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Fluorescence: Lessons learned from ground-based and airborne studies (for FLEX mission preparation and others)

Alexander Damm & Uwe Rascher

New Methods to Measure Photosynthesis from Space

Pasadena CA, USA

26-31 August 2012

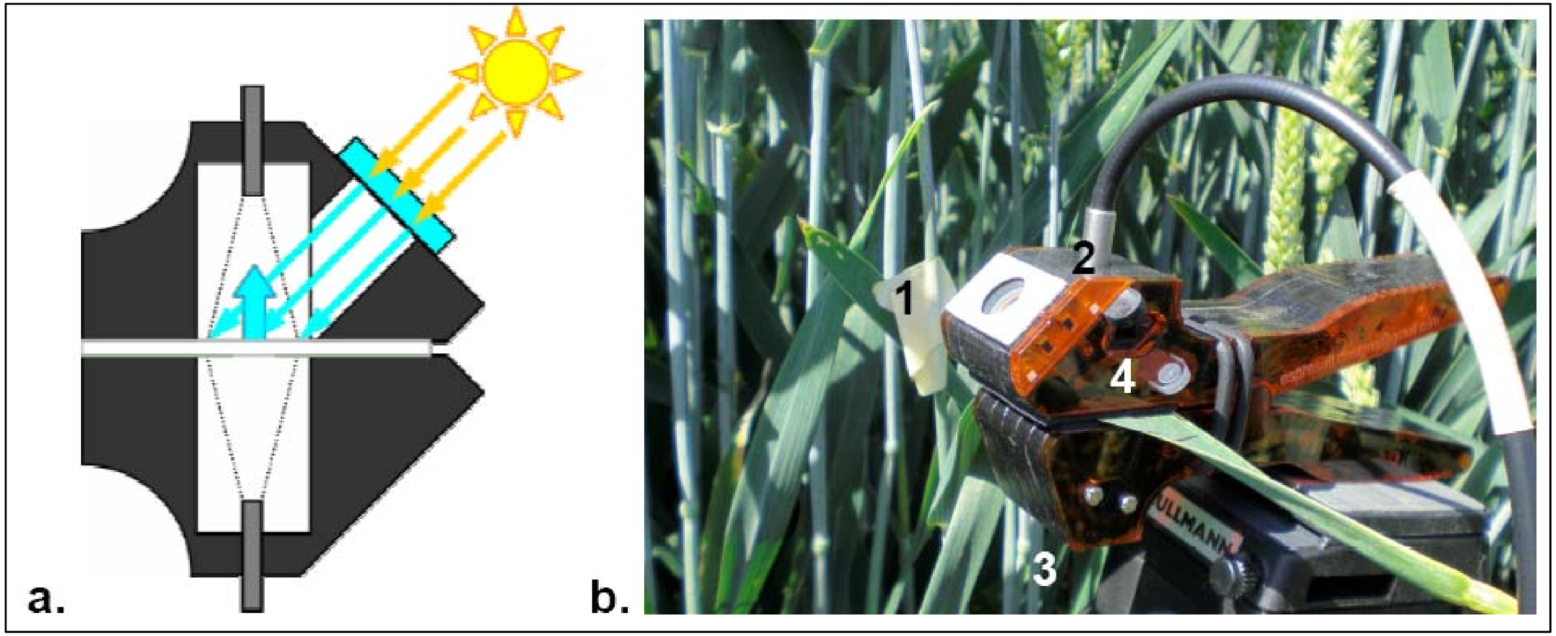
Keck INSTITUTE FOR SPACE STUDIES

Content

- Introduction
- Fluorescence at canopy level
  - spatial domain
  - temporal domain
- Scaling issues: From canopy to regional level
- Fluorescence at regional level
  - spatial domain
  - temporal domain
- Conclusions

Introduction: Fluorescence emission at leaf level

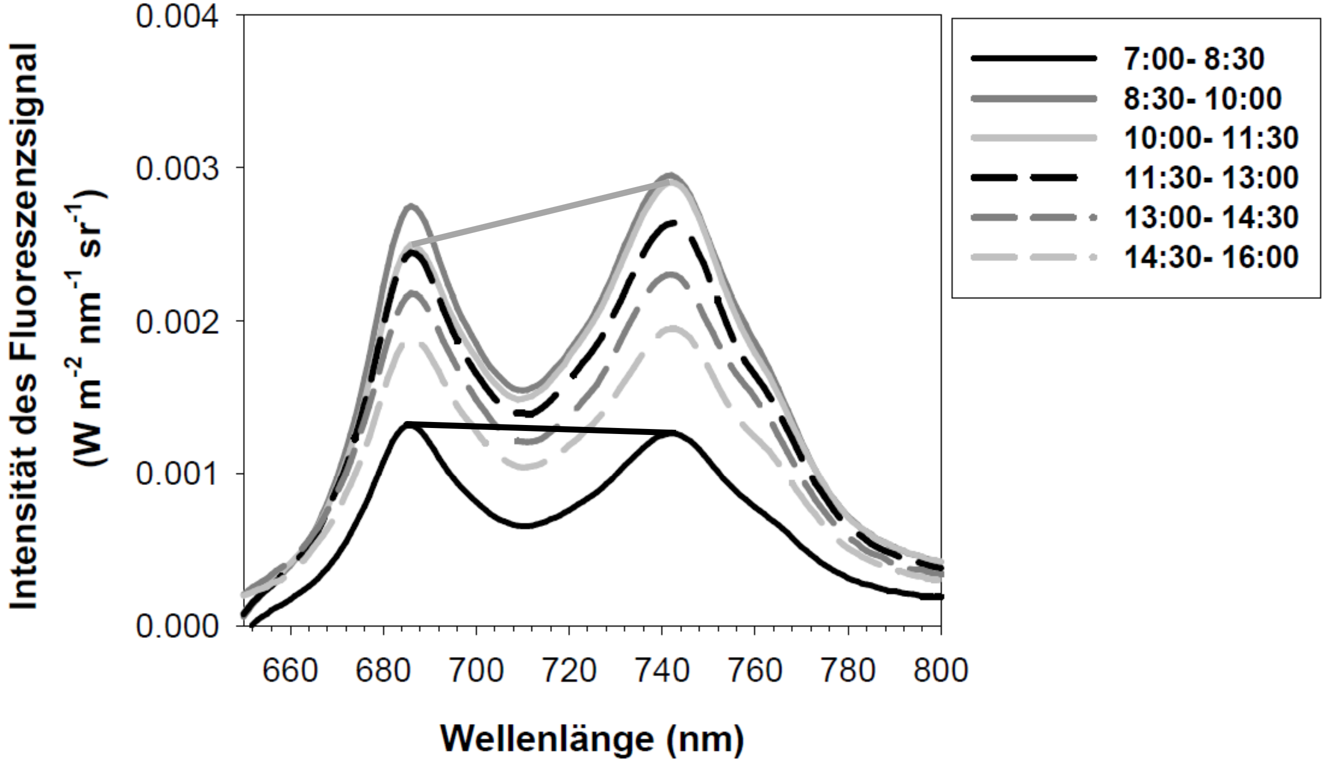
– A new leaf level device (Fluowat, University of Valencia) was developed and used to track diurnal courses of sun induced chlorophyll fluorescence at leaf level



C. Plückers, Research Center Juelich

Introduction: Fluorescence emission at leaf level

- Typical emission patterns and a diurnal course of integrated FS emission is obvious but also variations in the peak emission ratio



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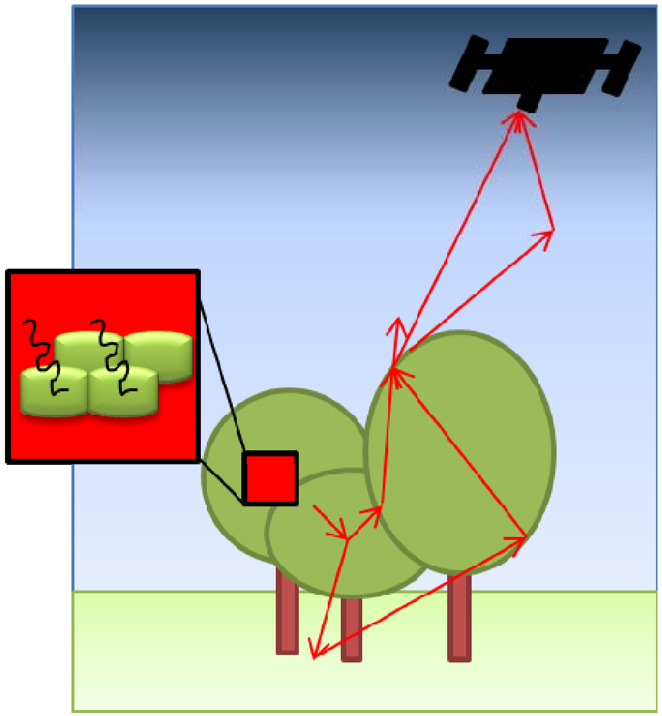
Introduction: field & airborne campaign objectives

– The chlorophyll fluorescence signal retrieved from optical measurements is complex

  – the signal itself is an emitted flux and depends on the physiological response of photosynthesis to environmental conditions

  – the emitted flux is influenced by canopy structure and partly re-absorbed due to atmospheric O_2

  – the signal reaching the sensor is superimposed by the reflected radiation flux and sampled using a sensor with specific characteristics



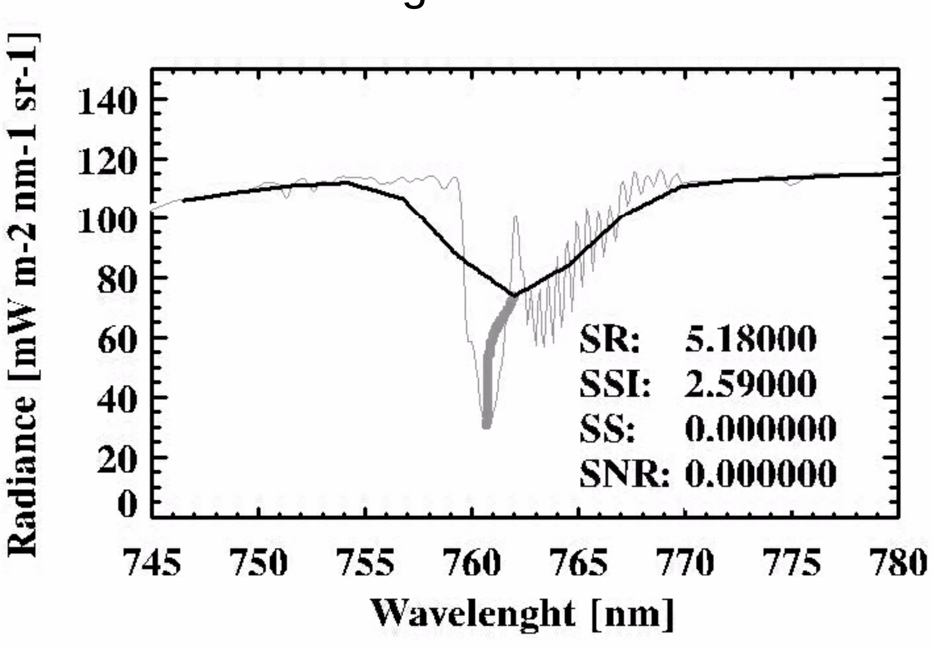
Introduction: field & airborne campaign objectives

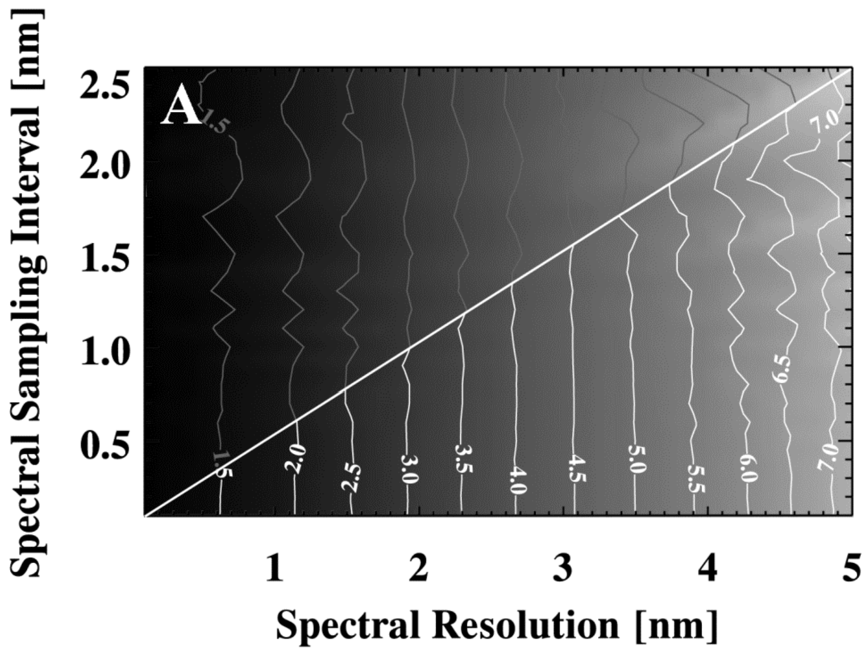
- Field & airborne campaigns were carried out (partly) in preparation of FLEX, e.g., Sen2FLEX (2005), CEFLES2 (2007) and aim
  - to evaluate the impact of first order and subtle effects impacting the retrieval of FS for developing reliable FS retrieval schemes
  - to assess the relation between sun-induced chlorophyll FS and photosynthesis and how environmental changes determine this relationship

Introduction: Instrument characteristics

Spectral resolution (SR)

- SR determines the contrast between emitted and reflected flux
- Decreasing SR shifts deepest band position (CWL) to longer wavelengths



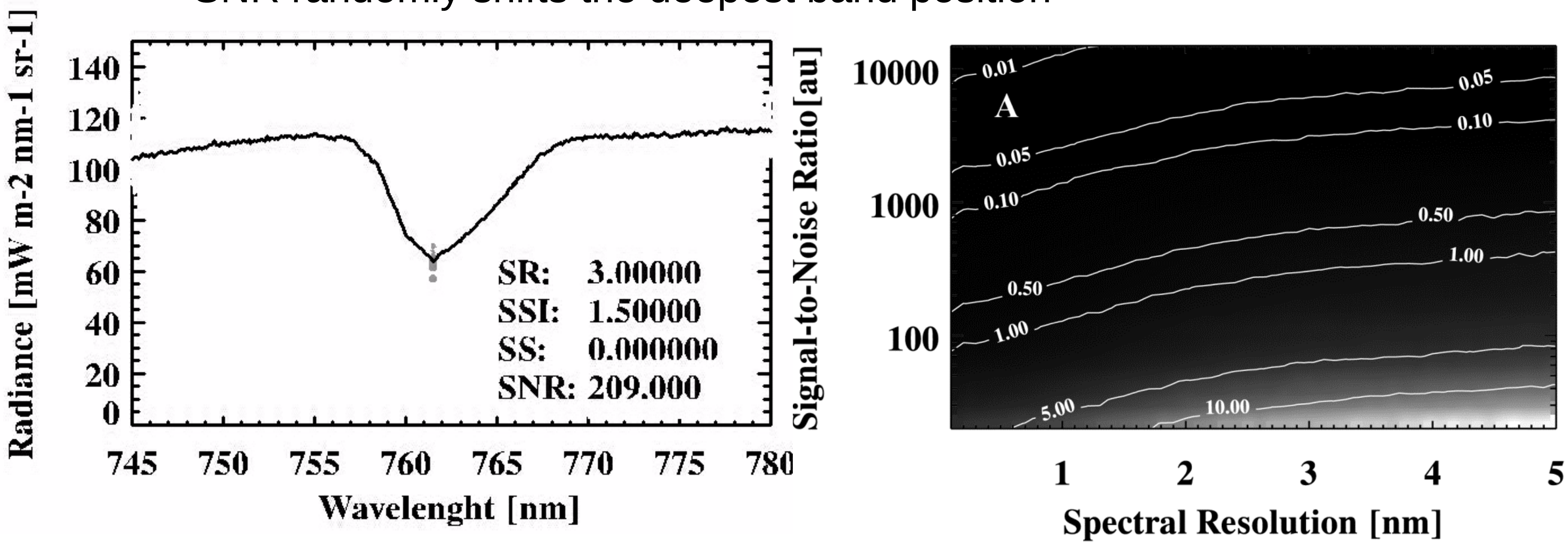


Damm et al. (2011). Modeling the impact of spectral sensor configurations on the FLD retrieval accuracy of sun-induced chlorophyll fluorescence. *Remote Sensing of Environment, 115, 1882-1892*

