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Advanced Earth Science Products using APEX

Michael E. Schaepman and the APEX team

2012 HyspIRI Science Workshop
NASA Decadal Survey Mission

Content

Short update on APEX

Product suite

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  - Constraint priors directional effects correction
  - Large scale simulation (ESA Sentinel-2)
- Level 2 (≈ HyspIRI Level 4)
  - Mapping biospheric variables from radiance data using Bayesian optimization and coupled models
  - GPP estimates based on Fs_{yield} retrieval
  - Improved LUE estimates using pigments
  - Scale invariant retrieval of vegetation properties
- Level 3
  - Alpine ecosystem services (agronomic, cultural, pollination, soil C)
  - Using NO_2 vertical column density for policy validation
- Outlook

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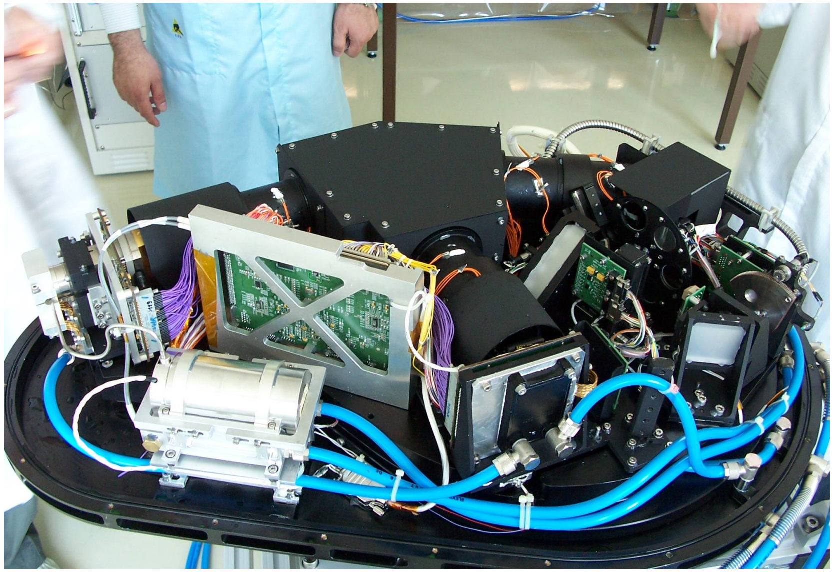
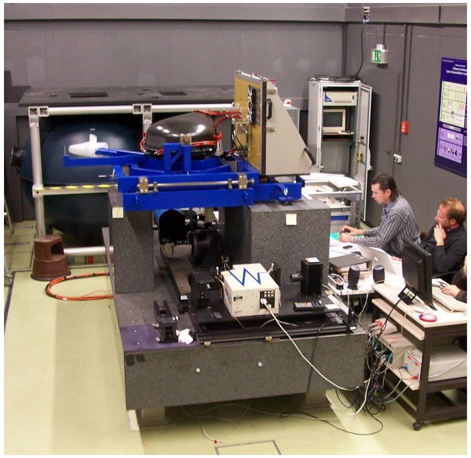
APEX – Airborne Prism Experiment





Short update on APEX

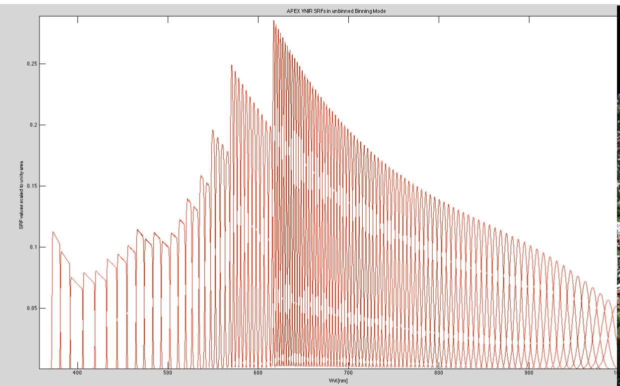
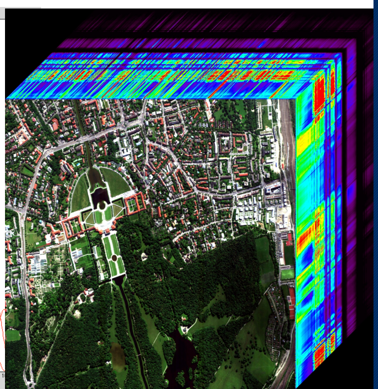
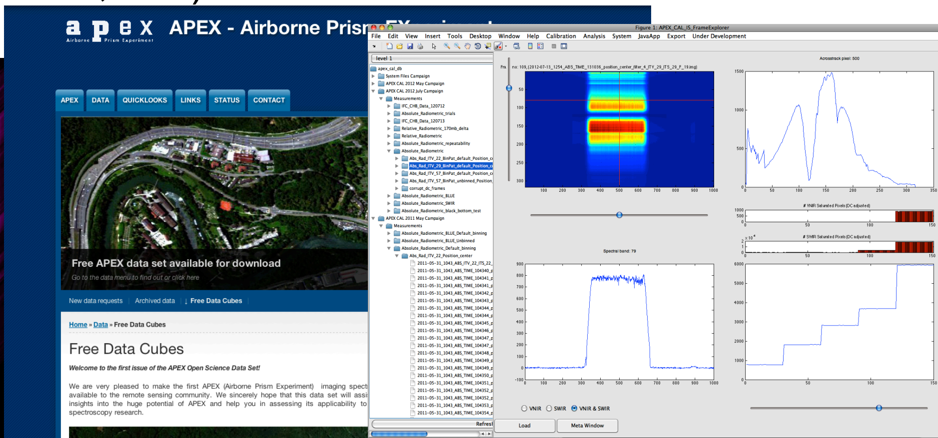
Successful and increasing data acquisition in Europe since 2009

Image data from 2011 (142 flight lines), and 2012 (116 flight lines) online (quicklooks on apex-esa.org)

Improvements in calibration, APEX (physically based) model, data processing, and archiving

Prospects for 2013ff are doubling to tripling data acquisition in Europe (and beyond)

APEX is outperforming much of the models and technologies currently available: next generation models and hardware are urgently needed (e.g., APEX can calibrate its Calibration Home Base, ASD FieldSpecs do not have sufficient spectral resolution for vicarious calibration, certain absorption features seen by APEX are not yet represented in models, etc.)!

Level 1: Constraint priors directional effects correction

Idea

- Minimize impact of directional effects on airborne imaging spectrometer data
- Normalize airborne acquisition observation/sun-angle geometries to nadir (later: predefined) geometries ('aNBAR')
- Minimize directional effects using image based information ('BRDF-correction')

Methods

- Select scattering ($BRDF_{iso,\ vol,\ geo}$) abundance classes from image data and correct image data using these classes as prior information to a kernel driven approach

Results

- 'BRDF' corrected image data (Weyermann, et al. (2012). *IEEE TGRSS*, in review)

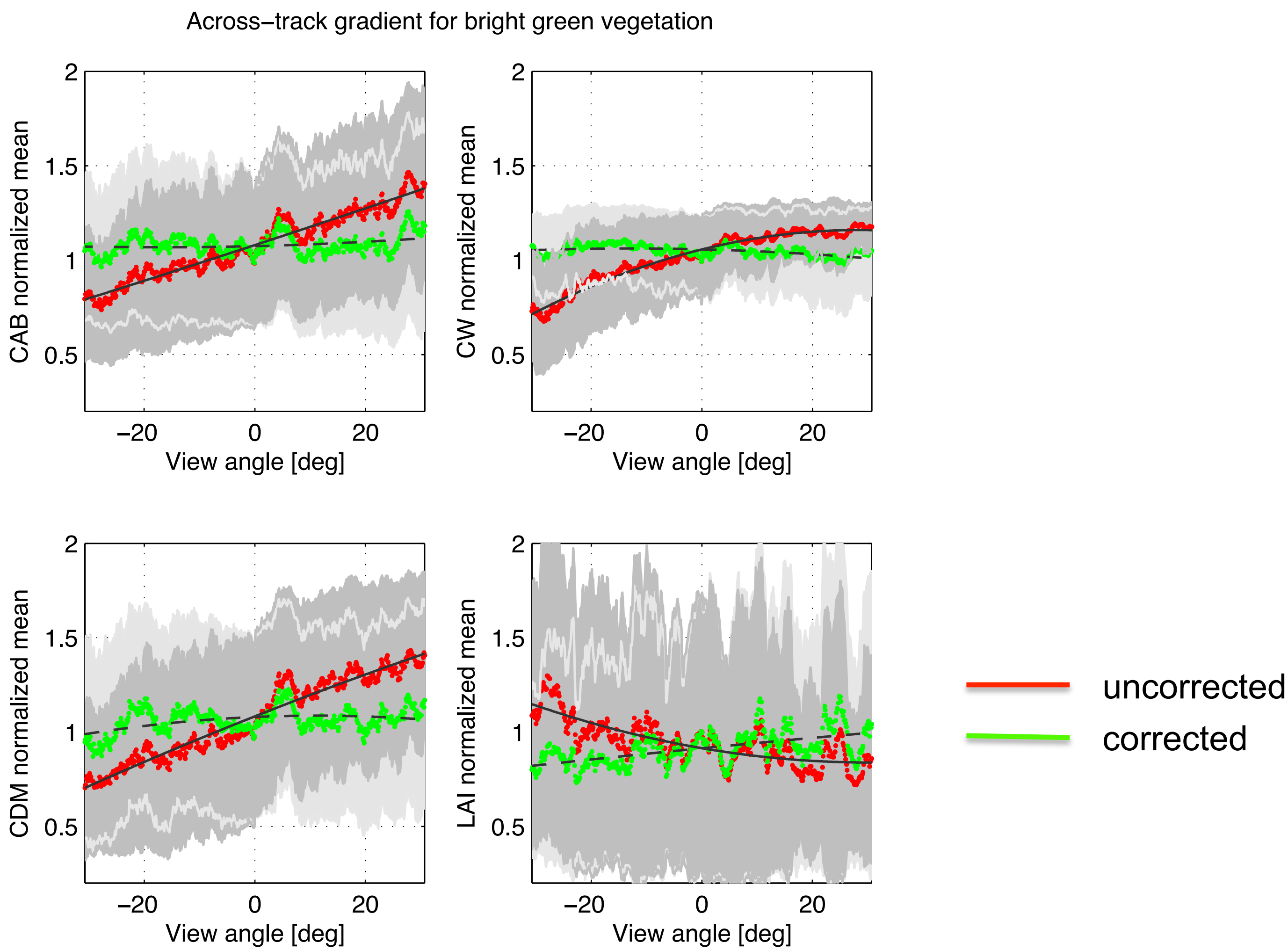
Outlook

- Implement operational approach, base prior estimates on RPV model inversion

Vegetation product differences on directional effects

Chl a/b

CDM



Weyermann et al. (2012), in review

Level 1: Large scale simulation (ESA Sentinel-2)

