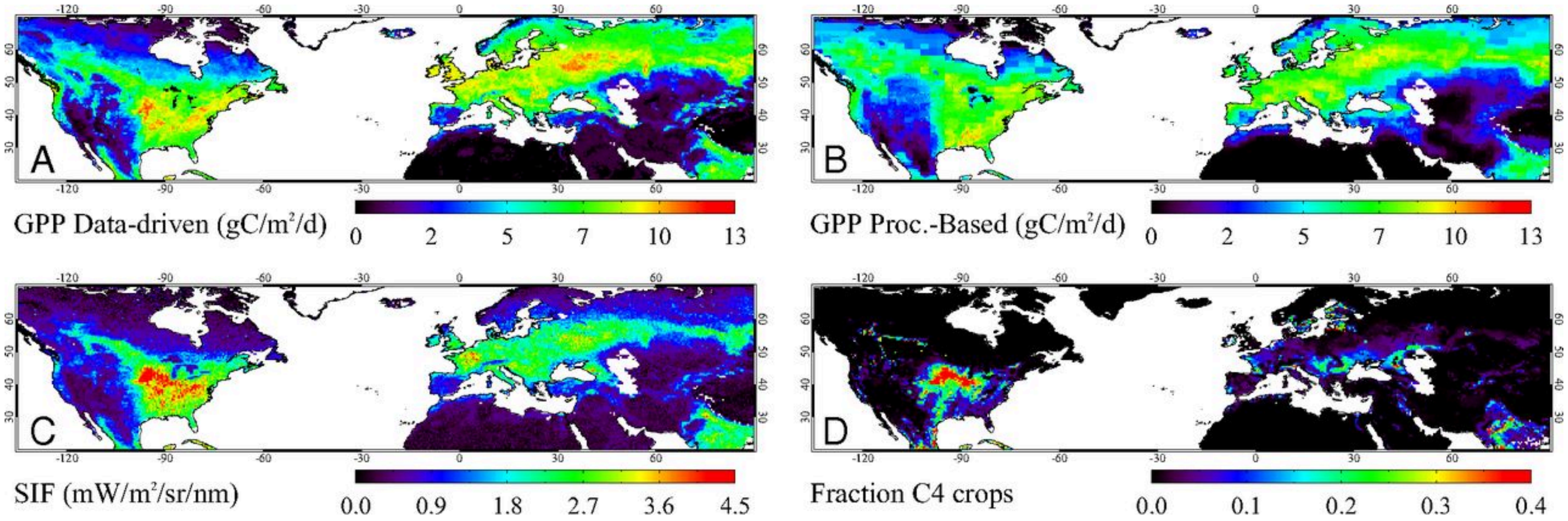

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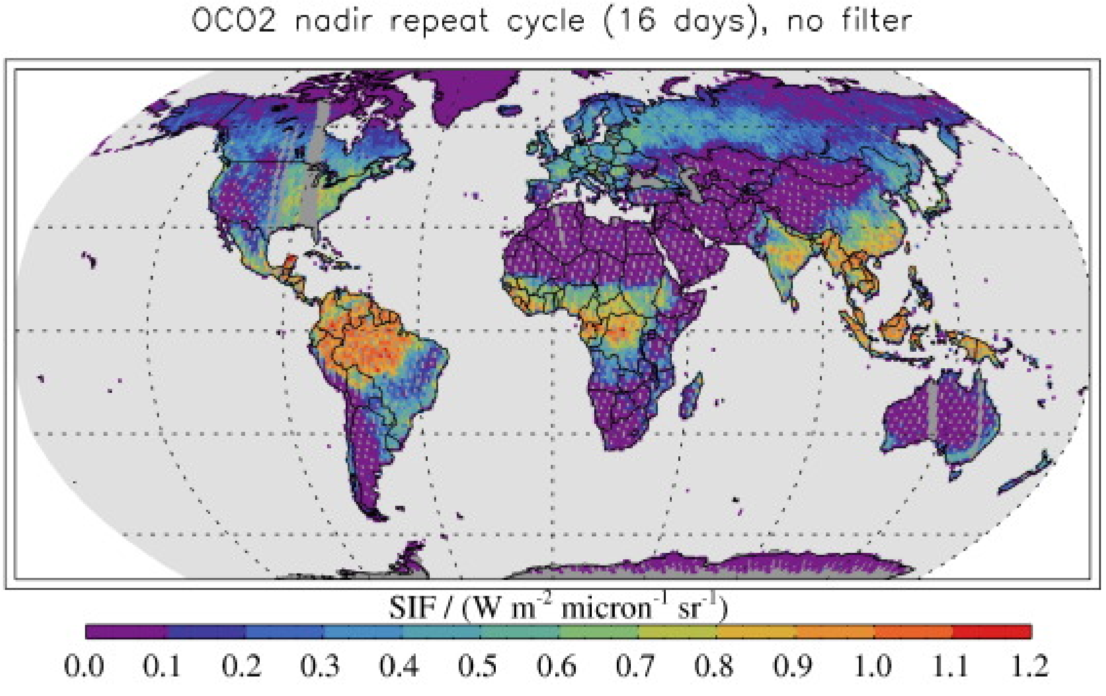
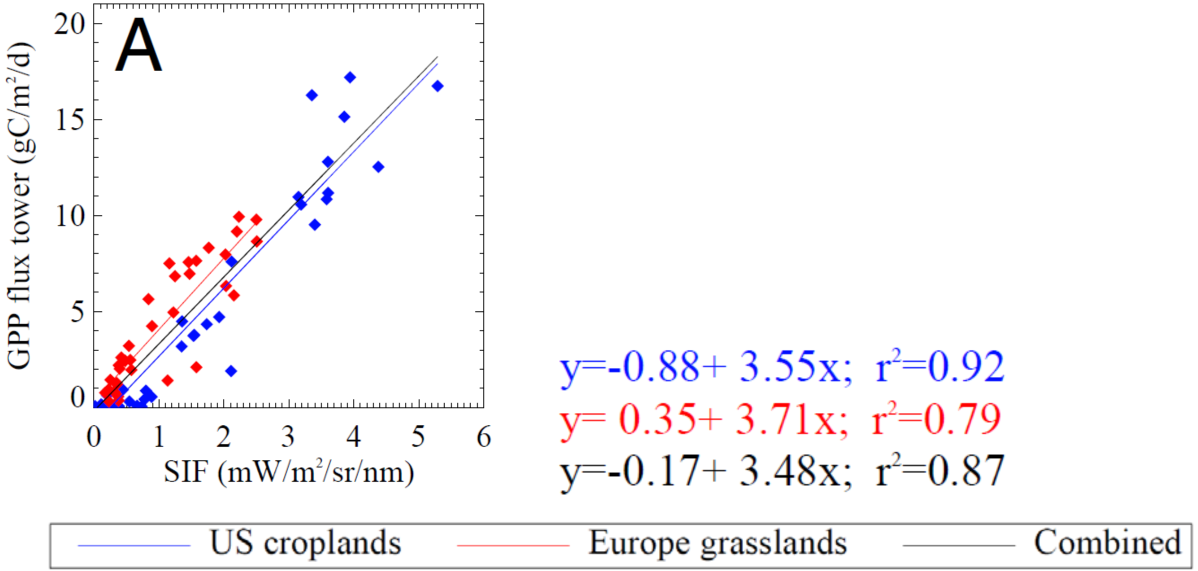
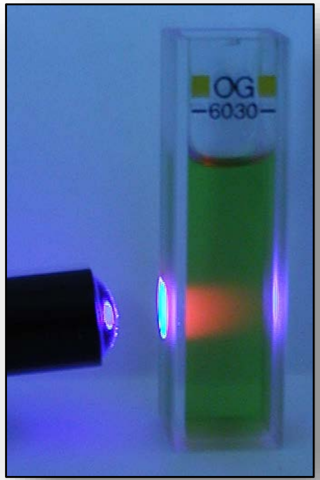
- Spatial and seasonal patterns of solar-induced fluorescence that are related to GPP (GOME-2 data)
  [Guanter et al (2014) PNAS, 111, 1327-1333]
- Further prospects on retrieving solar-induced fluorescence from future satellite missions (OCO-2 and TROPOMI)
  [Frankenberg et al. (2014) Remote Sensing of Environment, 147, 1-12]