Introduction: Instrument characteristics

Signal to noise ratio (SNR)

- SNR adds a random component on the measured signal
- SNR determines the contrast between emitted and reflected flux
- SNR randomly shifts the deepest band position

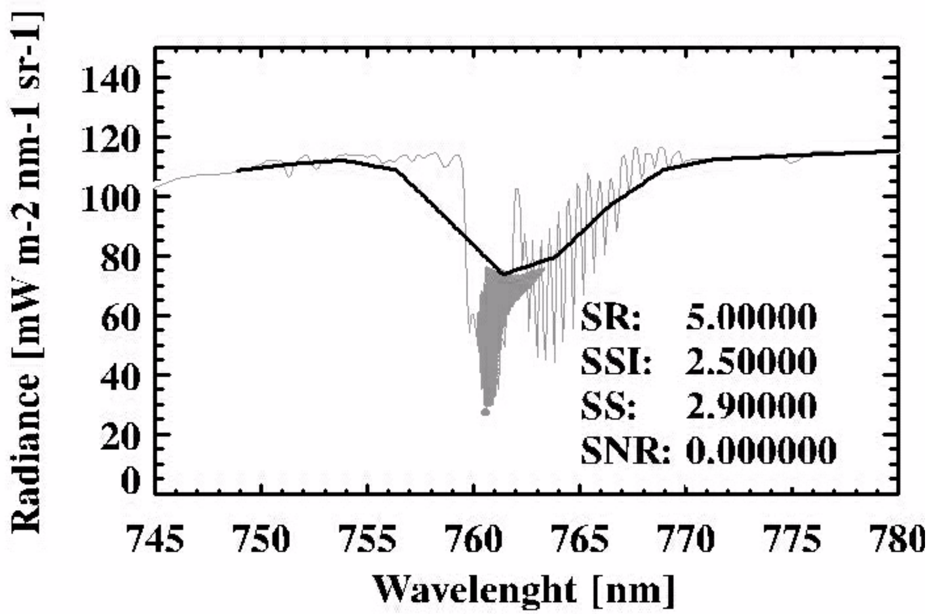


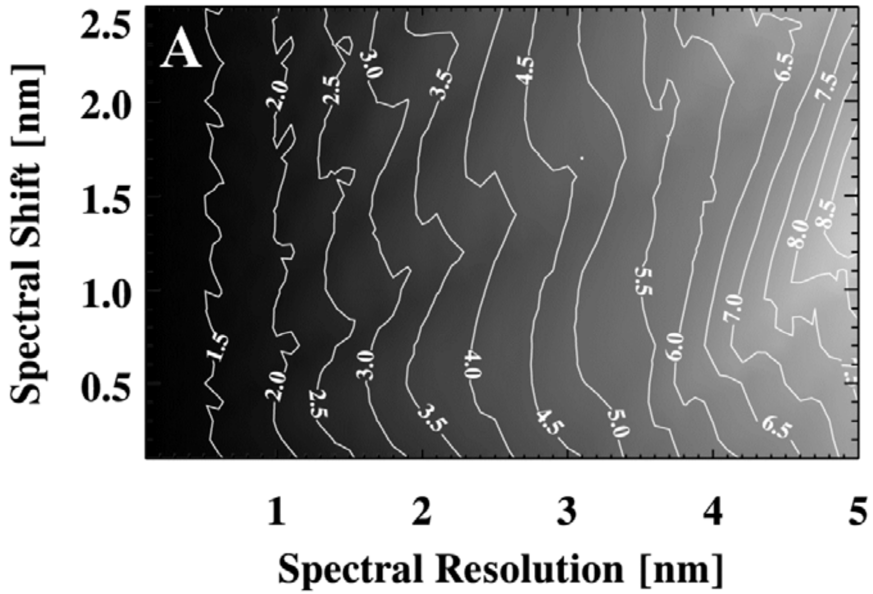
Damm et al. (2011). Modeling the impact of spectral sensor configurations on the FLD retrieval accuracy of sun-induced chlorophyll fluorescence. *Remote Sensing of Environment, 115, 1882-1892*

Introduction: Instrument characteristics

Spectral shift (SS)

- SS determines the contrast between emitted and reflected flux
- SS varies the deepest band position

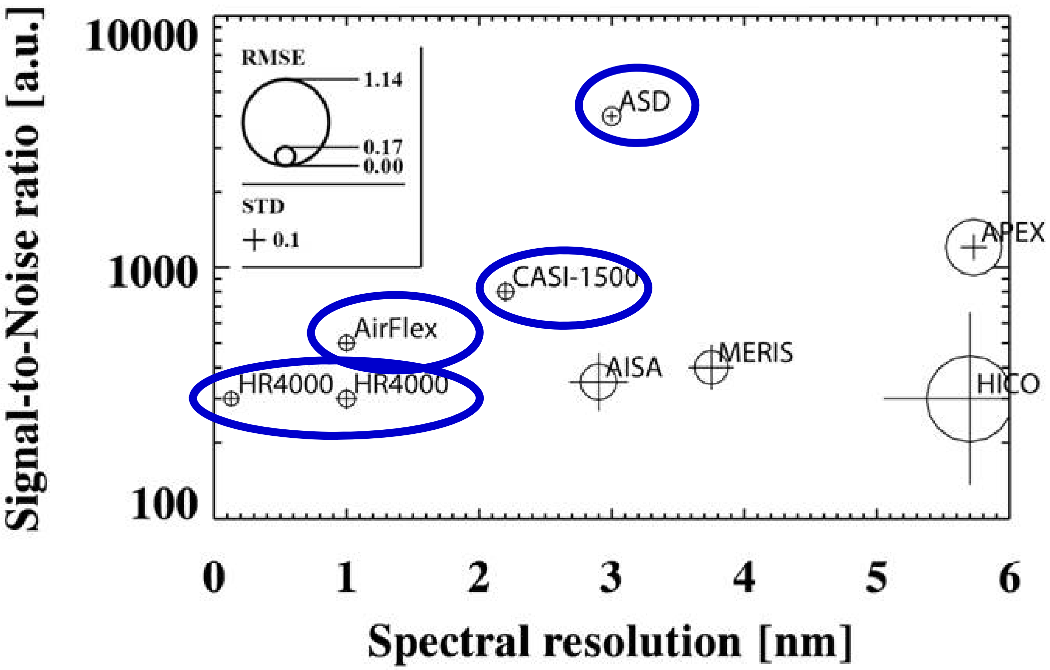




Damm et al. (2011). Modeling the impact of spectral sensor configurations on the FLD retrieval accuracy of sun-induced chlorophyll fluorescence. *Remote Sensing of Environment, 115, 1882-1892*

Introduction: Instrument characteristics

- FWHM and SNR are the most critical sensor properties impacting FS
- Commonly used field spectrometers provide sufficient accuracy to retrieve FS from O_2 absorption lines



Damm et al. (2011). Modeling the impact of spectral sensor configurations on the FLD retrieval accuracy of sun-induced chlorophyll fluorescence. *Remote Sensing of Environment, 115, 1882-1892*

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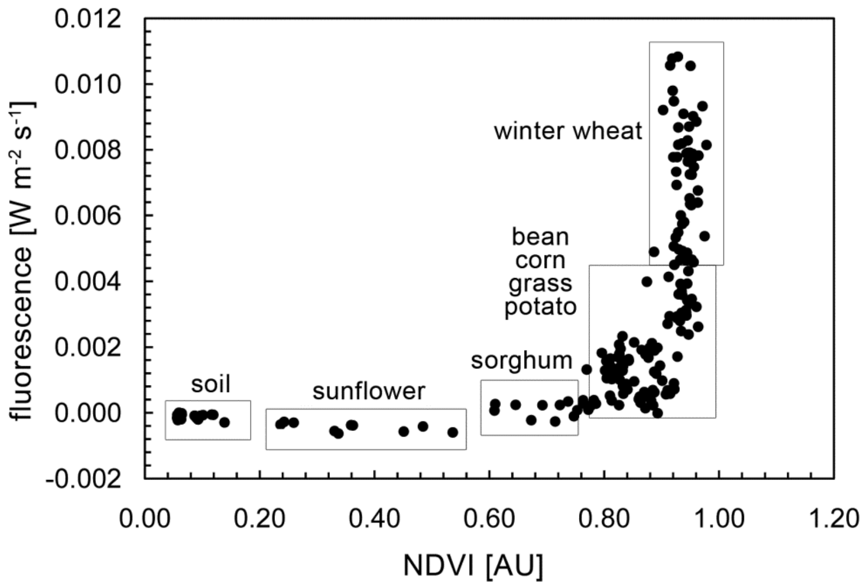
Fluorescence at canopy scale: spatial domain

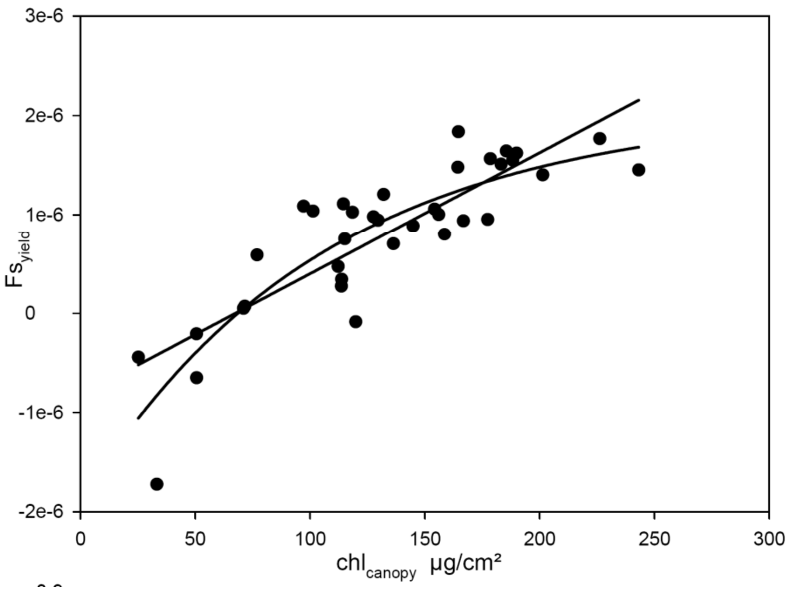
- Several crop types were investigated to gather knowledge on the spatial variation of FS
- First finding is that common vegetation indices saturate in dense canopies but not fluorescence

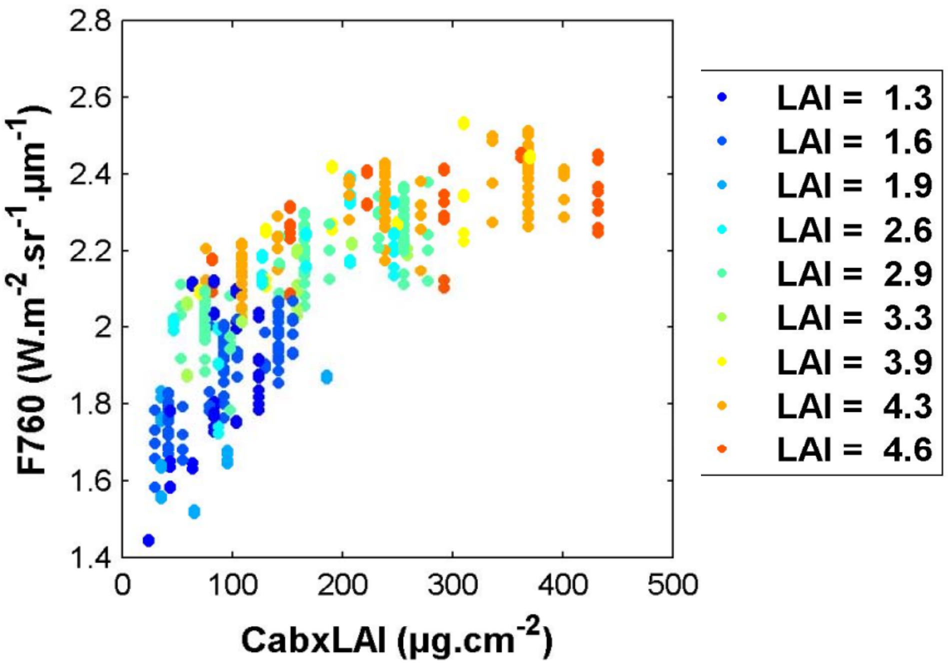


Rascher et al. (2010). Sensing of photosynthetic activity of crops. In *Precision Crop Protection – the Challenge and Use of Heterogeneity.*,Oerke E.C. et al. (eds), Springer Science+Buissness Media

Structural impact on FS signals

- FS and also FS_{yield} seems to depend on structure (e.g., cCAB)
- Model results confirm this finding and indicate LAI and chlorophyll content as most influencing factors





Magnani, F. et al., 2009. Assessment of vegetation photosynthesis through observations of solar induced fluorescence from space. *ESA final report. ESTEC contract No. 20678/07/NL/HE*