Idea

– Simulate a ‘full’ ESA GMES Sentinel-2 tile

Methods

– Next slide

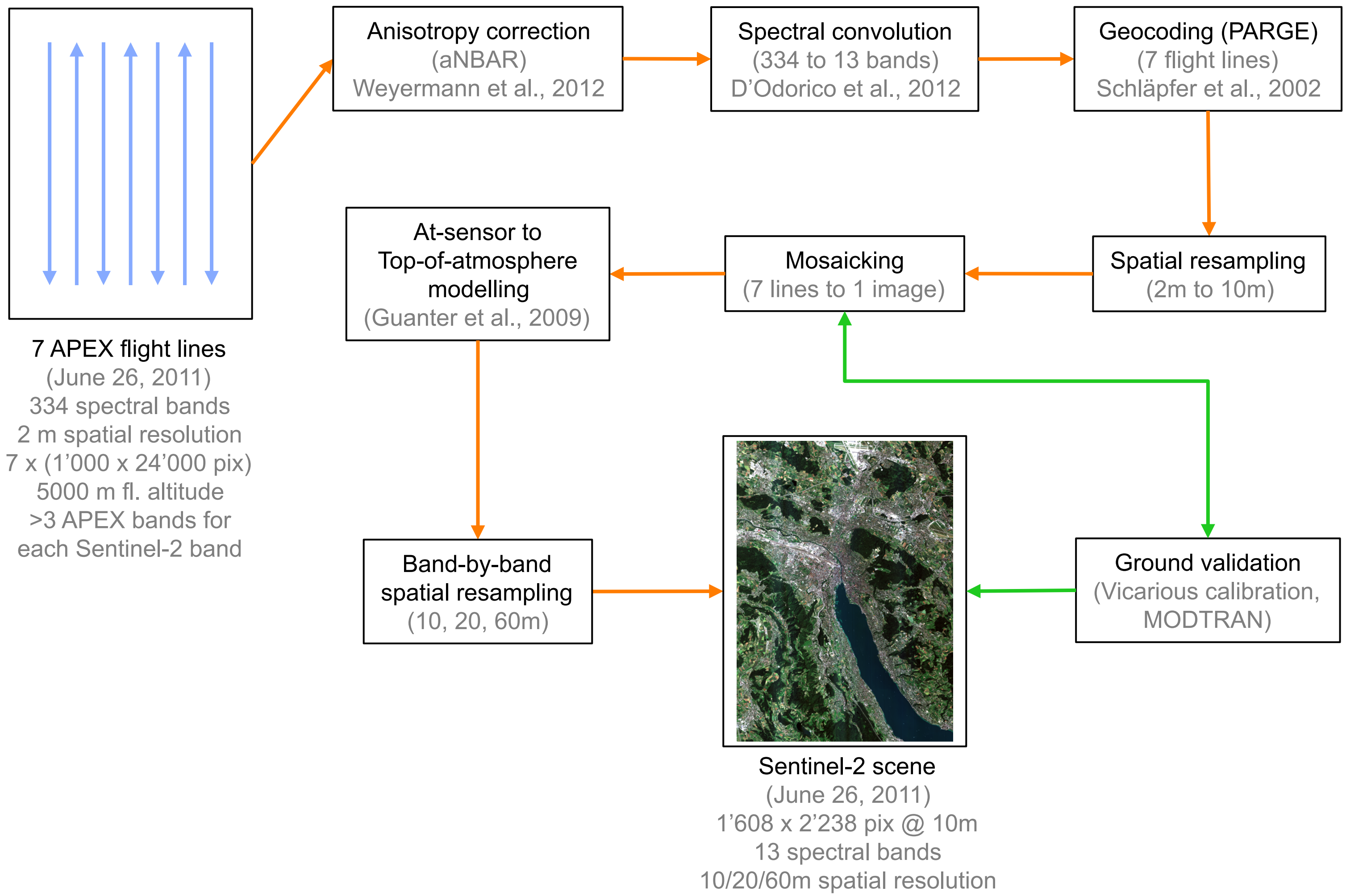
Results

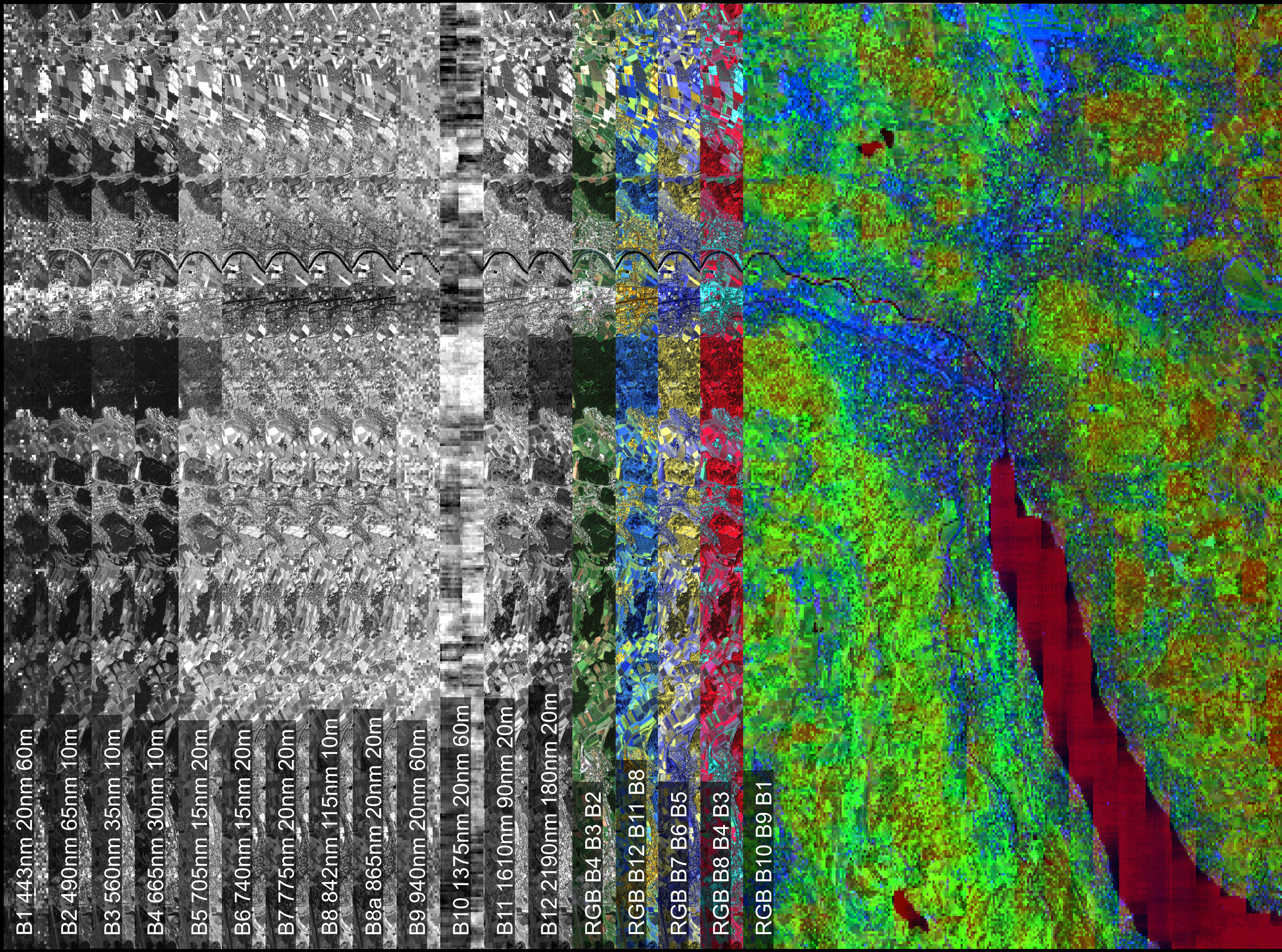
– Sentinel-2 scene, with almost realistic sun/observation angles (Laurent, et al. (2012). *RSE*, submitted)

Outlook

– Generating real data format (JPEG2000, NEdL ≈ compression noise & level)
– Normalization of geometrical-optical scattering
– Multitemporal simulation

Sentinel-2 simulation: methods





B1 443nm 20nm 60m
B2 490nm 65nm 10m
B3 560nm 35nm 10m
B4 665nm 30nm 10m
B5 705nm 15nm 20m
B6 740nm 15nm 20m
B7 775nm 20nm 20m
B8 842nm 115nm 10m
B8a 865nm 20nm 20m
B9 940nm 20nm 60m
B10 1375nm 20nm 60m
B11 1610nm 90nm 20m
B12 2190nm 180nm 20m
RGB B4 B3 B2
RGB B12 B11 B8
RGB B7 B6 B5
RGB B8 B4 B3
RGB B10 B9 B1

Level 2: Mapping biospheric variables from radiance data using Bayesian optimization and coupled models

Idea

– Use coupled models to retrieve as many free vegetation parameters from radiance data as possible

Methods

– Next slide

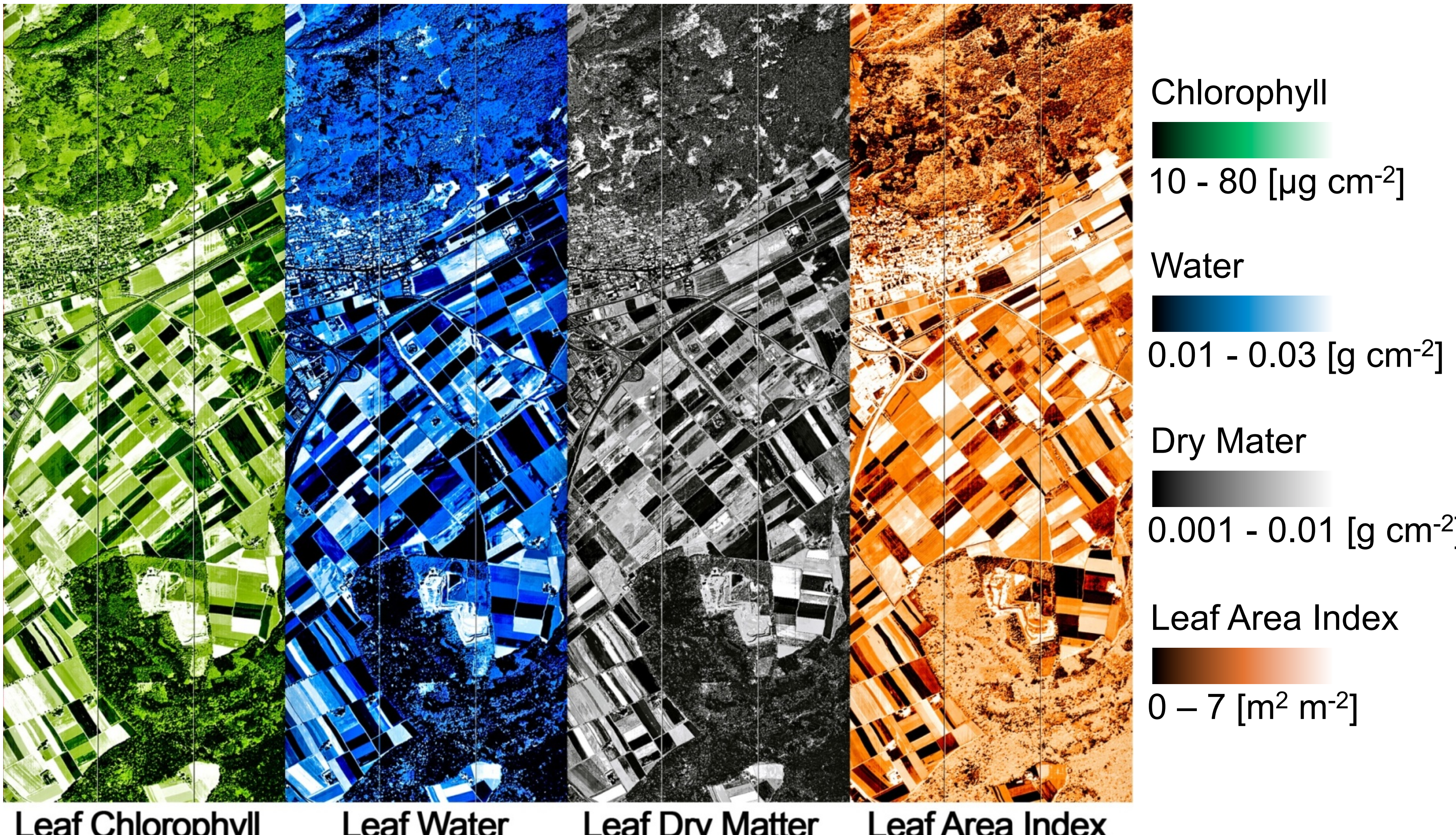
Results

– 2–7 free vegetation parameter estimated at much improved accuracy! (Laurent, et al. (2012). *RSE*, submitted)