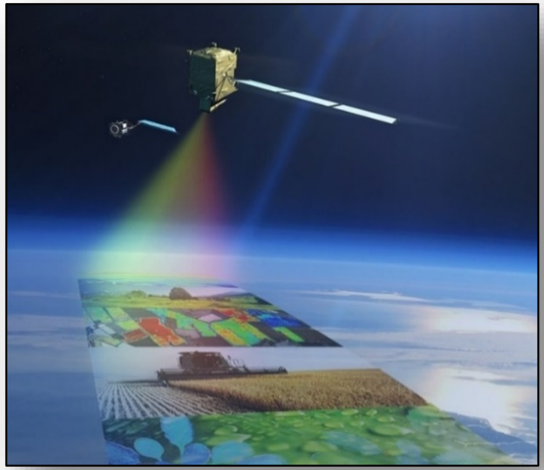




Summary

- How is solar-induced fluorescence related to photosynthetic carbon uptake? A matter of scale and integration.
- Two fluorescence peaks in combination with knowledge on non-photochemical protection mechanisms allow better understanding of the regulation of photosynthesis (stress response, seasonal adaptation, functional diversity)
- Ground-based instruments and airborne sensors are consolidated and being employed along the spatial scale (leaf to satellite). Preparation for Cal / Val network is ongoing
- Integration of ground-based, airborne and satellite missions will link mechanistic understanding of vegetation function with larger scale monitoring and decision making





Many thanks to my group

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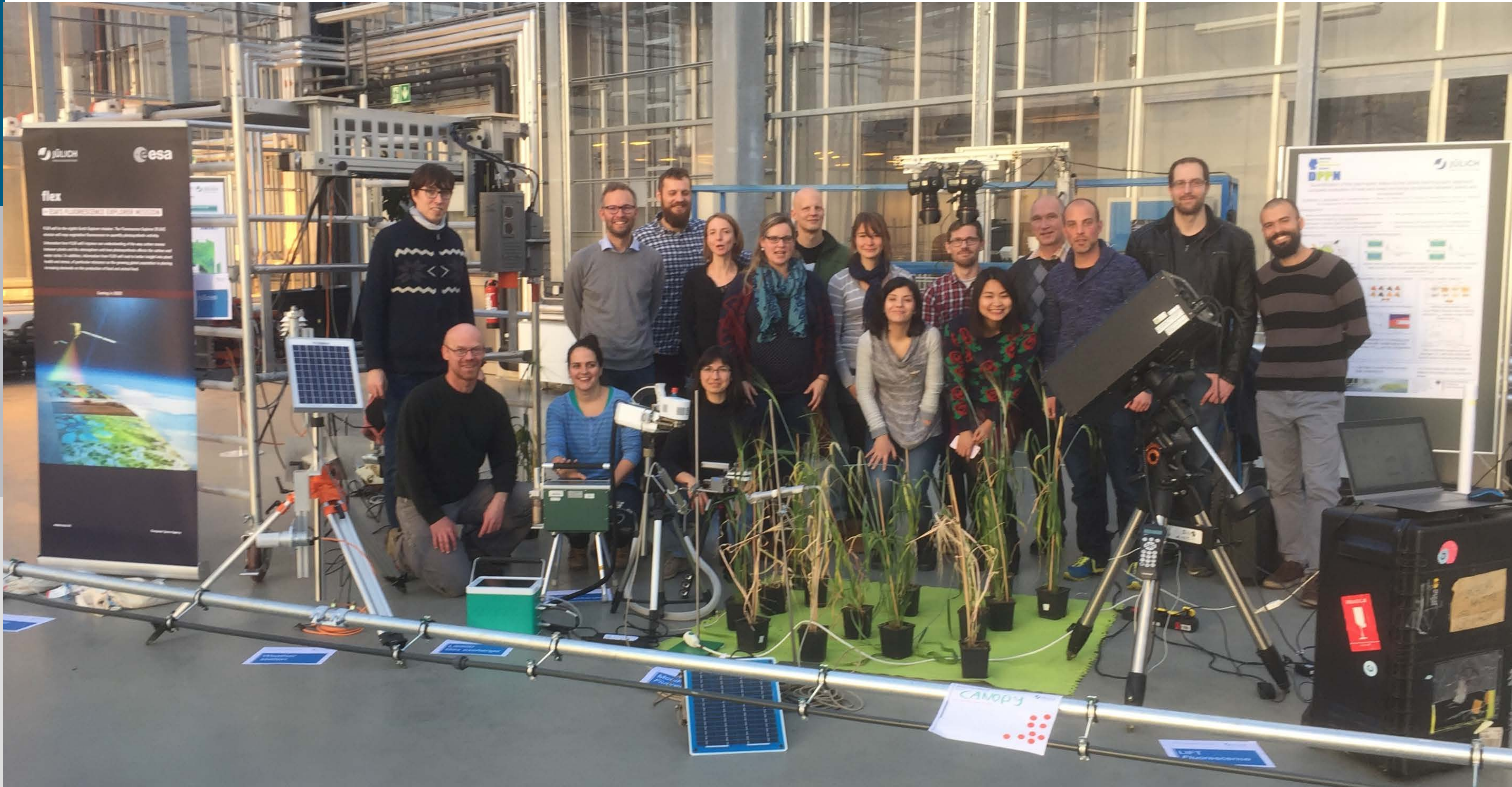