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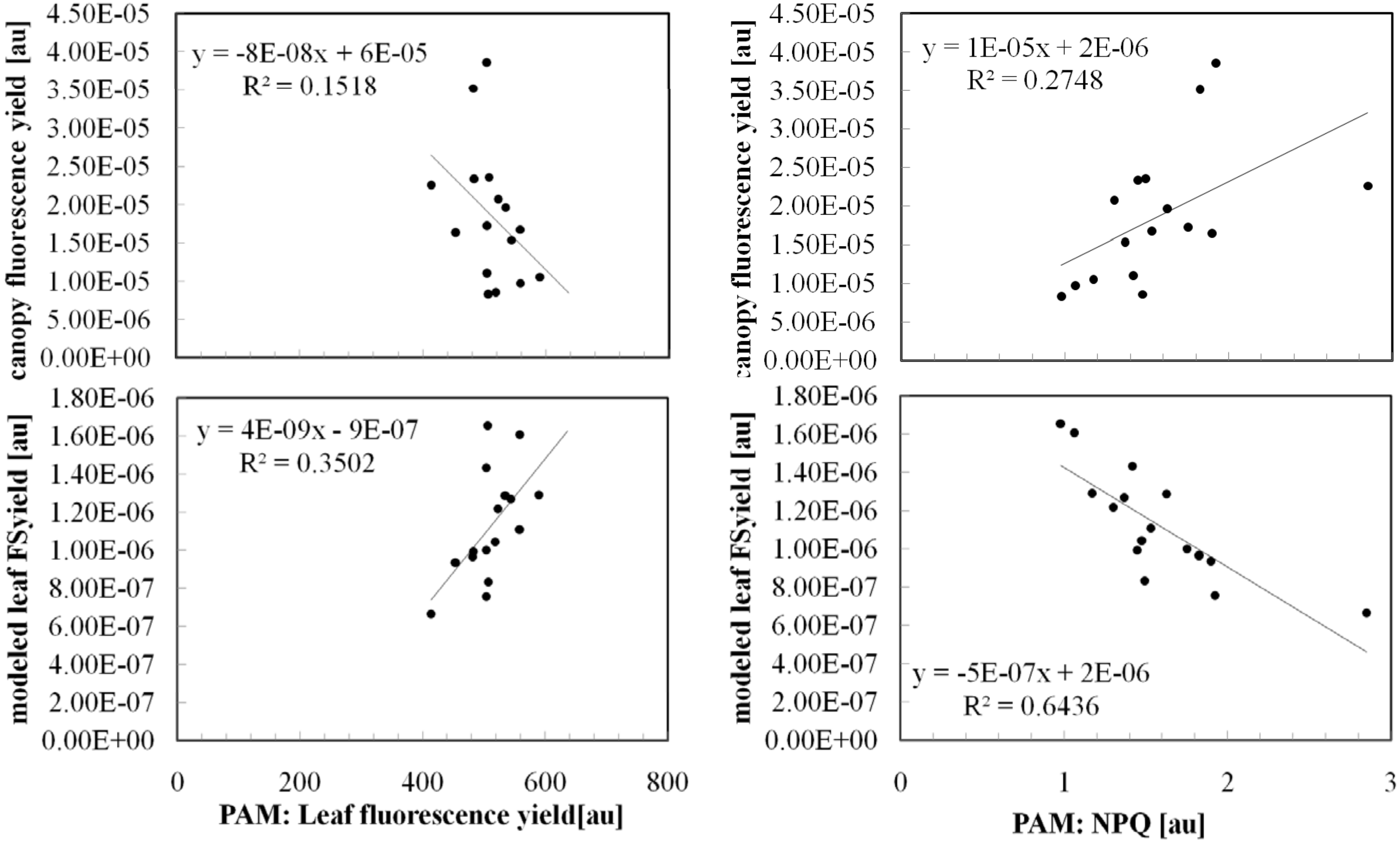
Structural impact on FS signals



Main findings

- Plausible patterns of FS were found at canopy scale

- The measured FS signal seems to be more sensitive to APAR compared to common vegetation indices, especially in dense canopies where reflectance based approaches typically saturate

- Canopy FS and also FS_{yield} are affected by structure. Reasons are
  - the scattering / absorption of emitted FS in the canopy
  - remaining uncertainties in ther retrieval of APAR

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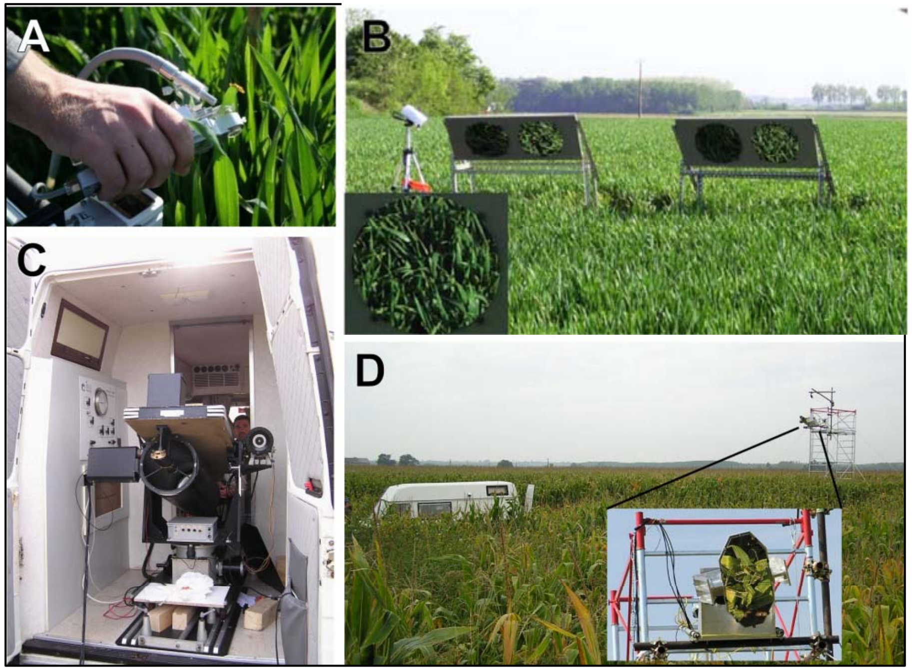
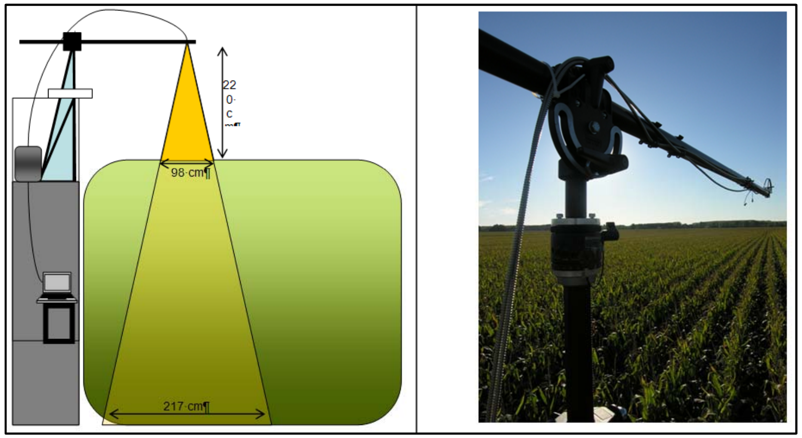
Fluorescence at canopy scale: temporal domain

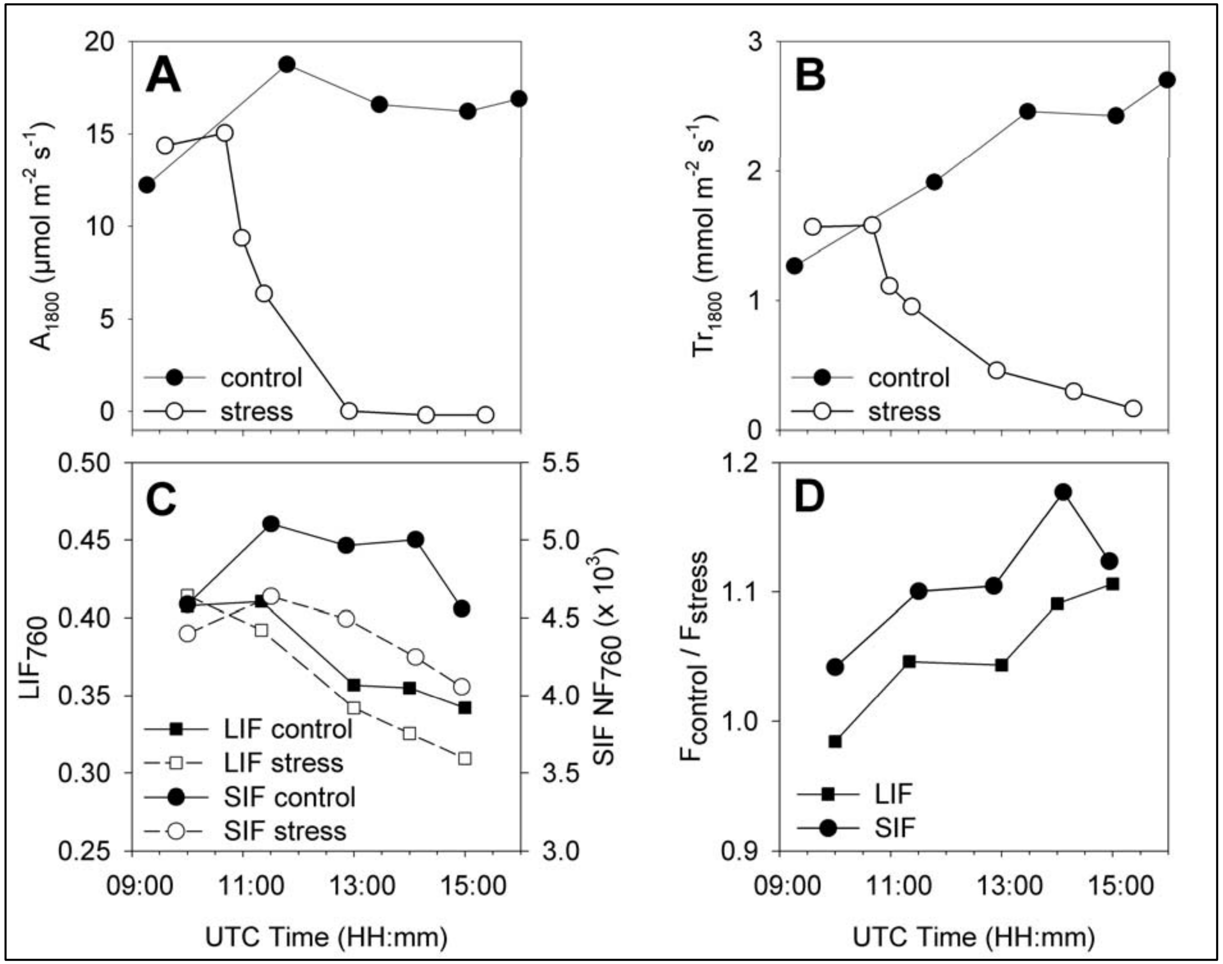
- Experiments assessing the temporal behavior of FS allow to
  - compensate for effects superimposing the FS retrieval (structure, instrumental effects)
  - evaluate the potential of FS to track physiological changes of photosynthesis





Rascher et al. (2009). The remote sensing component to quantify photosynthetic efficiency from the leaf to the region by measuring sun-induced fluorescence in the oxygen absorption bands. Biogeosciences, 6, 1181-1198

Fluorescence at canopy scale: temporal domain



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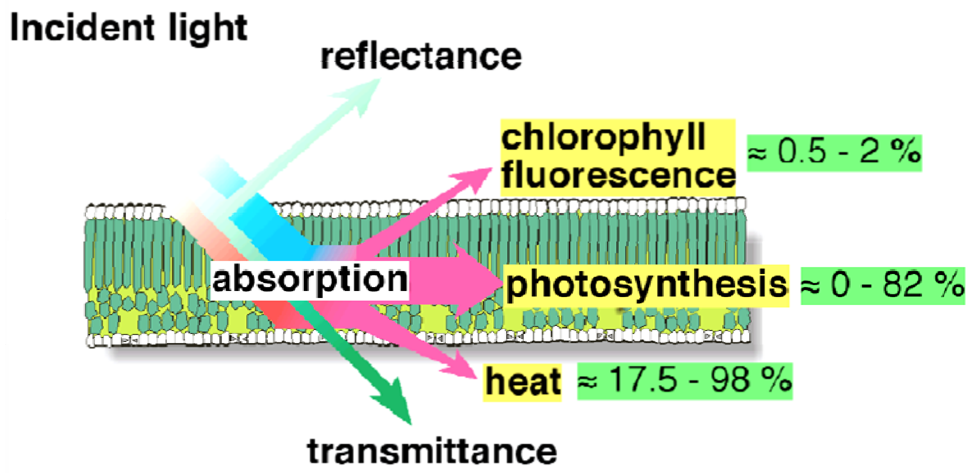
Competition between processes

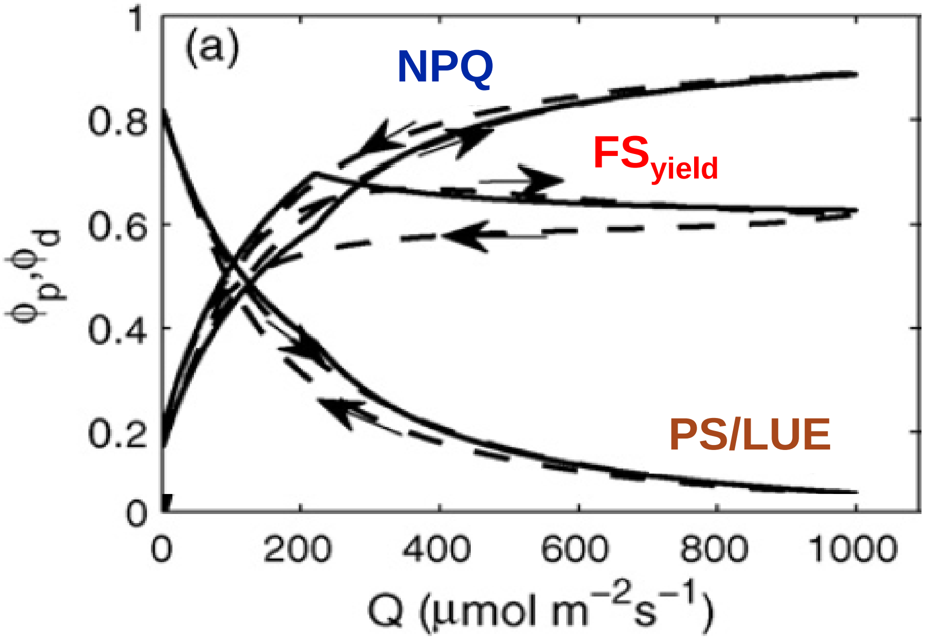
- Environmental stress (e.g., high light, vapor pressure deficit (VPD)) leads to a regulation of photosynthesis
- Absorbed energy which cannot be used to drive photosynthesis must be dissipated to avoid damages of the photosynthetic apparatus
- Absorbed photons are distributed between three processes



Drusch, M., & FLEX-Team (2008). FLEX Report for Assessment. In, ESA SP-1313/4. ESA-ESTEC, Noordwijk (The Netherlands)

Competition between processes

- Efficiency of photosynthesis changes in response to environmental factors, e.g., light intensity, temperature, water and nutrient availability
- Photosynthesis is species specific and variable in space and time
- In result, the relation between PS, NPQ and FS is highly variable



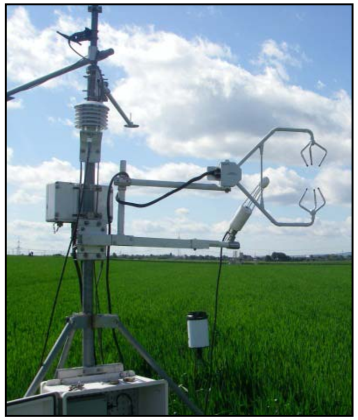
van der Tol, C., et. al, 2009, A model for chlorophyll fluorescence and photosynthesis at leaf scale. *Agricultural and Forest Meteorology, 149*