Outlook

– Ground truthing within spatial neighborhood
– Cost of *a priori* knowledge to be determined
– Estimates of probability distribution functions to be used as priors
– Estimate effects of biased and informative priors

‘Conventional’ inversion (LUT approach from refl. data)



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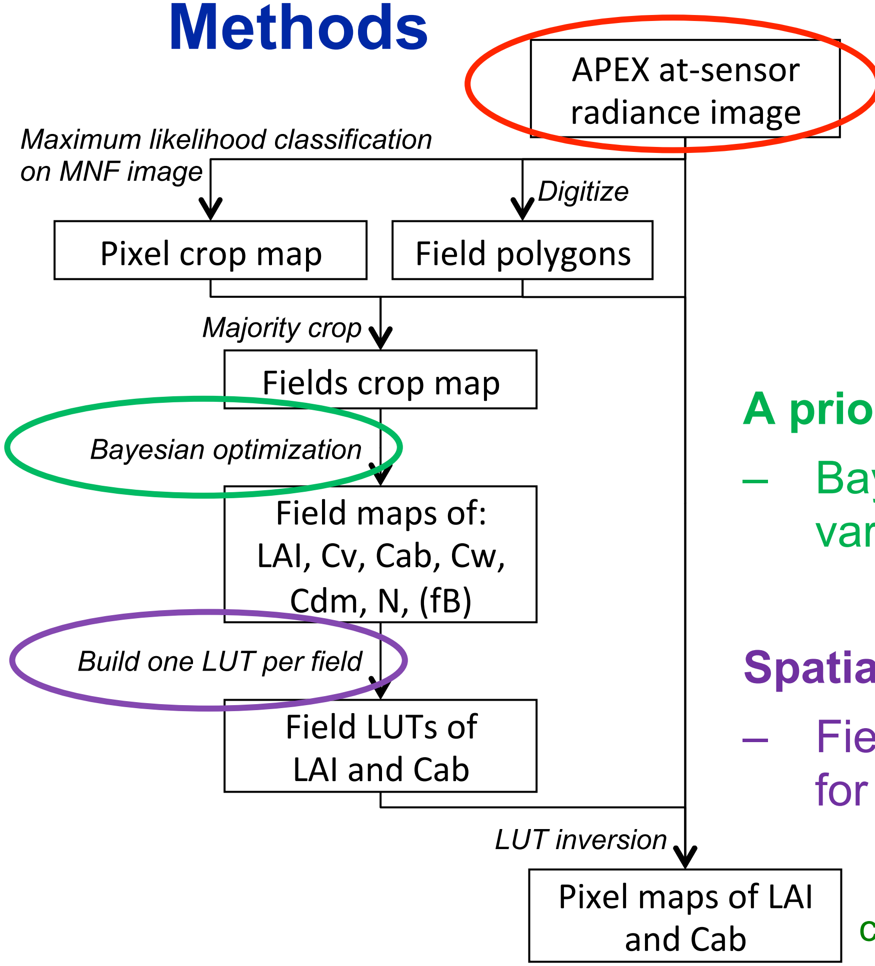
Methods



Model coupling

- SLC: PROSPECT & 4SAIL2 with canopy clumping
- MODTRAN 4: between ground level and APEX flight height

A priori data for each crop type

- Bayesian optimization of 6–7 variables for each field

Spatial constraint at field level

- Field-specific LUT inversion for LAI and Cab

$$\chi^2 = \tfrac{1}{2}\underbrace{(\mathbf{L}_o - \mathbf{L})^T \mathbf{C}_o^{-1} (\mathbf{L}_o - \mathbf{L})}_{\text{Radiometric cost}} + \tfrac{1}{2}\underbrace{(\mathbf{v}_a - \mathbf{v})^T \mathbf{C}_a^{-1} (\mathbf{v}_a - \mathbf{v})}_{\text{A priori cost}}$$

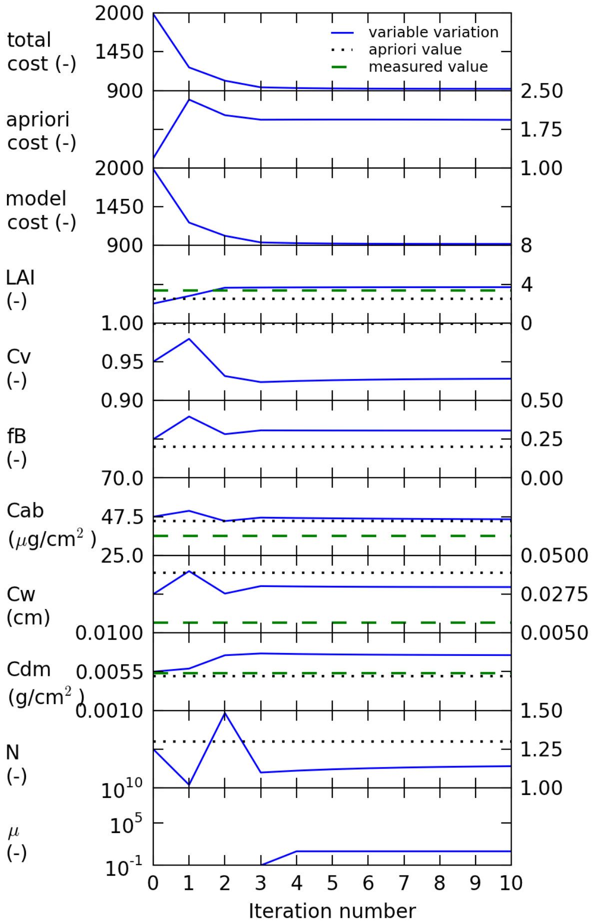
Observation covariance matrix ($\mathbf{C}_o$)

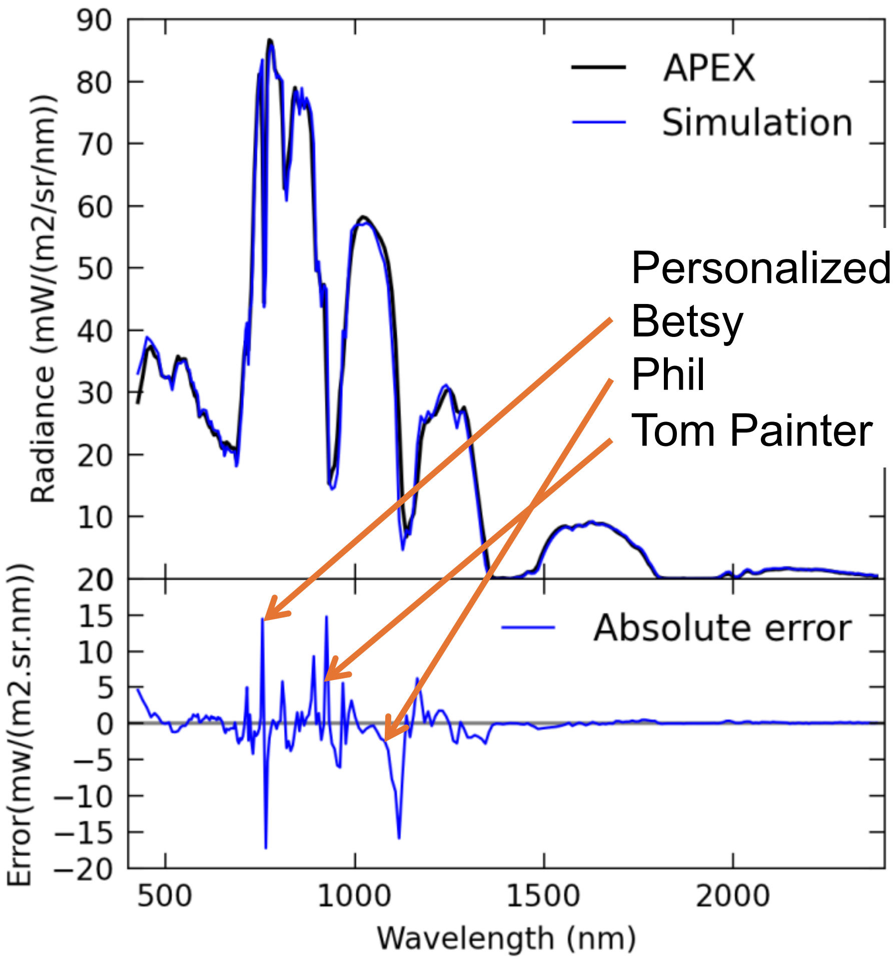
A priori covariance matrix ($\mathbf{C}_a$)