Many thanks to the numerous partners

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Consiglio Nazionale delle Ricerche

University of Cologne

Deutsche Forschungsgemeinschaft DFG

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ITC University of Twente.

Vniversitat de València

Goddard Space Flight Center

cost
European Cooperation in Science and Technology

GFZ
Helmholtz Centre Potsdam

NASA

HyPlant: list of publications

- 2015 -

Rascher U. et al. (2015) Sun-induced fluorescence - a new probe of photosynthesis: First maps from the imaging spectrometer HyPlant. *Global Change Biology*, 21, 4673–4684; doi: 10.1111/gcb.13017.

Rossini M. et al. (2015) Red and far red Sun-induced chlorophyll fluorescence as a measure of plant photosynthesis. *Geophysical Research Letters*, 42, 1632-1639.

Simmer C. et al. (2015) Monitoring and modeling the terrestrial system from pores to catchments – the Transregional Collaborative Research Center on Patterns in the Soil-Vegetation-Atmosphere System. *BAMS – Bulletin of the American Meteorological Society*, 96, 1765-1787.

- 2016 -

Wieneke S., Ahrends H., Damm A., Pinto F., Stadler A., Rossini M. & Rascher U. (2016) Airborne based spectroscopy of red and far-red sun-induced chlorophyll fluorescence: Implications for improved estimates of gross primary productivity. *Remote Sensing of Environment*, 184, 654-667, doi: 10.1016/j.rse.2016.07.025

- 2017 -

Drusch M. et al. (2017) The FLuorescence EXplorer mission concept - ESA’s Earth Explorer 8. *IEEE Transactions on Geoscience and Remote Sensing*, 55, 1273-1284, doi: 10.1109/TGRS.2016.2621820.

Middleton E.M.et al. (2017) The 2013 FLEX – US Airborne Campaign at the Parker Tract Loblolly Pine Plantation in North Carolina, USA. *Remote Sensing*, 9, article no. 612, doi:10.3390/rs9060612.

HyPlant: list of publications

- 2018 -

Colombo R. et al. (2018) Variability of sun-induced chlorophyll fluorescence according to stand age-related processes in a managed Loblolly pine forest. *Global Change Biology*, 24, 2980-2996, doi: 10.1111/gcb.14097.

Gerhards M., Schlerf M., Rascher U., Udelhoven T., Juszczak R., Alberti G., Miglietta F., & Inoue Y (2018) Remote sensing of water stress symptoms based on airborne optical and thermal images. *Remote Sensing*, 10, article no. 1139, doi: 10.3390/rs10071139.

Liu X. et al. (2018) Downscaling of solar-induced chlorophyll fluorescence from canopy level to photosystem level using a random forest model. *Remote Sensing of Environment*, doi: 10.1016/j.rse.2018.05.035.

von Hebel C. et al. (2018) Understanding soil and plant interaction by combining ground-based quantitative electromagnetic induction and airborne hyperspectral data. *Geophysical Research Letters*, doi: 10.1029/2018GL078658.

- review -

Damm A., et al. (2018) Remote sensing of plant-water relations: An overview and future perspectives. *Journal of Plant Physiology*, 227, 3-19, doi: 10.1016/j.jplph.2018.04.012- 2017 -