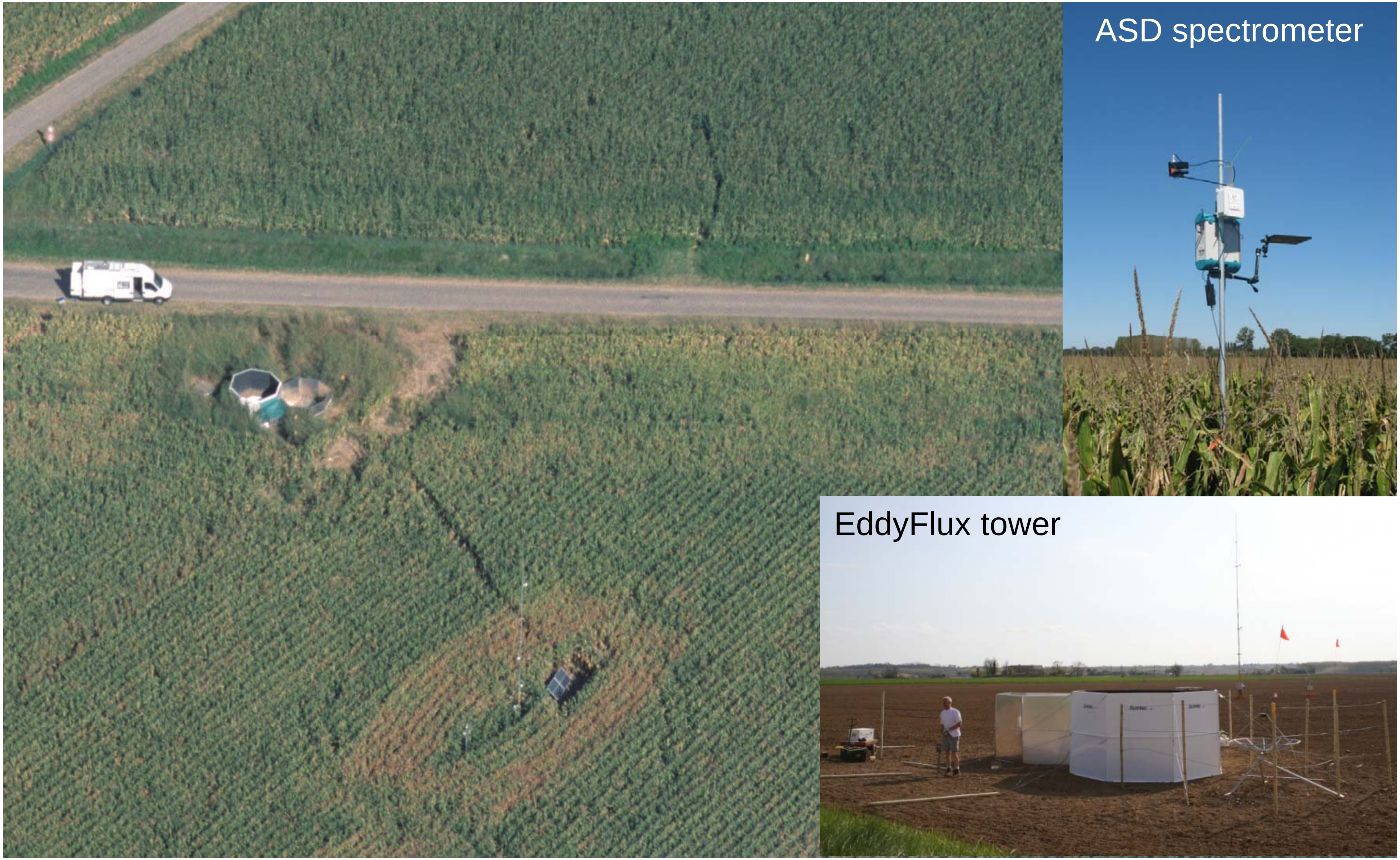
Fluorescence as proxy to estimate photosynthesis

- Two temporal experiments were carried out:
  - I in a senescent corn canopy; NPQ is expected to be downregulated
  - II in vital crops; NPQ is expected to act normal
- Acquisition of diurnal courses of FS_{yield} using ground based ASD data
- Measurement of canopy photosynthesis using an eddy flux tower

$$\boxed{GPP = LUE * f_{APAR} * PAR}$$







ASD spectrometer
EddyFlux tower

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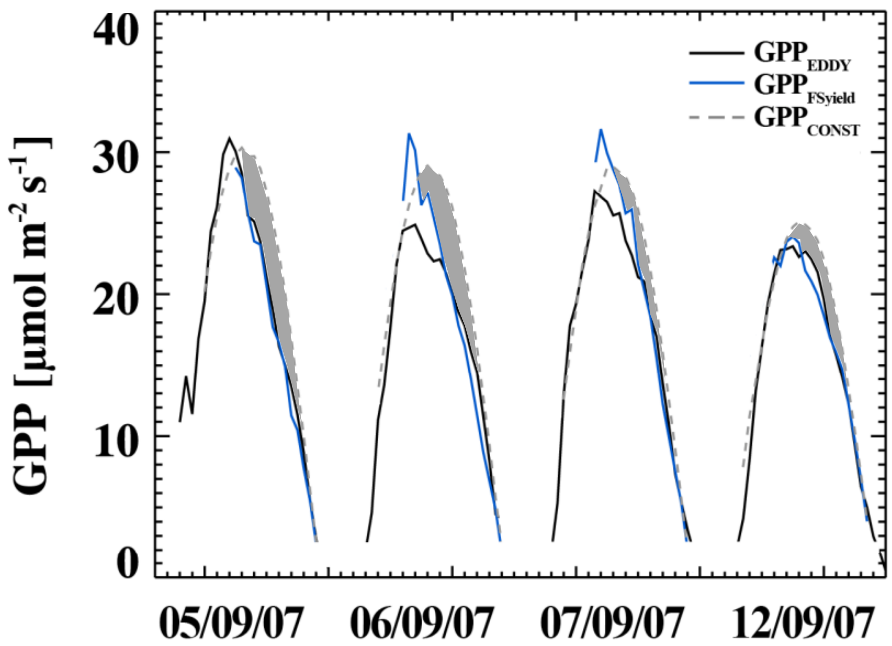
Fluorescence as proxy to estimate photosynthesis

- Replacing LUE with FS_{yield} in Monteith's LUE concept allows tracking the diurnal variation of photosynthesis
- A constant LUE leads to strong overestimation of photosynthesis especially during stress induced midday depression



Damm et al. (2010). Remote sensing of sun induced chlorophyll fluorescence to improve modelling of diurnal courses of Gross Primary Production (GPP) .*Global Change Biology, 16, 171-186*

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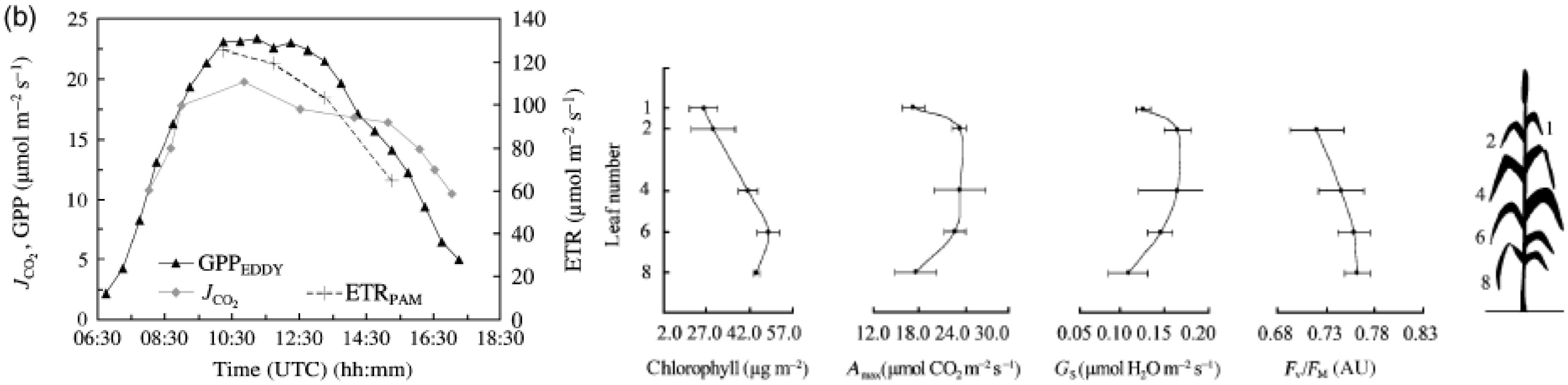
Fluorescence as proxy to estimate photosynthesis

- The midday depression could be confirmed with leaf level measurements of the electron transport rate (ETR, PAM) and the CO2 assimilation rate (J_{CO2}, LiCOR 6400)
- Vertical profiles indicate a higher photoinhibition in the upper layers of the canopy, means a potentially reduced NPQ



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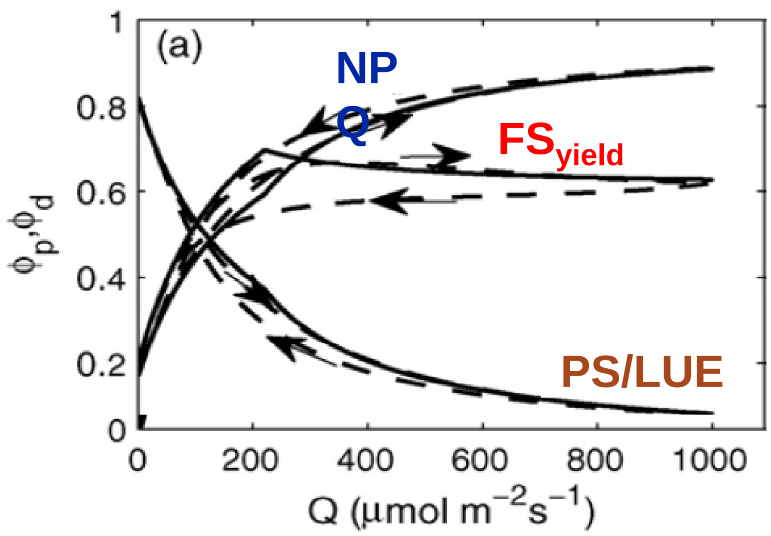
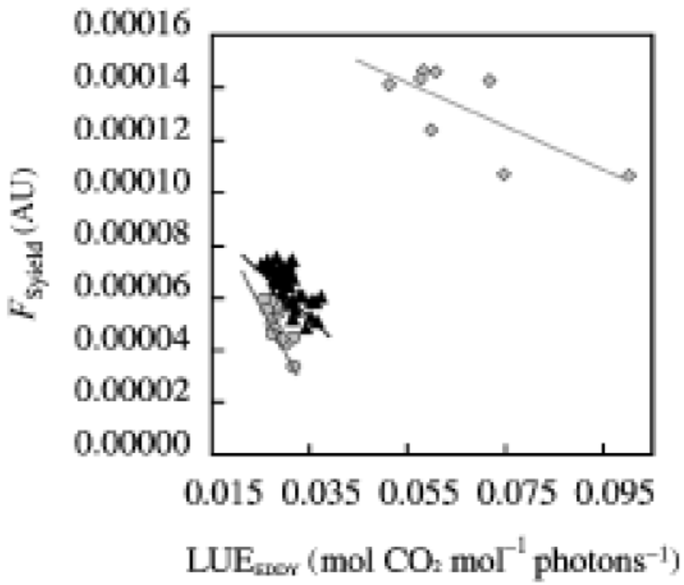
Fluorescence as proxy to estimate photosynthesis

- In case NPQ is limited (e.g., in photoinhibited canopies), a negative relationship between LUE and FS_{yield} appears in the diurnal course
- In between days, the relationship between LUE and FS_{yield} is positive

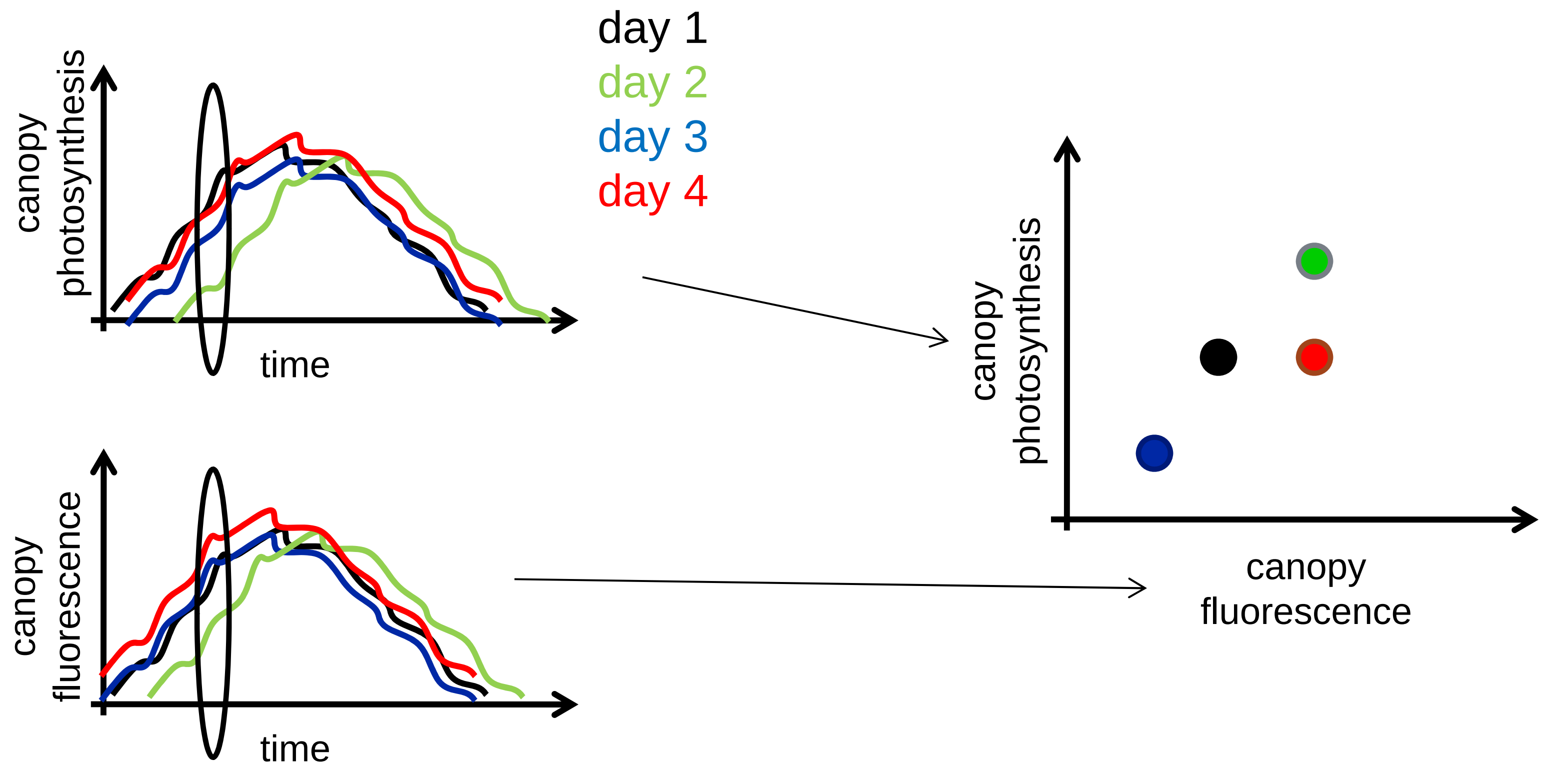




Damm et al. (2010). Remote sensing of sun induced chlorophyll fluorescence to improve modelling of diurnal courses of Gross Primary Production (GPP) .*Global Change Biology, 16, 171-186*

Fluorescence as proxy to estimate photosynthesis

– Models indicate a reasonable relationship between FS_{yield} and LUE in the morning where NPQ is limited (van der Tol et al 2009)