Radiometric cost

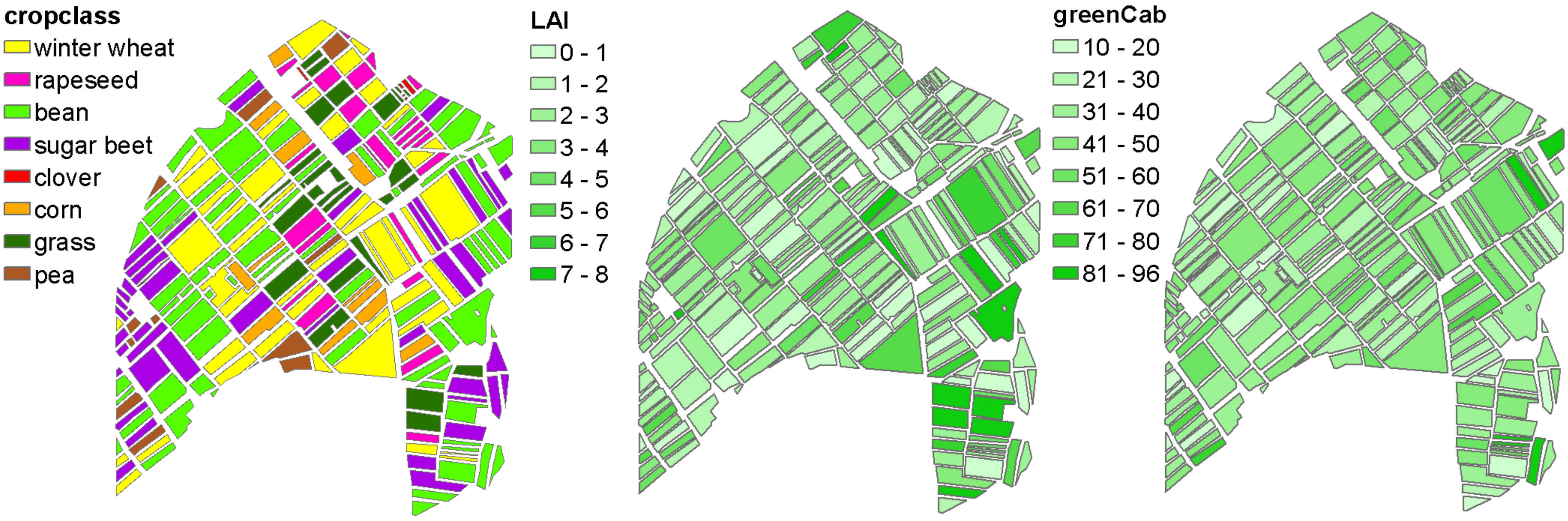
A priori cost

Variation of costs, variables, and damping factor



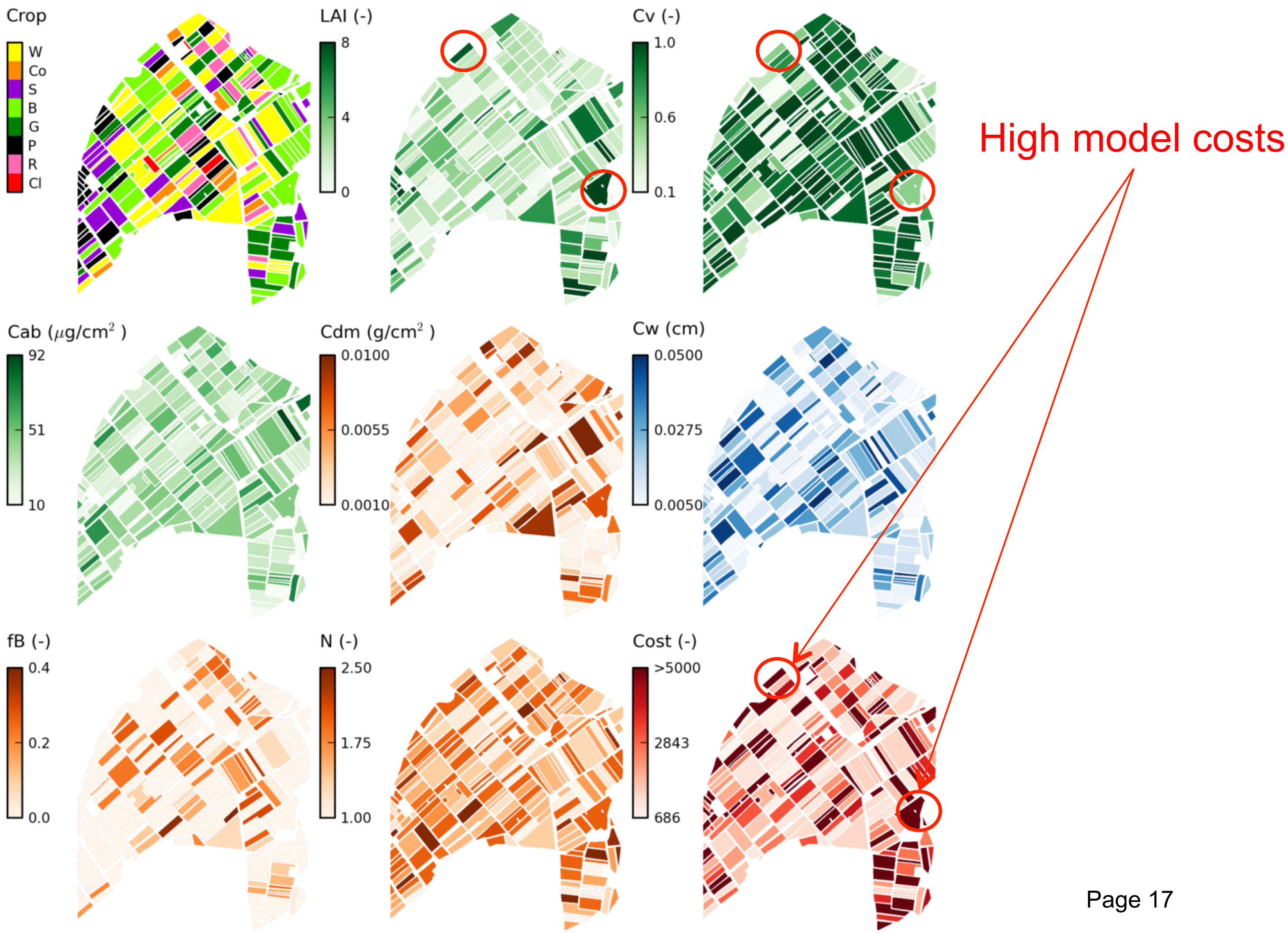


Land cover specific retrievals

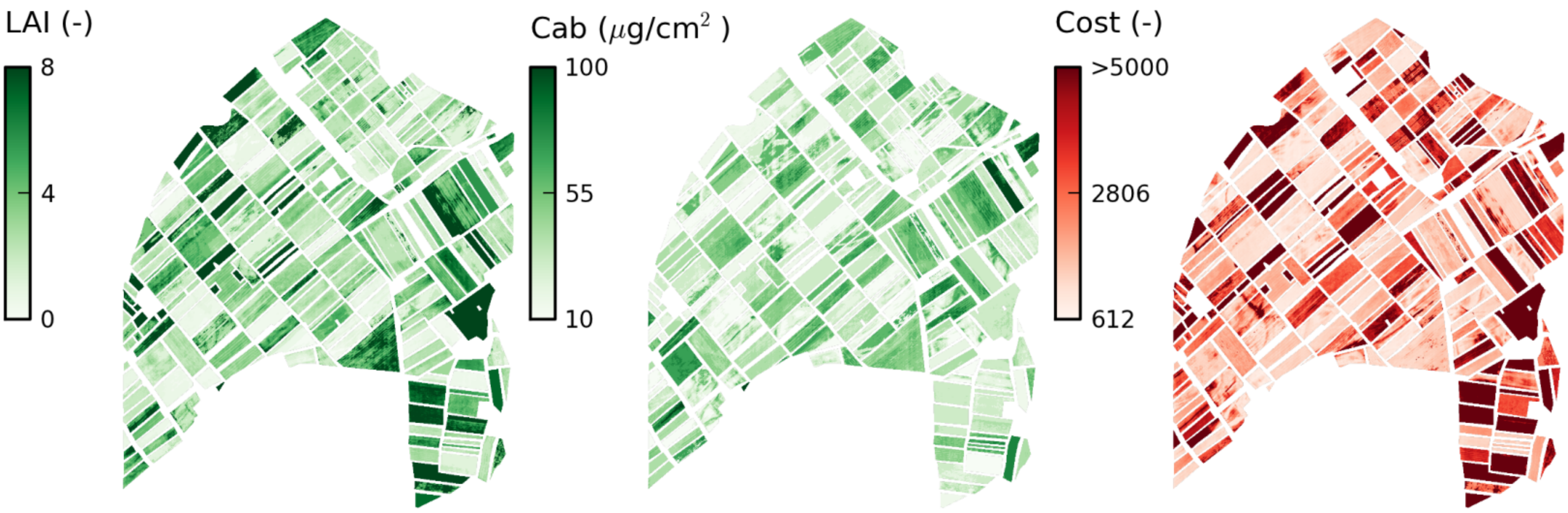


Maps of crop type, estimated LAI and Cab for the fields in the study area

Bayesian optimization for agricultural fields



Results: Field-specific LUT inversion of LAI and Cab



Laurent et al., (2012), RSE, in review

Level 2: GPP estimates based on Fs_{yield} retrieval

Idea

– Improve GPP estimates (PAR x fAPAR x LUE) using Fs_{yield} (in place of $LUE_{land\_cover=const}$)

Methods

– Next slide

Results

– Large scale mapping of GPP using Fs_{yield}

Outlook

– Further refine method by including pigments

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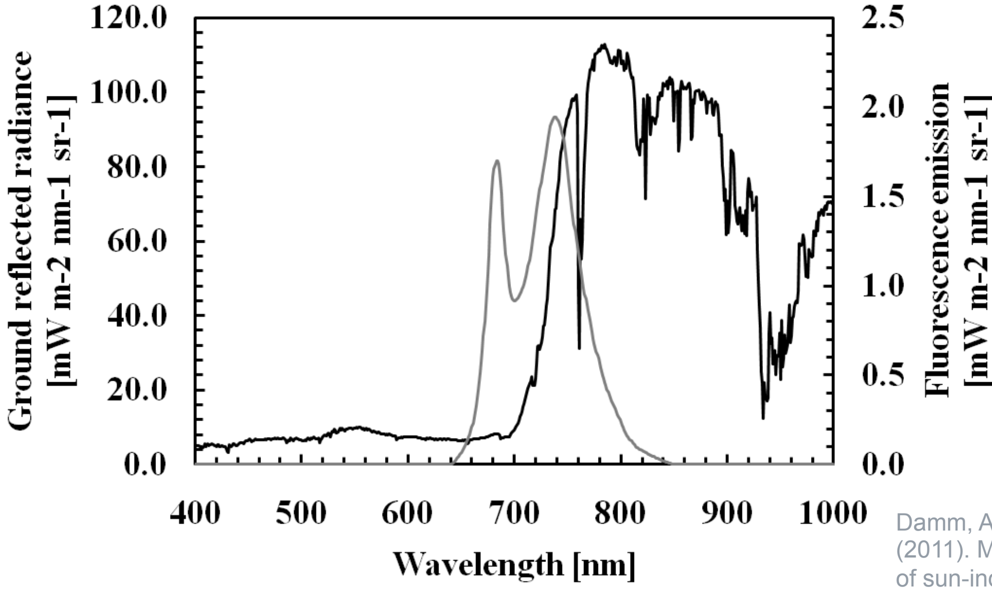
APEX products – fluorescence

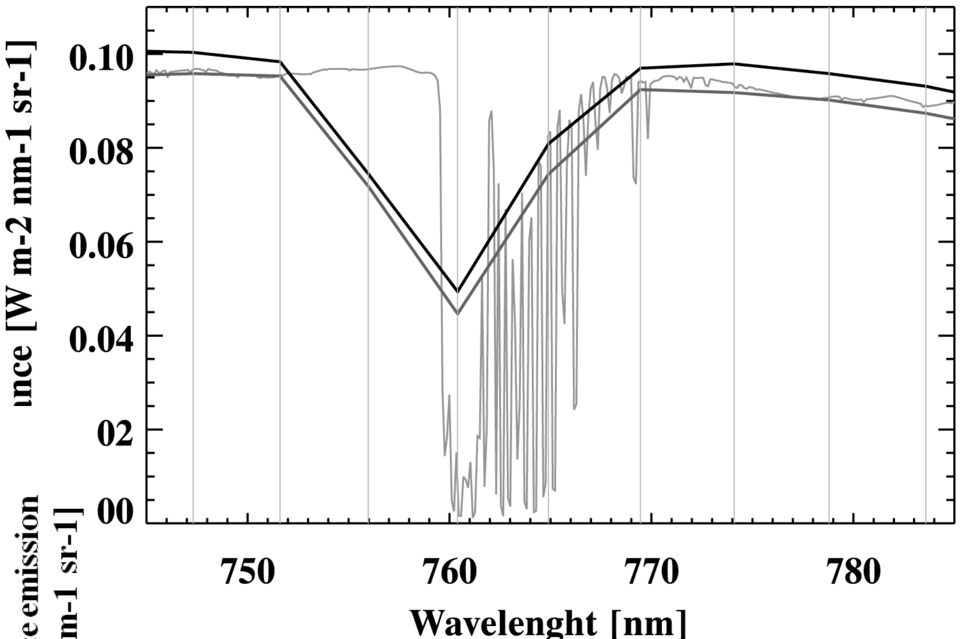
Approach (adapted from Guanter 2010 JGR):