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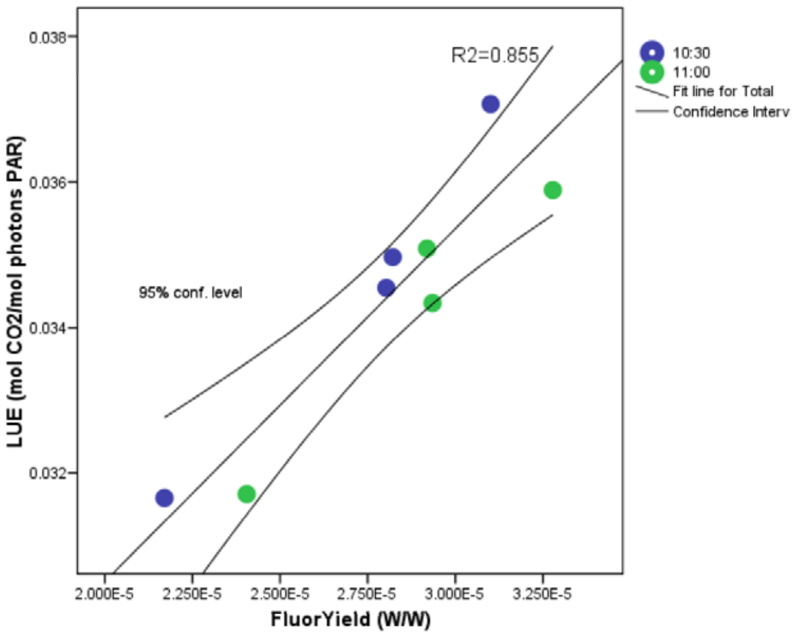
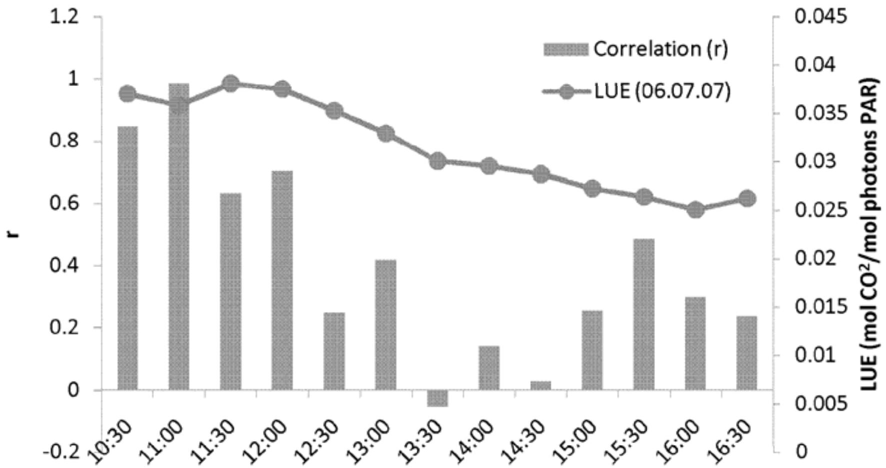
Fluorescence as proxy to estimate photosynthesis

– First results obtained from measurements in a senescent corn canopy seem to correspond to the model prediction





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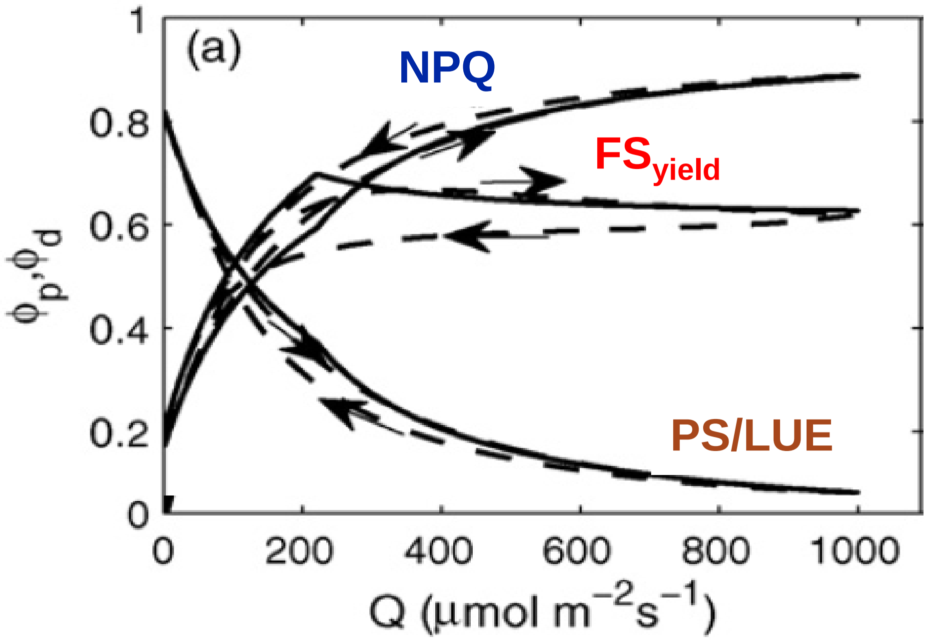
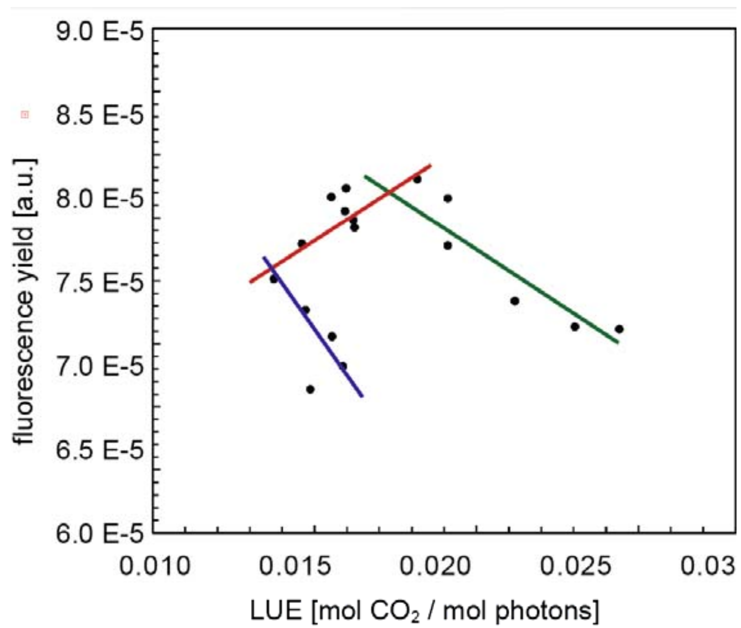
Photosynthesis and Fluorescence - Results

- In vital crops, NPQ causes a changing relationship between FS_{yield} and LUE
- All three terms – APAR, NPQ and FS are required to predict PS





van der Tol, C., et. al, 2009, A model for chlorophyll fluorescence and photosynthesis at leaf scale. *Agricultural and Forest Meteorology, 149*

Main findings

– Manipulative experiments clearly show the potential of FS to track stress imposed physiological responses of the photosynthetic apparatus

– The energy absorbed to drive photosynthesis is distributed in three pathways. In case NPQ is less present (e.g., due to photoinhibition or under low light conditions), a reliable relationship between FS and photosynthesis can be found

– For a comprehensive monitoring of photosynthesis, the quantification of APAR, NPQ and FS is required. Automatic measurement setups will provide insights into the relationship of all these processes at canopy scale

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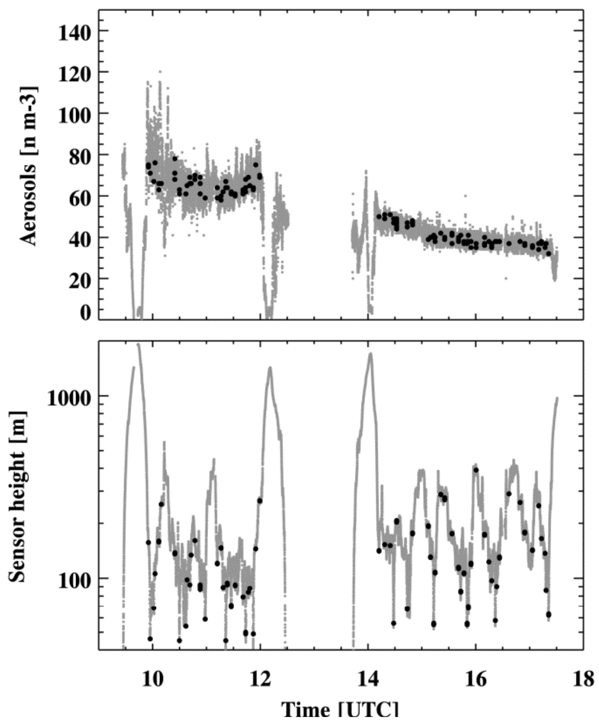
Scaling FS from canopy to regional scale

- Atmospheric oxygen reabsorbs the emitted FS signal and impacts the retrieval of FS from airborne and spaceborne instruments
- A specific airborne experiment was applied to
  - evaluate the feasibility of retrieving FS from airborne instruments
  - quantify the impact of atmospheric conditions and observation geometry on FS retrieval



Scaling FS from canopy to regional scale

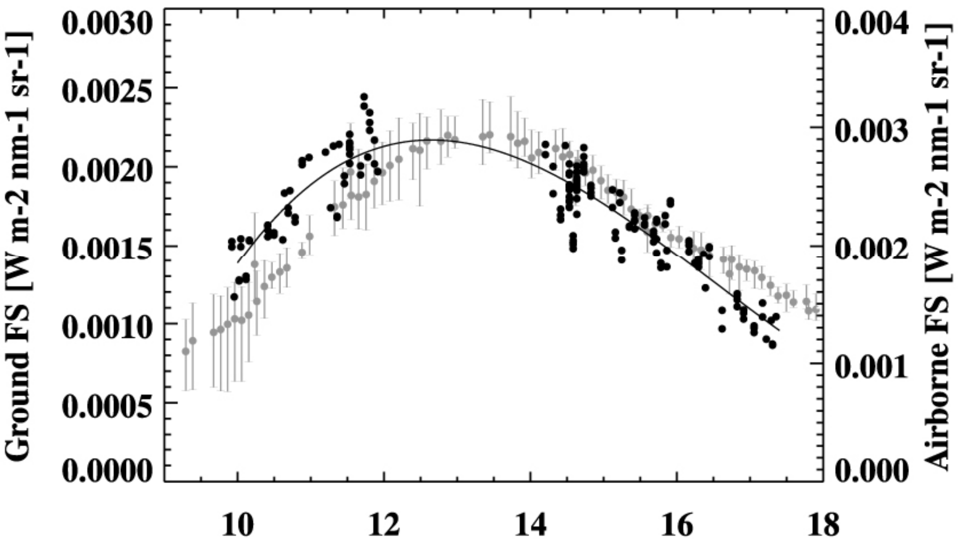
– A DIMONA aircraft was equipped with an ASD non-imaging spectrometer and several instruments for atmospheric research (particle counter, etc.)



Damm et al. (in prep). Airborne based assessment of spatio-temporal characteristics of sun-induced chlorophyll fluorescence and factors determining its retrieval.

Scaling FS from canopy to regional scale

– Realistic temporal behavior of airborne based FS signals, but
  – overestimation of airborne signal esp. in the morning caused by an insufficient characterization of the atmosphere
  – scattering induced by variable footprint (entire field, changing flight height)



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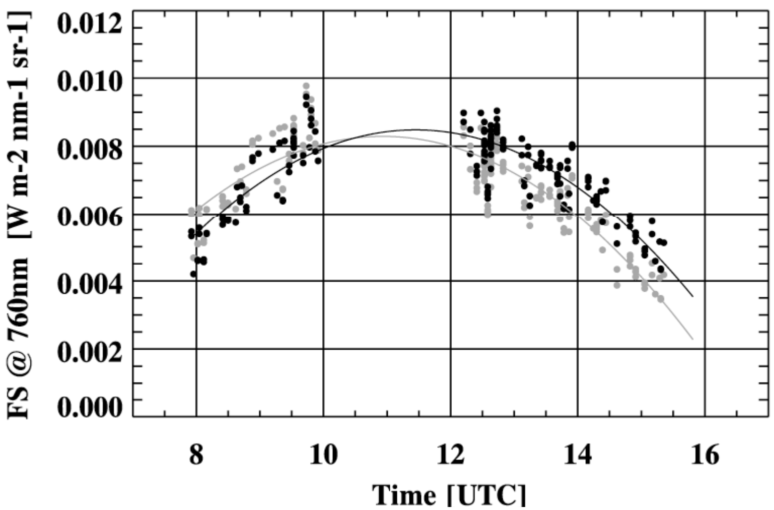
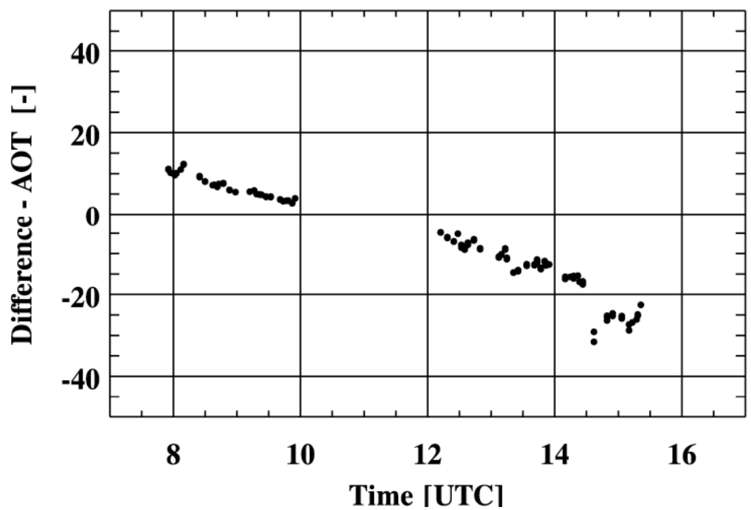
Impact of model parameters on FS signal

Parameter	Max error [%]	Range [%]	STD error [%]
AOT	31.56	43.90	10.82





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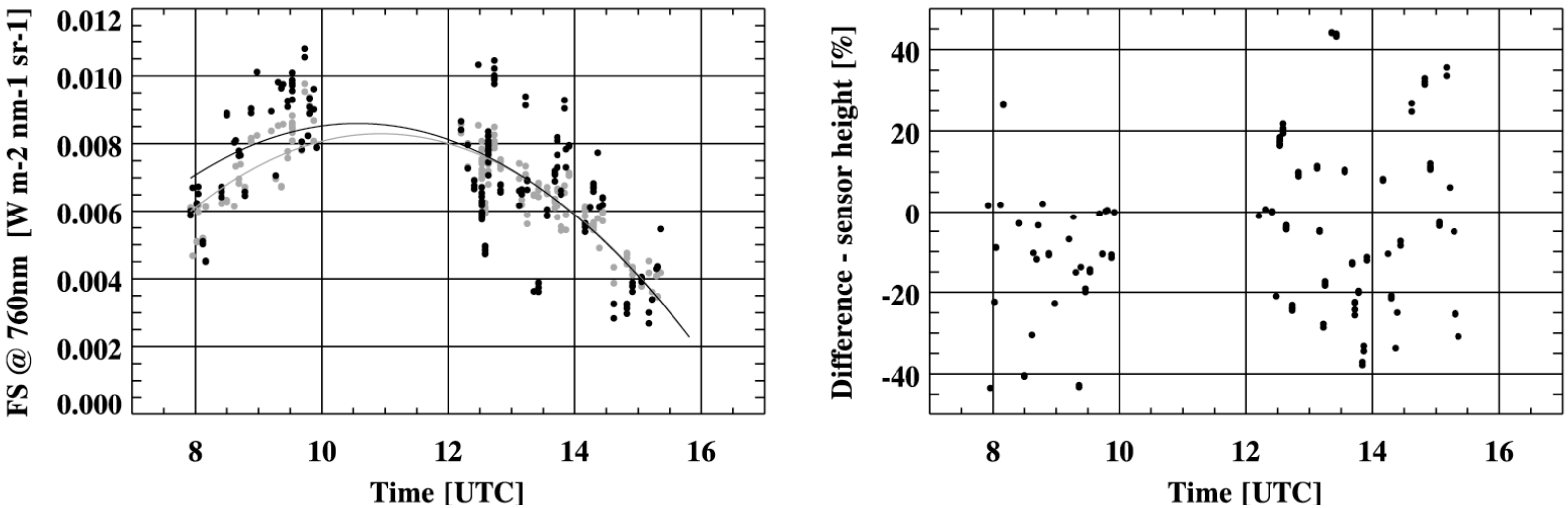
Impact of model parameters on FS signal

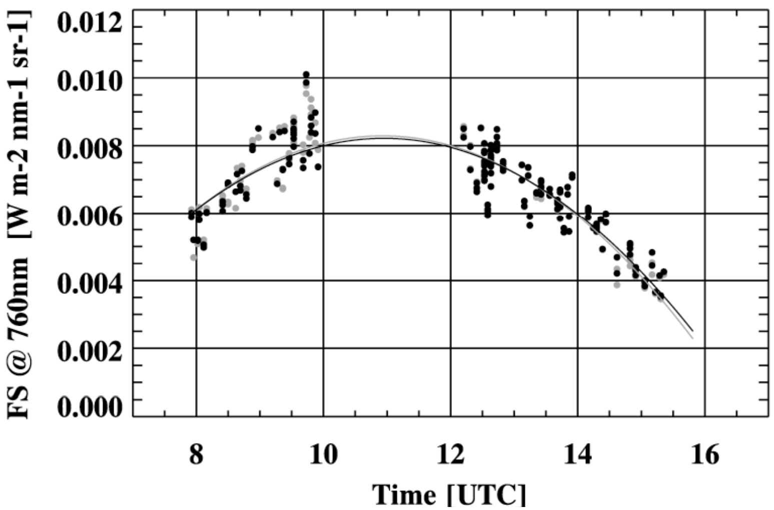
Parameter	Max error [%]	Range [%]	STD error [%]
AOT	31.56	43.90	10.82
Sensor height	44.18	87.65	19.57

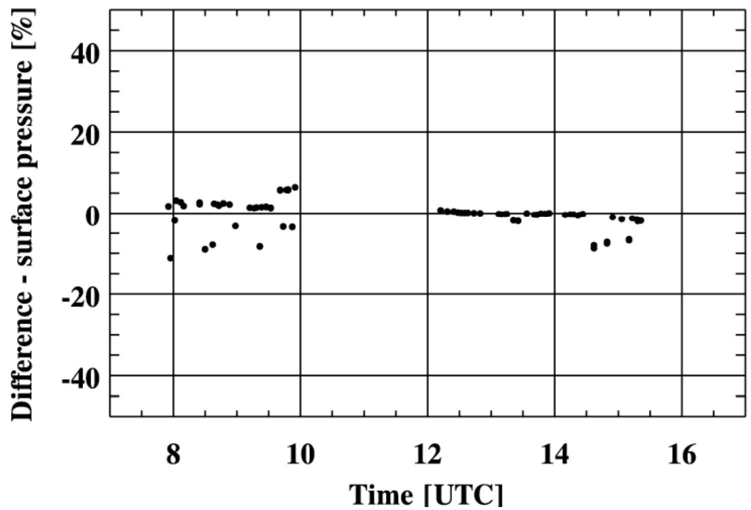


Damm et al. (in prep). Airborne based assessment of spatio-temporal characteristics of sun-induced chlorophyll fluorescence and factors determining its retrieval.

Impact of model parameters on FS signal

Parameter	Max error [%]	Range [%]	STD error [%]
AOT	31.56	43.90	10.82
Sensor height	44.18	87.65	19.57
Surface pressure	11.18	17.63	2.92





Damm et al. (in prep). Airborne based assessment of spatio-temporal characteristics of sun-induced chlorophyll fluorescence and factors determining its retrieval.

Main findings

- FS can be retrieved from airborne operated instruments (proof for flight heights up to 1500m)

- Re-absorption of emitted FS due to atmospheric oxygen is a severe problem and must be properly accounted in the FS retrieval scheme

- Considering a constant flight height a wrong assumption of aerosol load and distribution can strongly impact the FS retrieval.

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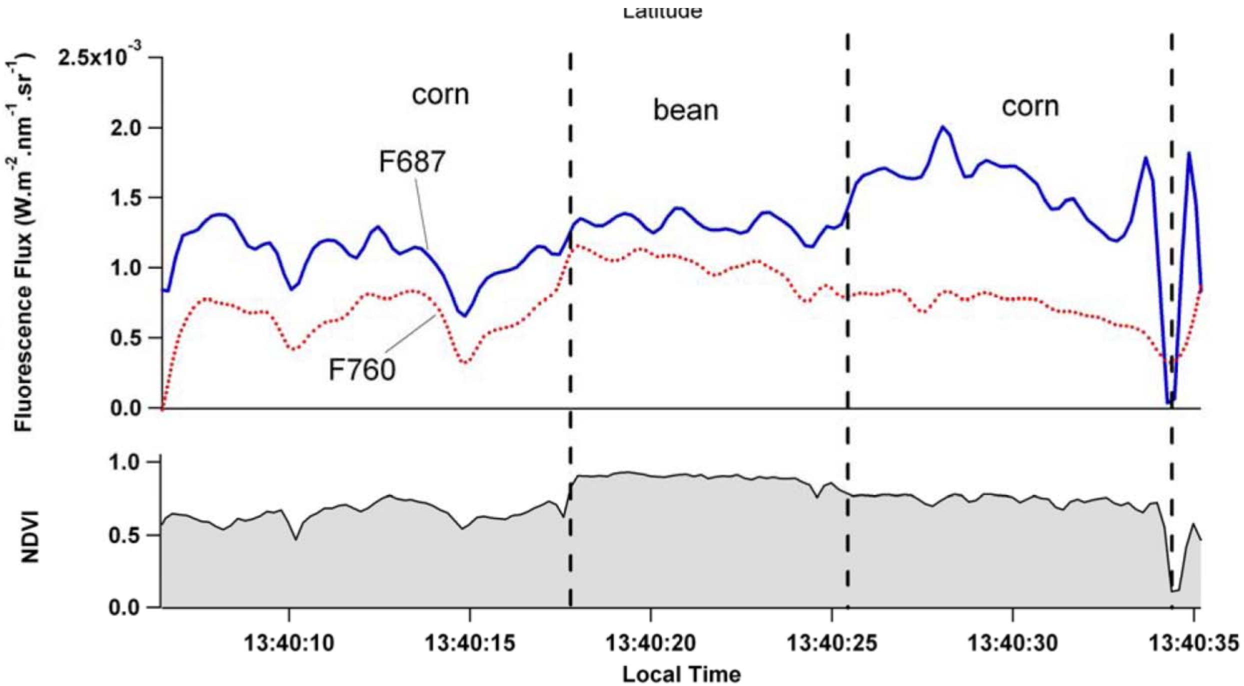
Fluorescence at regional level: Spatial domain

- How evolves FS over larger areas? Do we only see another vegetation index which is strongly affected by structure or is FS indeed an independent signal?
- First attempts of Guanter et al. show that an infilling in the oxygen bands due to FS can be detected from airborne data (CASI) and also from satellites (MERIS)
- To further assess and confirm these promising findings, profiling and imaging instruments were newly developed and existing were intensively exploited to assess spatial variation of FS
  - Profiling instruments: AirFLEX, ASD installed in a DIMONA aircraft
  - Imaging systems: APEX, HyPlant

Fluorescence at regional level: Spatial domain

– AirFLEX (LMD-CNRS, PARIS) was a first profiling instrument mimicking the configuration of FLEX and allows measuring FS at 680 and 760nm



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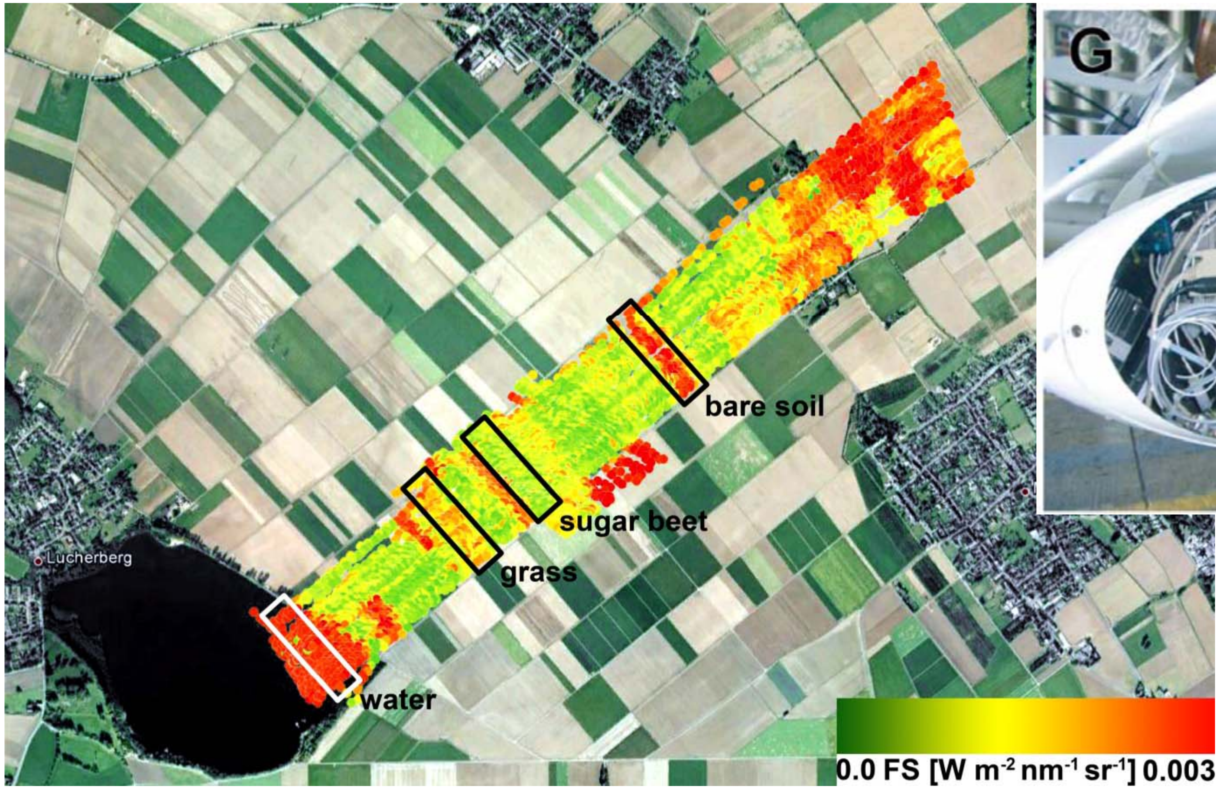
Fluorescence at regional level: Spatial domain

– The DIMONA-setup (ASD) allows investigating spatio-temporal pattern of FS at 760nm



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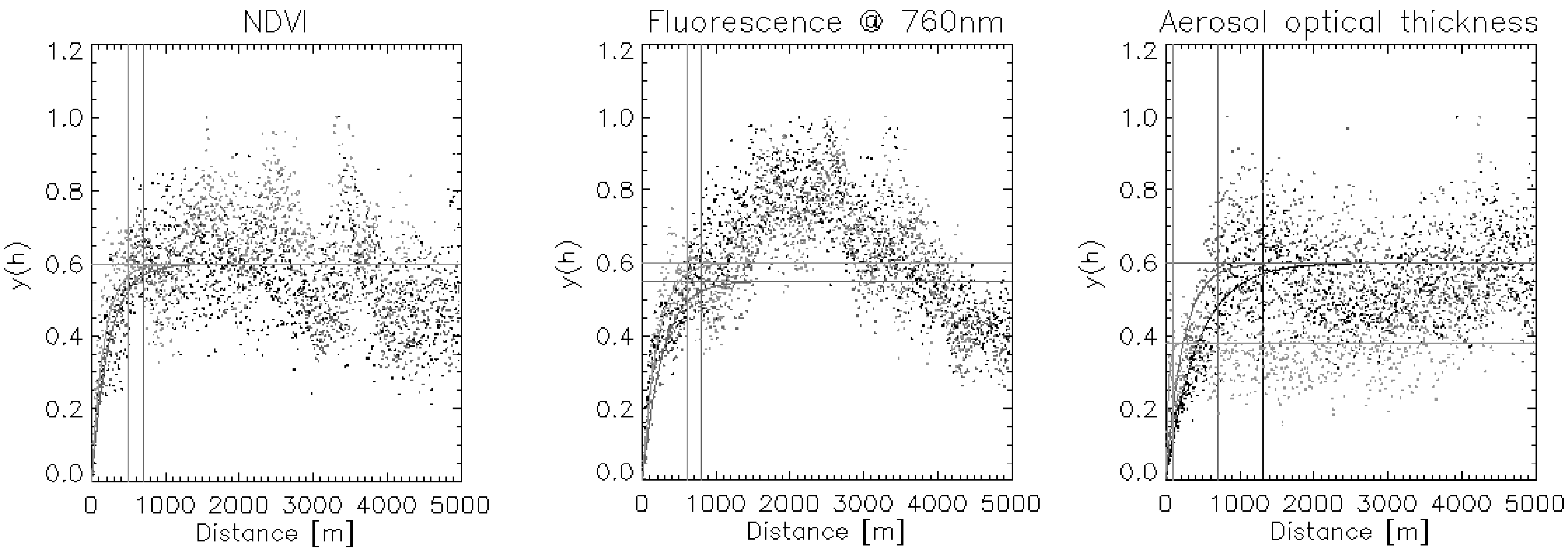
Fluorescence at regional level: Spatial domain

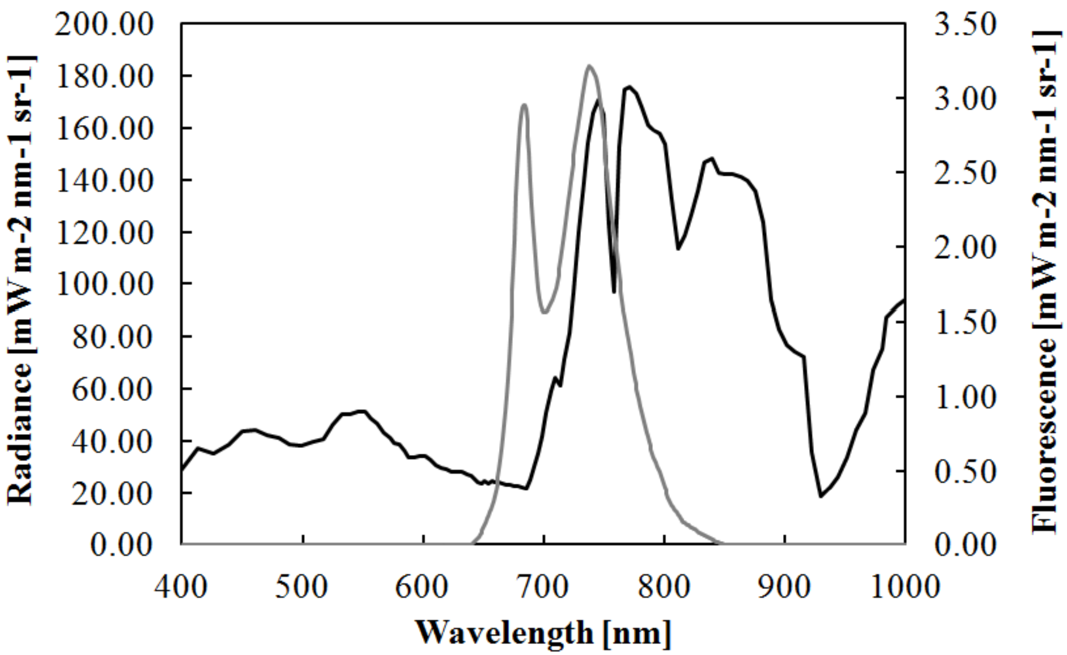
– The length scales of FS and NDVI are comparable at regional scale
– Length scales of FS and AOT differ, means the spatio-temporal influence of AOT can be minimized in the FS retrieval scheme



Damm et al. (in prep). Airborne based assessment of spatio-temporal characteristics of sun-induced chlorophyll fluorescence and factors determining its retrieval.