- MODTRAN5 to simulate LUT's of L_{Path}, E, T, S
- 3FLD method to relate R in- / outside of the band
- Use of reference targets (bare soil) to constrain FS retrieval



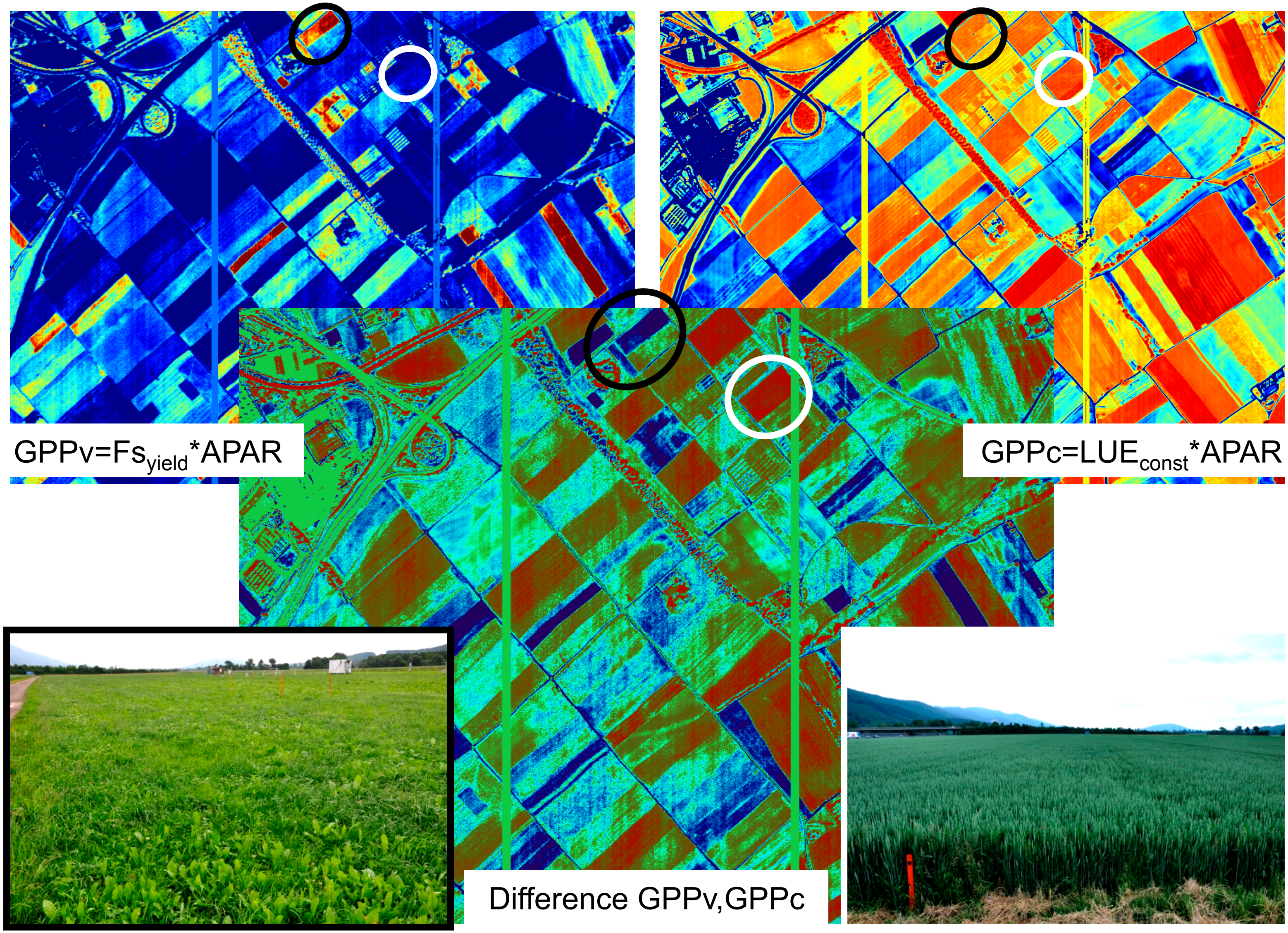
black: APEX

grey: MODTRAN (0.1nm and APEX resolution)

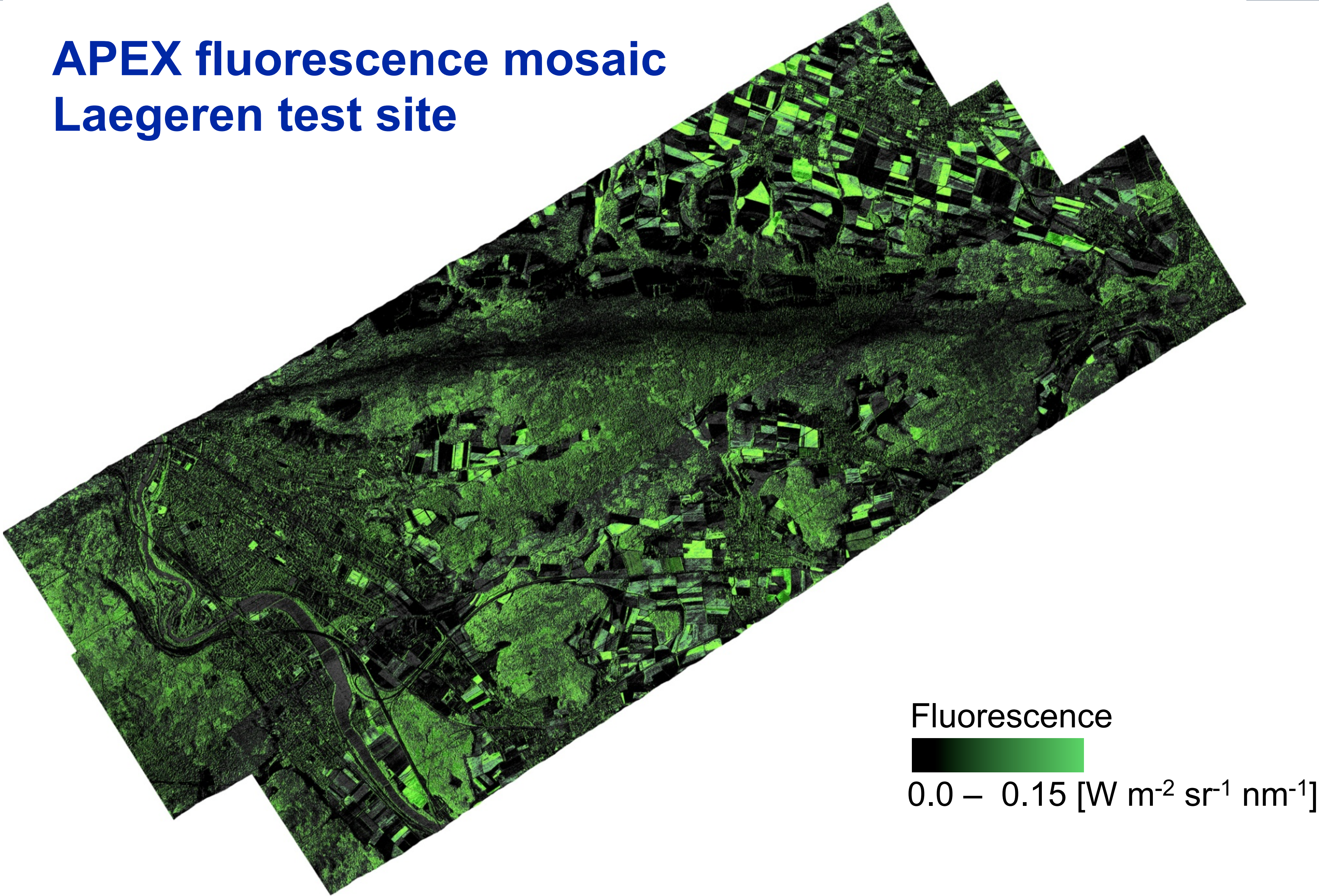


$$
\begin{cases} L_i = L_i^p + \dfrac{\left(E_i^0 \cdot \frac{R_i}{\pi} + Fs_i\right) \cdot T_i}{1 - S_i \cdot R_i} \\ L_o = L_o^p + \dfrac{\left(E_o^0 \cdot \frac{R_o}{\pi} + Fs_o\right) \cdot T_o}{1 - S_o \cdot R_o} \end{cases}
$$

Damm, A., Erler, A., Hillen, W., Meroni, M., Schaepman, M.E., Verhoef, W., & Rascher, U. (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


$GPPv=Fs_{yield}*APAR$
$GPPc=LUE_{const}*APAR$
Difference GPPv,GPPc

APEX fluorescence mosaic Laegeren test site



Level 2: Improved LUE estimates using pigments

Idea

– Improve GPP estimates (PAR x fAPAR x LUE) using pigments

Methods

– Improving LUE by using PRI in combination with pigments

Results

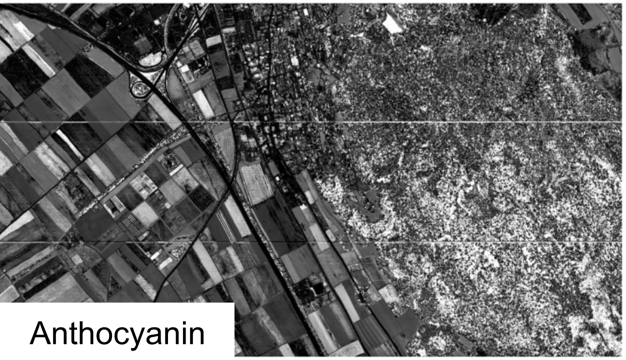
– Work in progress

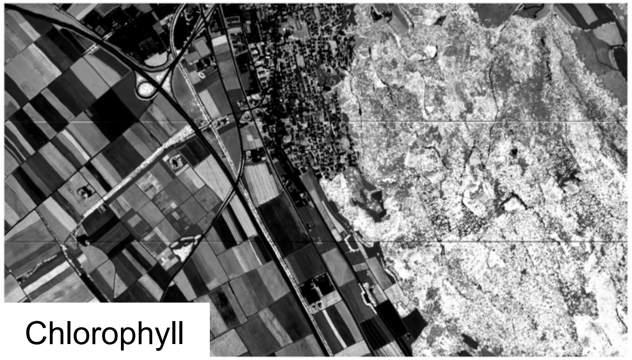
Outlook

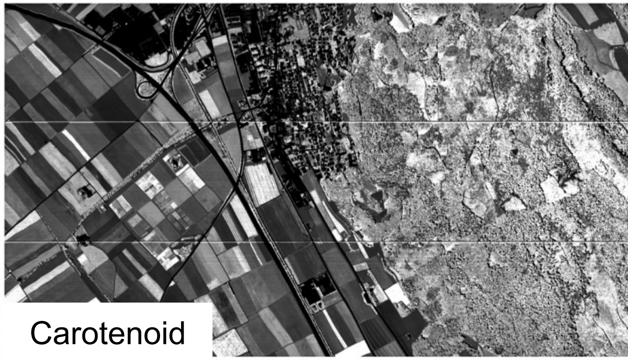
– Diurnal and phenological cycles measurements of pigments and pigment pool shifts
– Use light acclimation of leaf traits with time kinetics (long: LMA & N; medium: Chl a/b, Car/Chl; short: fluorescence (F_v/F_m)) (cf Hallik et al. (2012), Plant Biology)

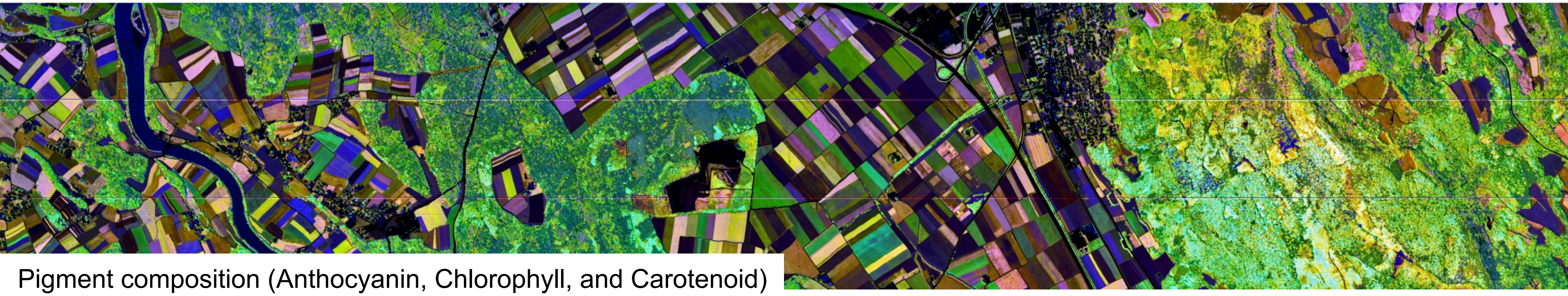
Pigment retrieval (modified after Gitelson)


APEX-CIR


Anthocyanin


Chlorophyll


Carotenoid


Pigment composition (Anthocyanin, Chlorophyll, and Carotenoid)

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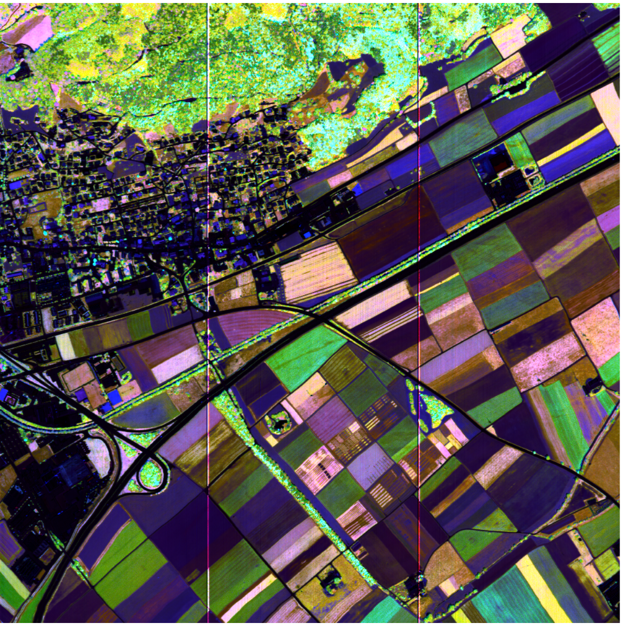
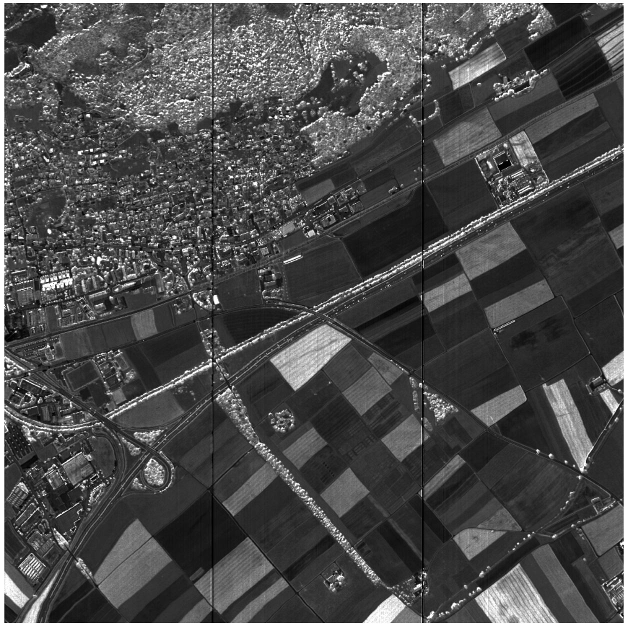
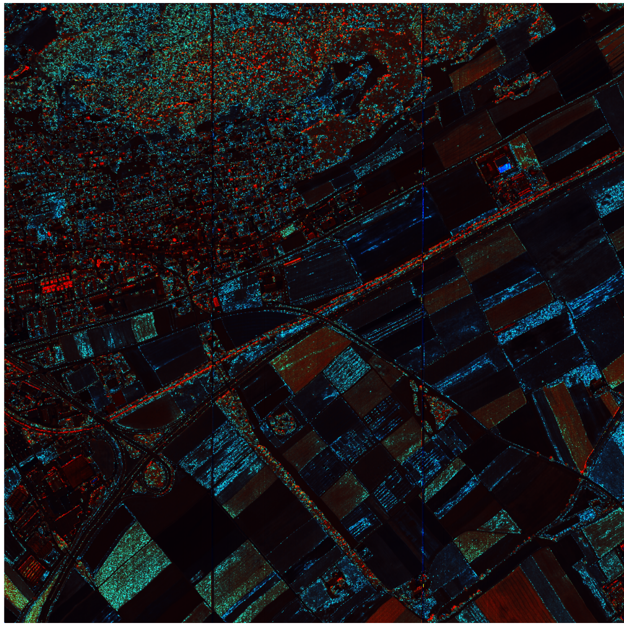
Towards improved pigment estimates


False color pigment composition


Chlorophyll/Carotenoid relation


Fractions of Chl/Car, Chl/Ant, Car/Ant

Level 2: Scale invariant retrieval of vegetation properties

Idea

- Use ecological concepts of catastrophic shifts, criticality, and scale invariance in combination with physical models in remote sensing

Methods

- Next slide

Results

- Retrieval of vegetation parameters in all relevant dimensions (spectral, spatial, temporal, directional) at their typical length scale.
- First results are very promising! Validation requires spatially extended ground truth

Outlook

- High dimensional data only available with HyspIRI, EnMap, etc.!
- Coupling of physical approaches (ecology and Earth observation)

Combining concepts of Earth observation with ecology

Catastrophic shifts

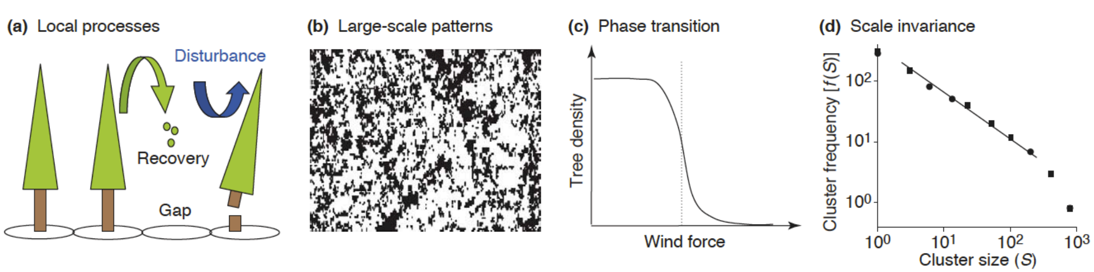
– Sudden and drastic change in the state of the system in space or time

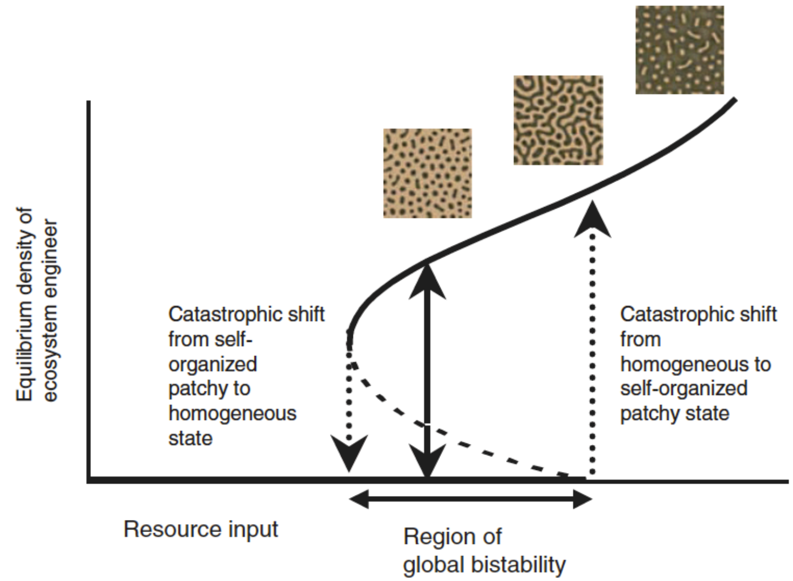
Criticality

– State of the system is critical, if poised at a phase transition

Scale invariance

– Distribution characterized by a power law is said to be scale invariant





Scheffer et al., Nature, 2001; Rietkerk et al., Science, 2004; Pascual et al., Trends in EE, 2005

Dimensionality of remote observations

Optical remote observations are dependent on spatial, spectral, temporal, angular, and polarization sampling approaches

Often, methods are implemented functioning at scale independence in a certain range of the dimensions observed (spectral invariants (Knyazikhin et al., 2010), BRDF kernels (GlobAlbedo, Lewis et al., 2012), etc.)

If processes are observed at inappropriate scales, scale mismatches will occur and may lead to feedback omissions.

Assessing new feedback mechanisms substantially increases our understanding of the functioning of the system Earth (shrub shading (Blok et al., 2012); increased light absorption (Pinty et al. 2012)).