APEX imaging spectrometer

	VNIR	SWIR
Spectral Range	**380.5 – 971.7 nm**	941.2 – 2501.5 nm
Spectral Bands	**Max. 334 (nominal 114)**	198
Sampling interval	**0.45 – 7.50 nm**	5.00 – 10.00 nm
FWHM	**0.70 – 9.70 nm**	6.20 – 12.00 nm



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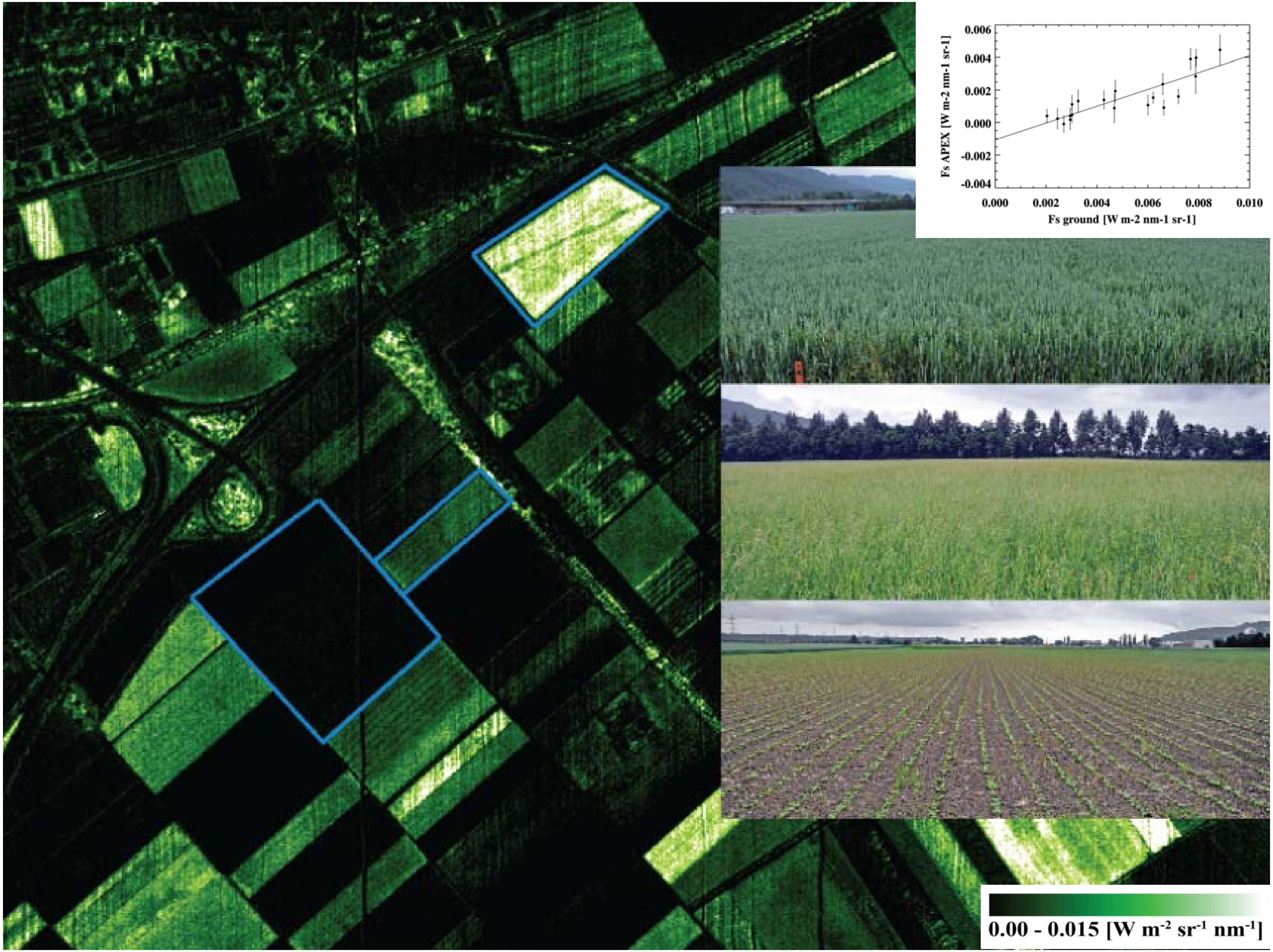
Laegeren test site



Fs APEX [W m-2 nm-1 sr-1]
Fs ground [W m-2 nm-1 sr-1]
0.006
0.004
0.002
0.000
-0.002
-0.004
0.000
0.002
0.004
0.006
0.008
0.010
0.00 - 0.015 [W m-2 sr-1 nm-1]

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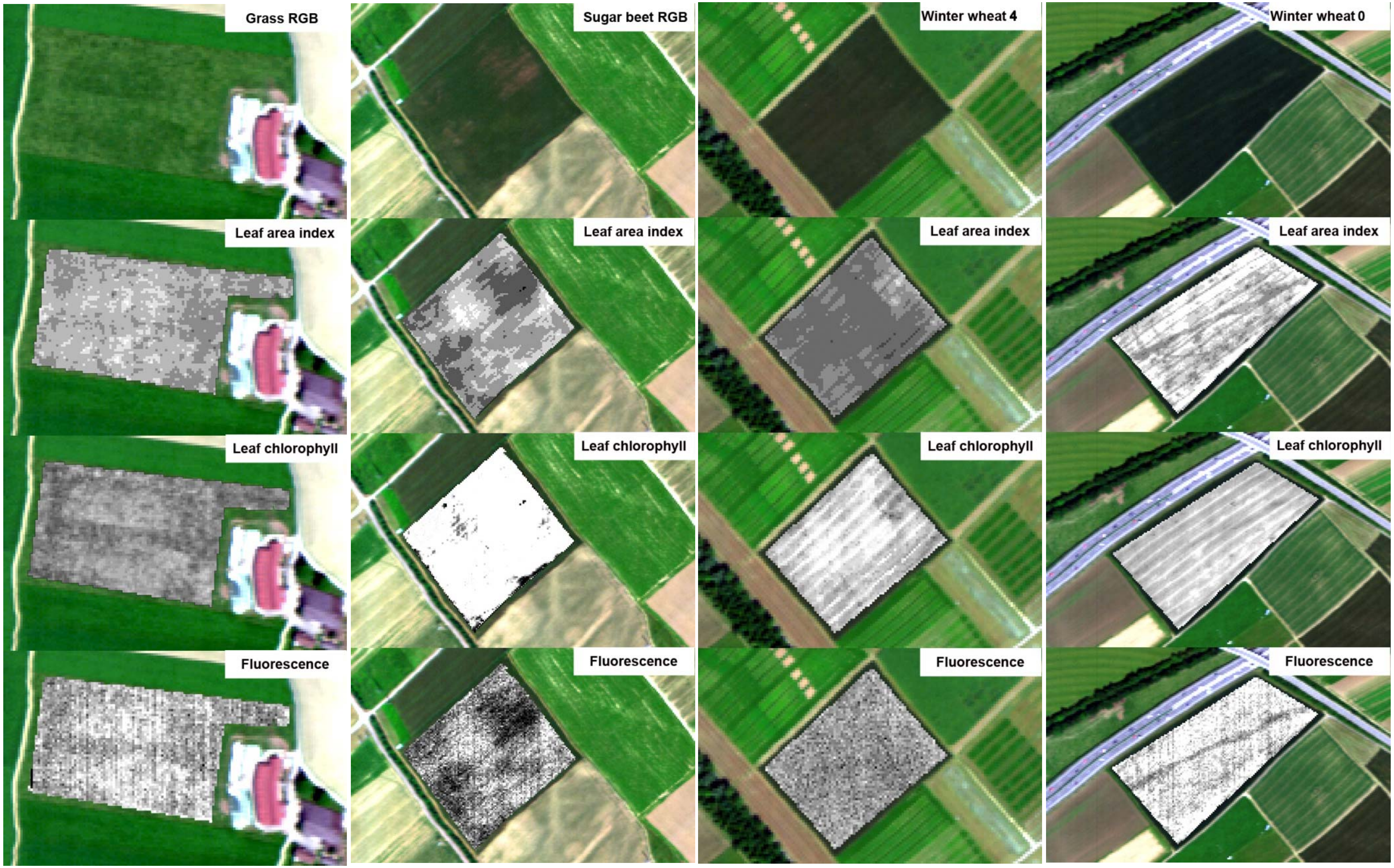
measurements | products | policy



Main findings

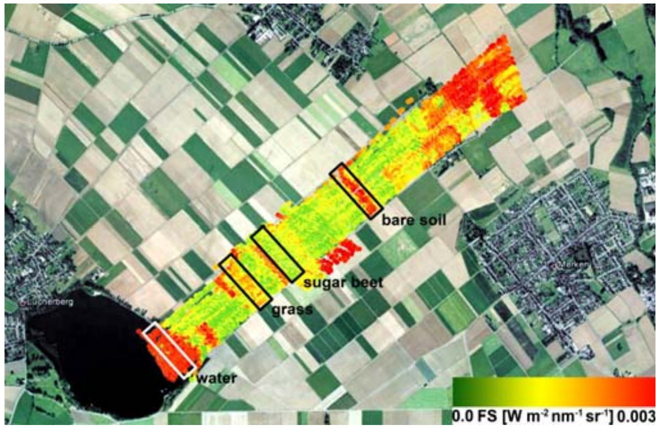
- Airborne based spatial assessments indicate that FS is an independent signal and provides additional/complementary information to common vegetation variables
  - AirFlex measurements show that FS is related to canopy structure but also differs in some cases. Different pattern of FS at 680 and 760nm were observed
  - Dimona observations indicate at larger scale in heterogeneous environments (agriculture), FS is dominated by structure
  - APEX observations show different spatial pattern of FS compared to other vegetation variables at field scale. Especially in case of small spatial disturbances (tractor tracks) FS appears to be less affected by structure

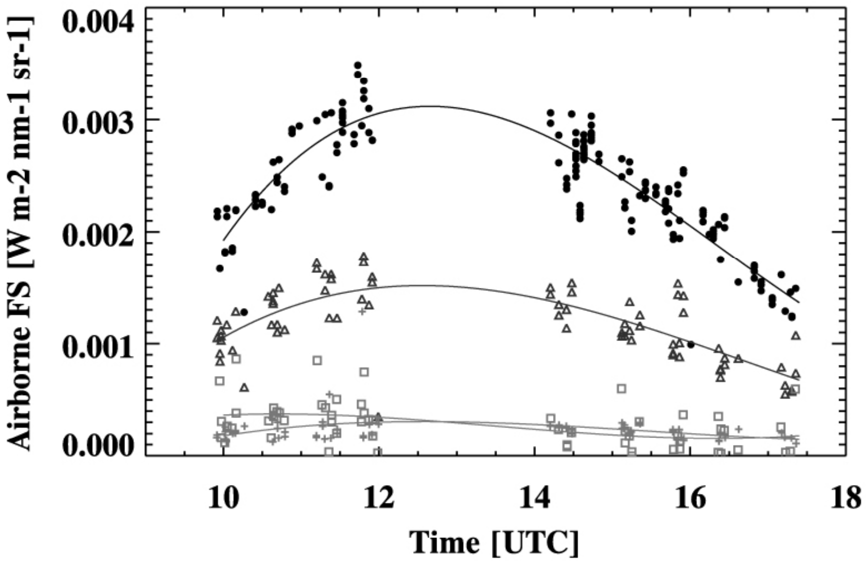
Content

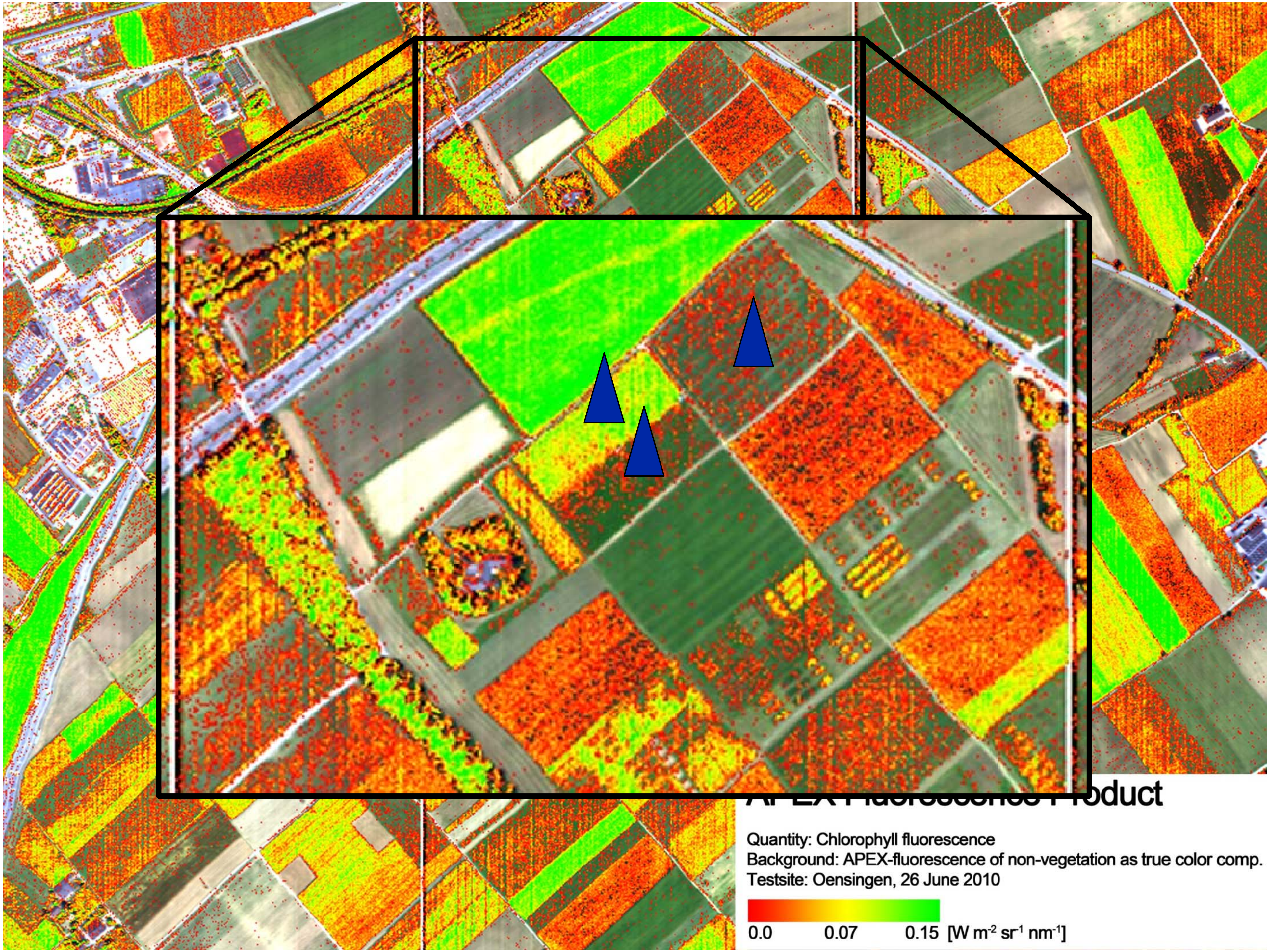
- Introduction
- Fluorescence at canopy level
  - spatial domain
  - temporal domain
- Scaling issues: From canopy to regional level
- Fluorescence at regional level
  - spatial domain
  - temporal domain
- Conclusions