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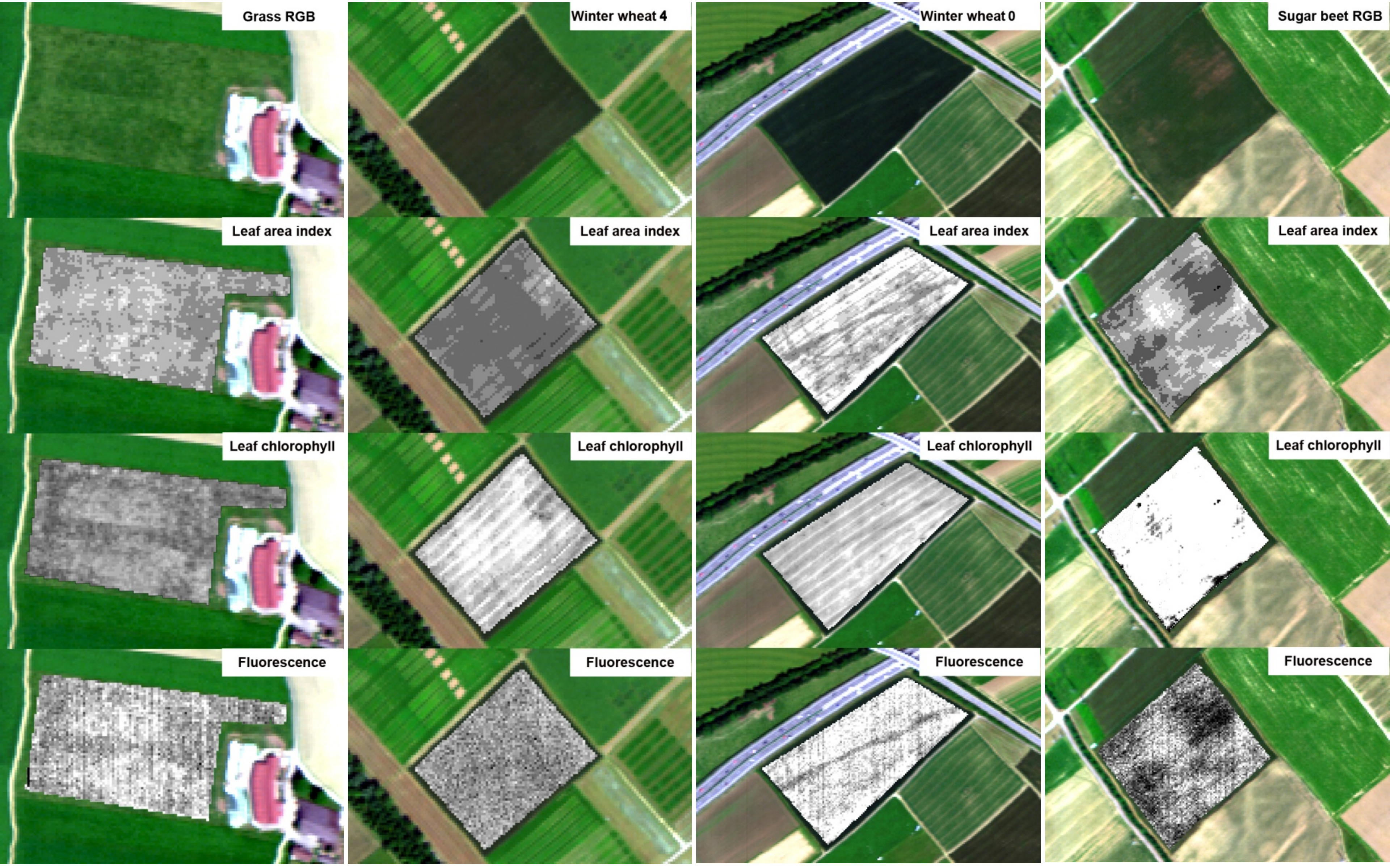
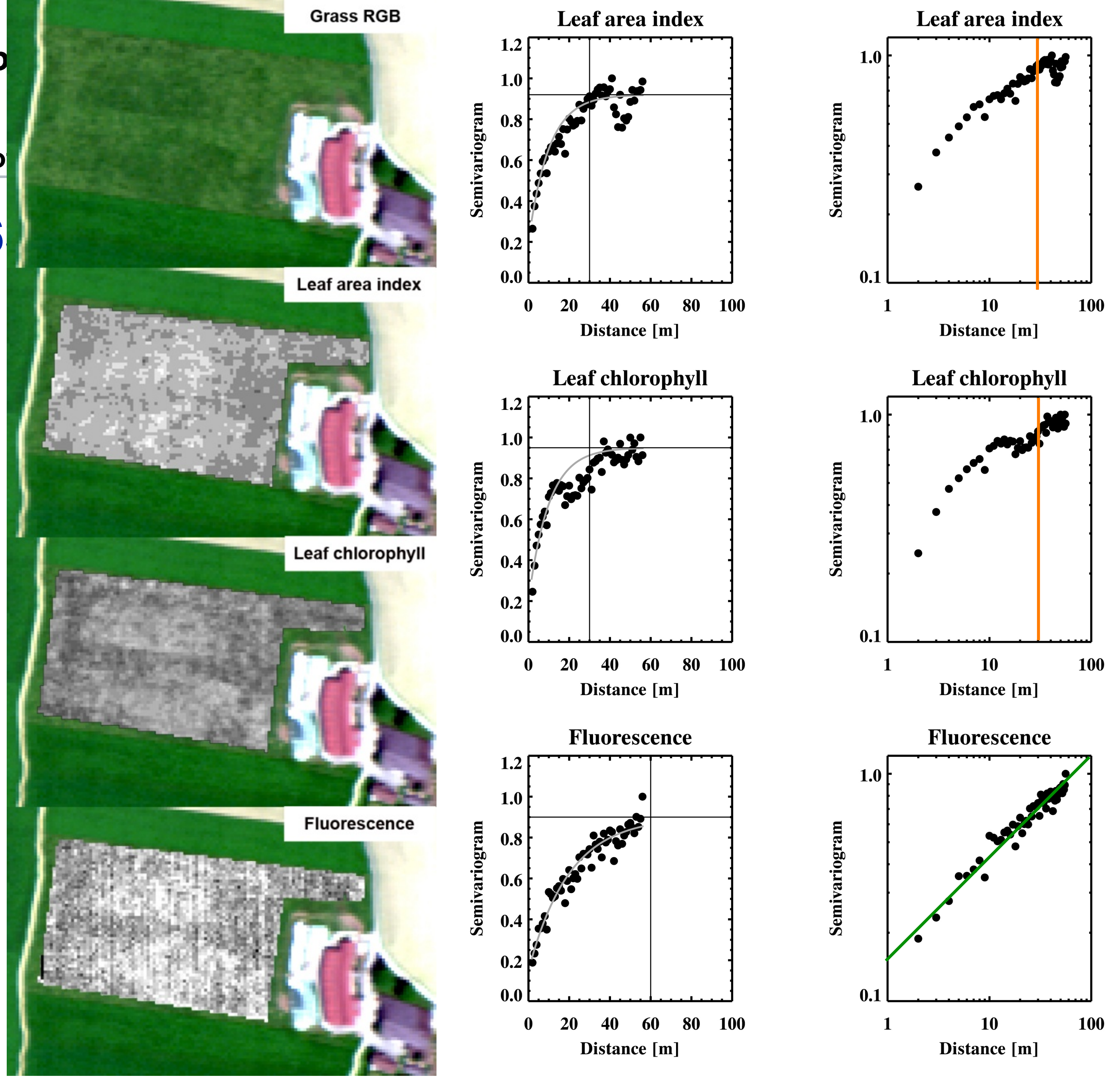
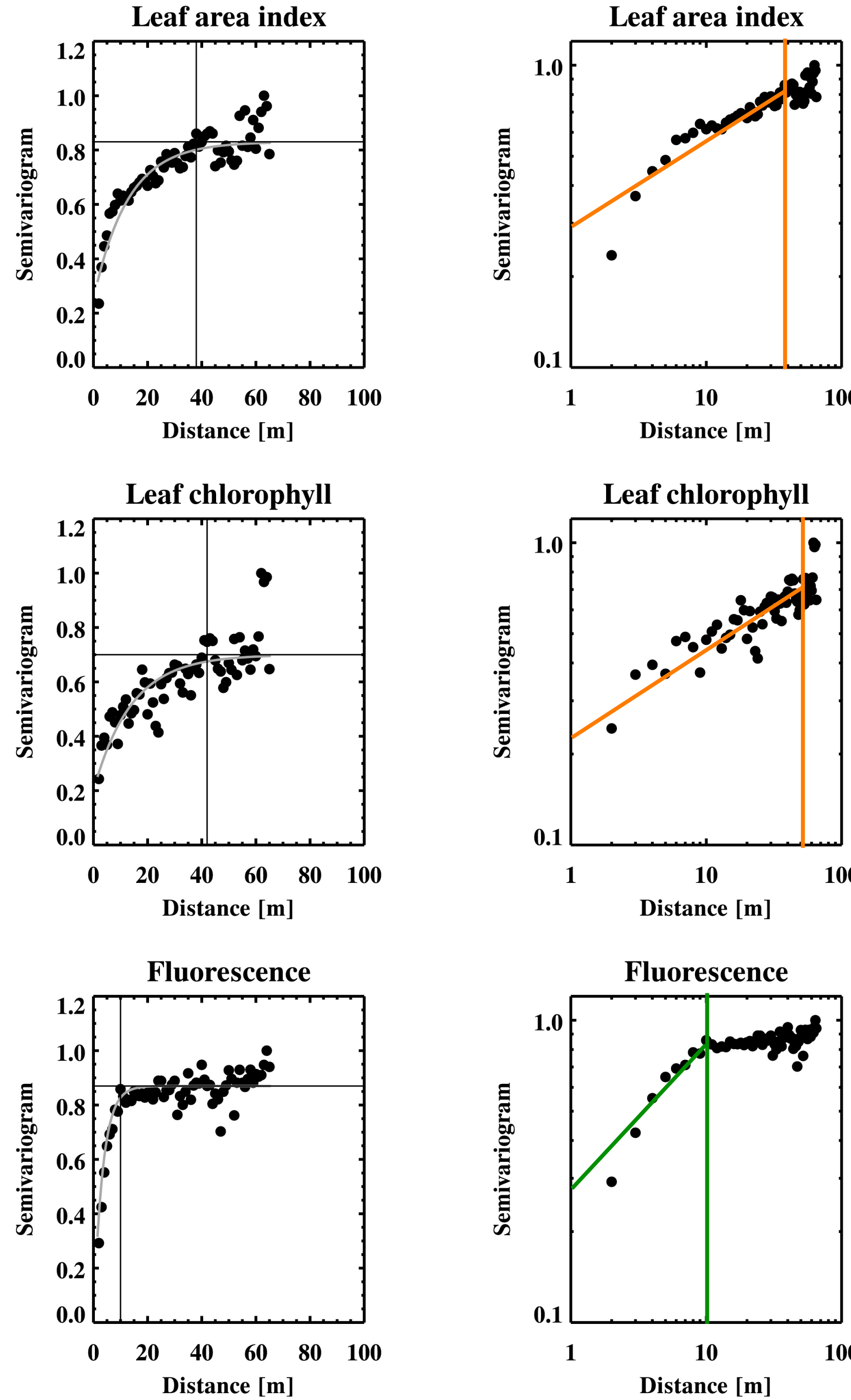


Field 16
Grass



Field 0 Winter Wheat



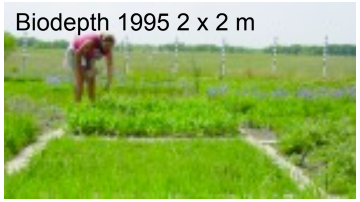
Effects of scale: regionalization

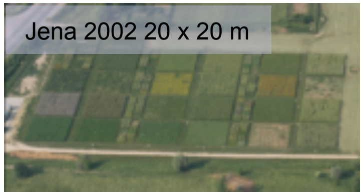
Much change is driven by feedback mechanisms that take place at spatial and temporal scales that are smaller than those currently incorporated in global models (e.g. characteristic length scale is mixed).

This severely limits our ability to predict, mitigate and adapt to environmental change at local and regional scales.

Global modelling, reference sites and data will gradually converge to spatial and temporal scales where processes at their characteristic length scale can be compared (scale invariance is the goal).

However, spatio-temporal homogeneity is a concern (53 of 138 FLUXNET sites correspond (r^2=.82) well wrt. satellite observations and ground measurements (Cescatti et al., 2012, RSE)).