Fluorescence at regional level: Temporal domain

- Consistent temporal behavior of FS over several targets observed under varying flight conditions
- Typical diurnal courses due to the dependency of FS on APAR is obvious but, as expected, disappears with less vegetation cover

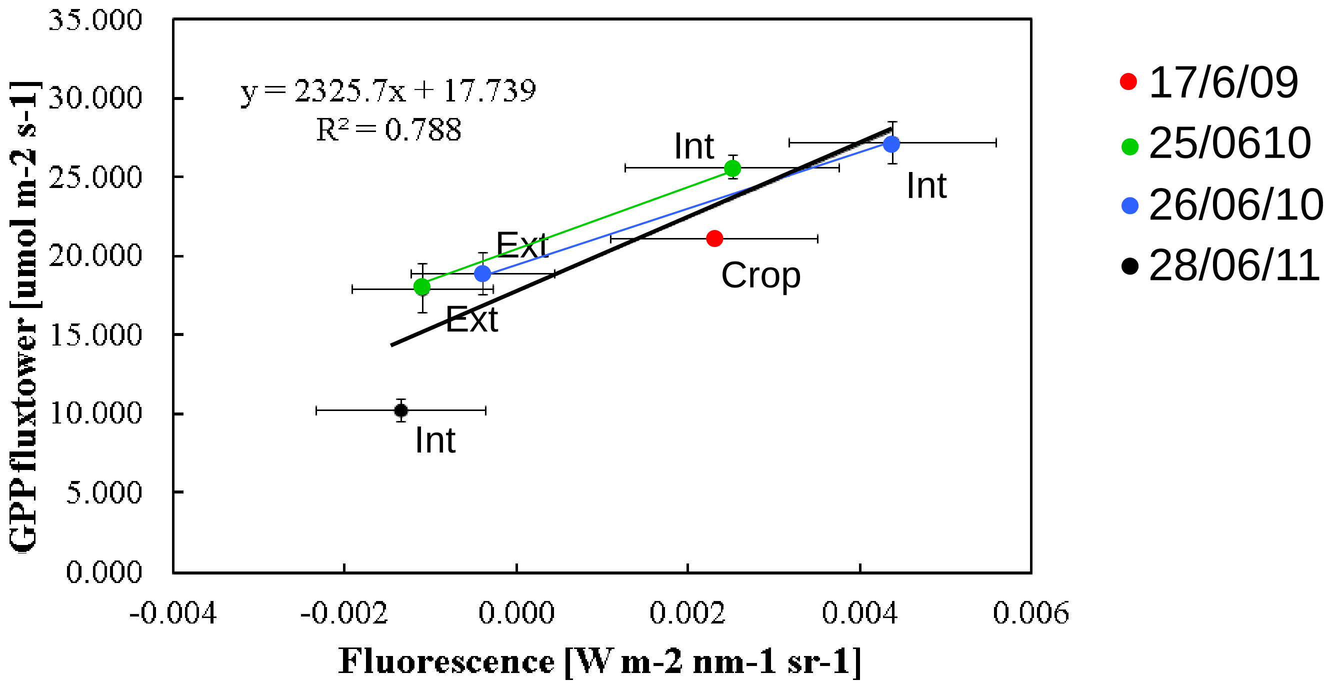





APEX Fluorescence Product
Quantity: Chlorophyll fluorescence
Background: APEX-fluorescence of non-vegetation as true color comp.
Testsite: Oensingen, 26 June 2010
0.0 0.07 0.15 [W m-2 sr-1 nm-1]

Fluorescence at regional level: Temporal domain

- Fluorescence vs. GPP measured on 3 eddy flux towers on 4 days
- Tower located in extensive/intensive grass and a rotating crop field
- APEX acquisitions carried out on 17/6/09, 25/6/10, 26/6/10, 28/6/11



Flux tower maintained and data kindly provided by: ETH-Zurich (N. Buchmann); ART (C. Ammann)

Main findings

– FS can be reliably retrieved from airborne instruments even under different atmospheric conditions

– First preliminary results based on APEX data show that FS has a relationsip to GPP

  – this is expected as FS and GPP both depend on APAR

– Temporal assessment of FS at regional level is still preliminary and requires further data and attempts

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Conclusions

- FS is an independent and complementary signal to characterize the function of vegetation and vegetated ecosystems
- Because FS is an emitted signal, the characterization of vegetation properties relies on less assumptions compared to reflectance based approaches
- Superimposing effects, e.g., instrumental errors and characteristics, atmospheric re-absorption must be properly addressed in retrieval schemes
- Most experiments right now focus on the FS emission at 760nm. It is however essential to concentrate on both peak emissions (680, 740nm) and to investigate other quenching mechanisms (NPQ) in parallel
- Data assimilation strategies must be developed to make full use of the FS signal in global carbon models

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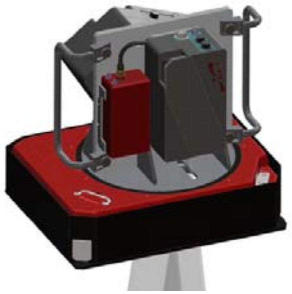
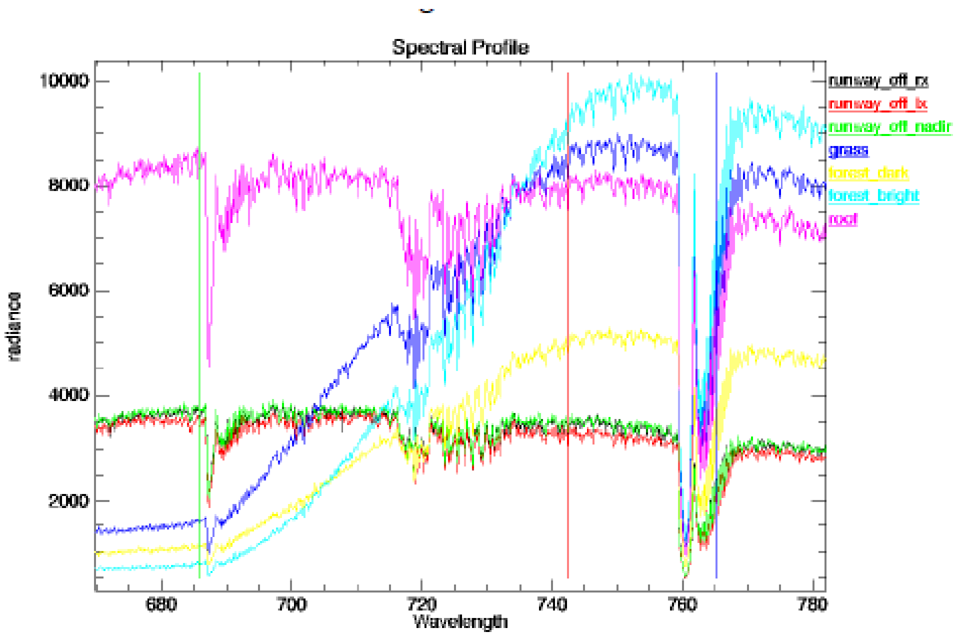
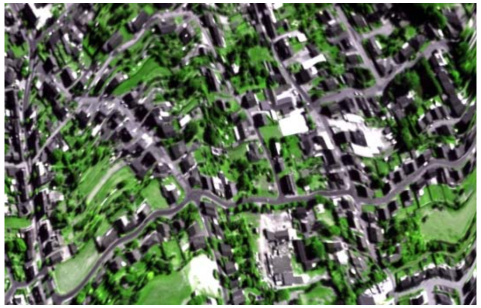
Outlook – use of dedicated fluorescence imagers

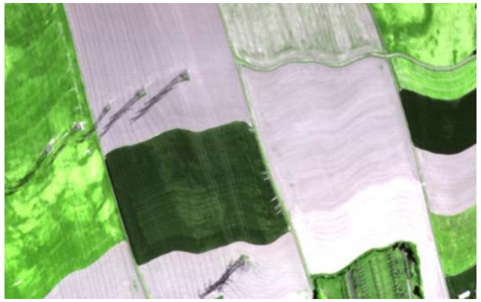
– New HyPlant sensor (Research center Juelich) was developed and first flown in the last weeks

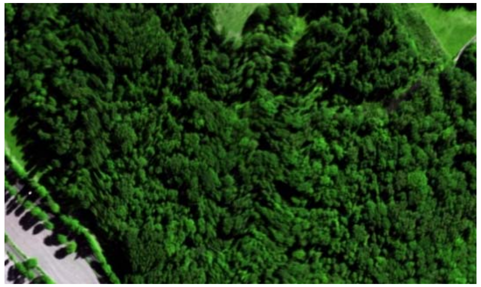
– HyPlant was especially developed to measure FS at 680/760nm and to test the FLEX sensor configuration





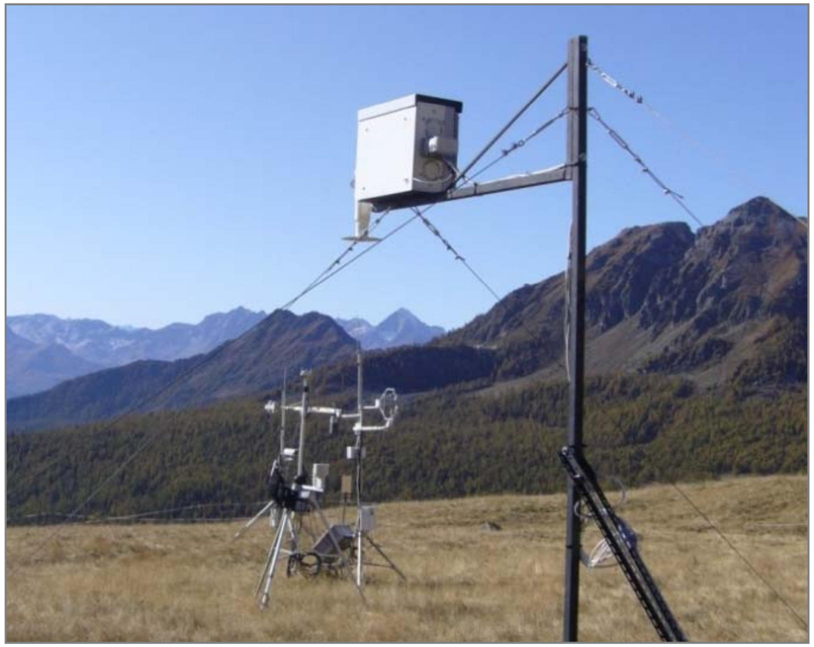






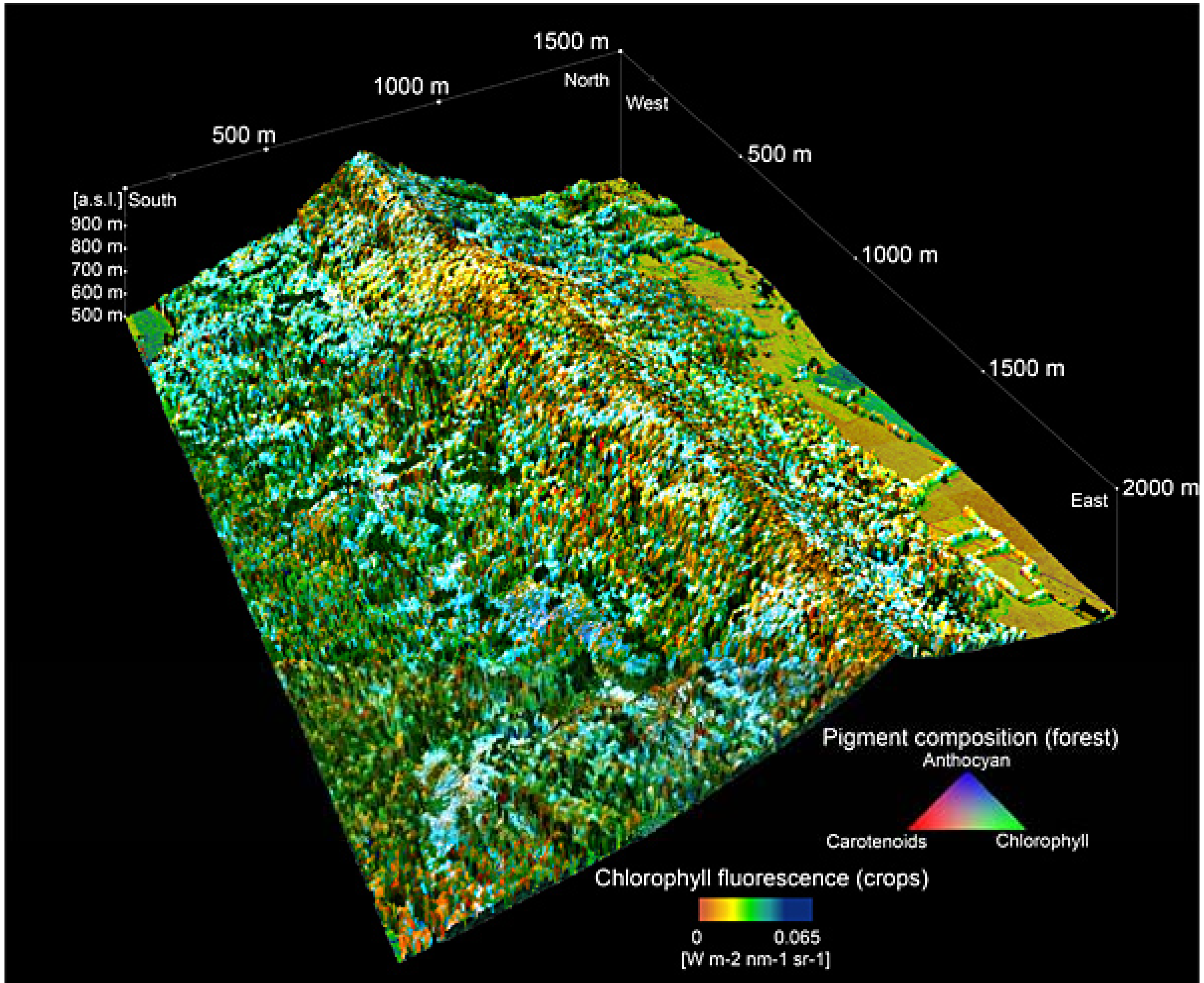
Outlook – long term monitoring of FS, NPQ, PS

- Long term monitoring of photosynthesis, APAR, FS and NPQ will reveal the interlink between all pathways on a diurnal and seasonal base
- Currently such systems are installed in several ecosystems in Italy (University of Milano) and Germany (research center Juelich)



Credits: Michol Rossini

Outlook – integrated data analysis



http://www.geo.uzh.ch/en/units/rsl/news/2012/200712

Thanks to

JÜLICH
FORSCHUNGSZENTRUM

Ulrich Schurr
Anke Schickling
Christine Plückers
Andre Erler
Karim Hamdi
Francisco Pinto
Roland Pieruschka

Centre de Recherche Public
Gabriel Lippmann

Thomas Udelhoven

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Michele Meroni
Roberto Colombo
Michol Rossini
Sergio Cogliati

LMD

Yves Goulas
Fabrice Daumard

IFAC

Giovanni Agati
Giovanna Cecchi

Jose Moreno
Luis Alonso

the whole CEFLES2 team and the FLEX MAG

esa

Thank you for your attention!