Vegetation structure

Vegetation structure at shoot (canopy) level is very poorly defined (eg is not well expressed in single/multiple SI variables) and therefore is its measurement tricky!

Photos: © http://www.ursusnadeschkin.ch/

3DVegLab

Reconstruct vegetation canopies using TLS/ALS

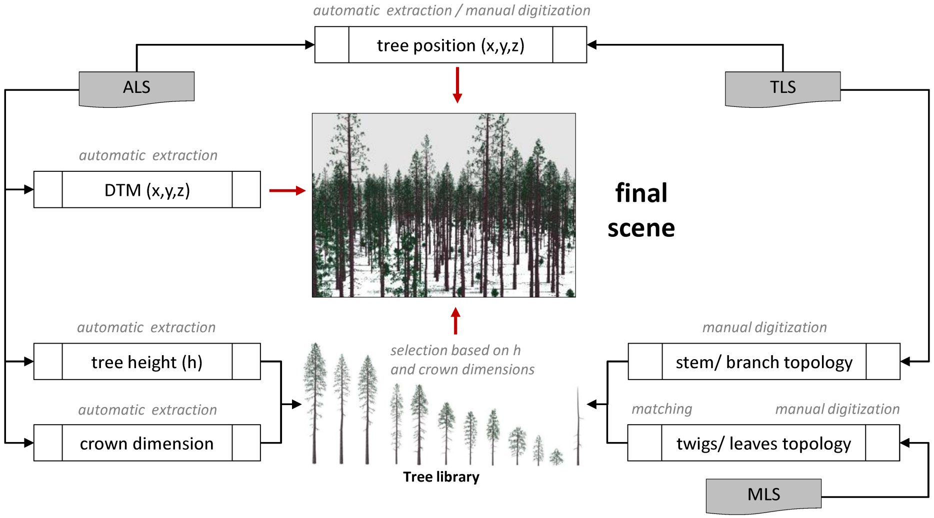
Measure LOP (Leaf Optical Properties) and reconstruct trees

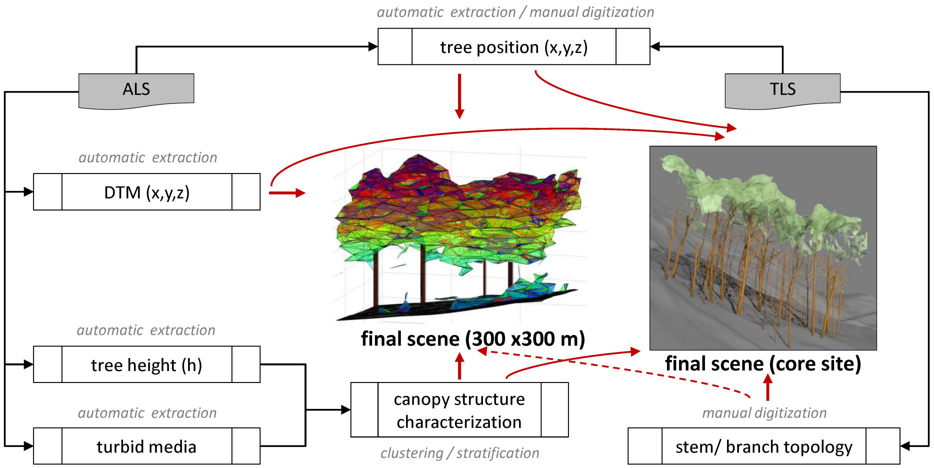
Collect 'all' (!) Earth observation data above sites

Implement toolbox using 1D and 3D RTM approaches (BEAM: librat, DART)

Make everything open source (ca. spring 2013)

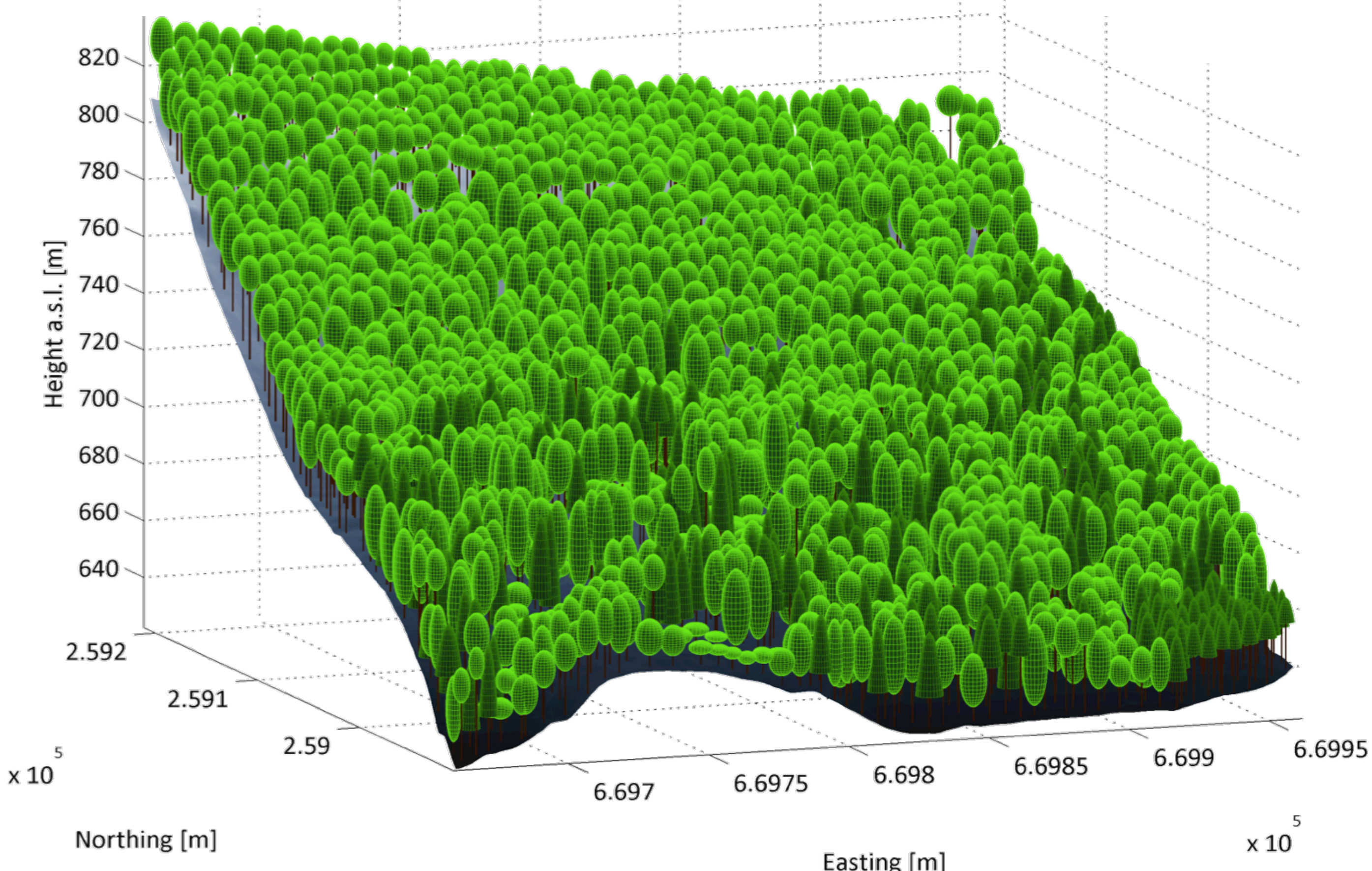
(ESA STSE project: UZH, UCL, TU Vienna, CESBIO, Netcetera AG)

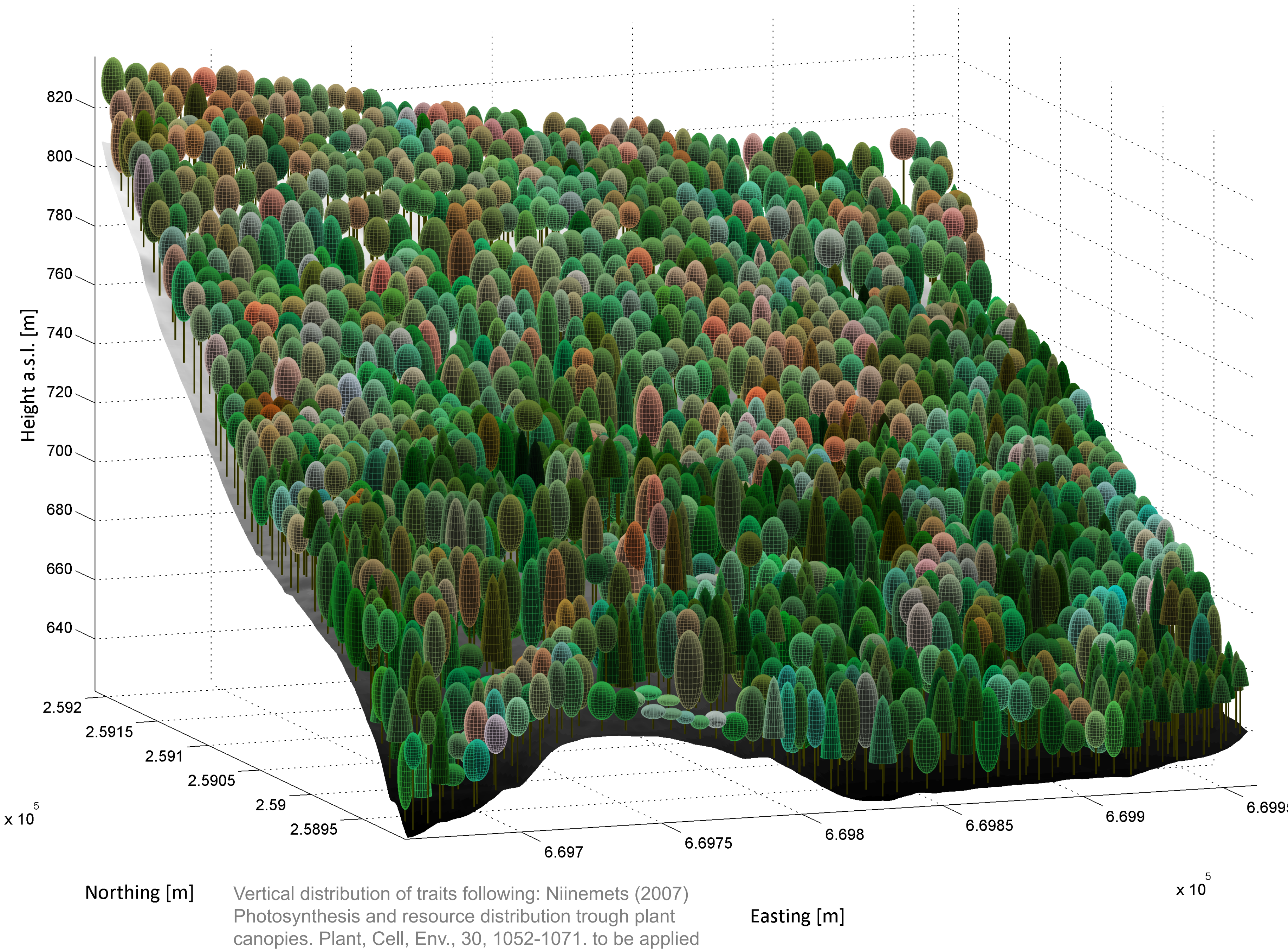


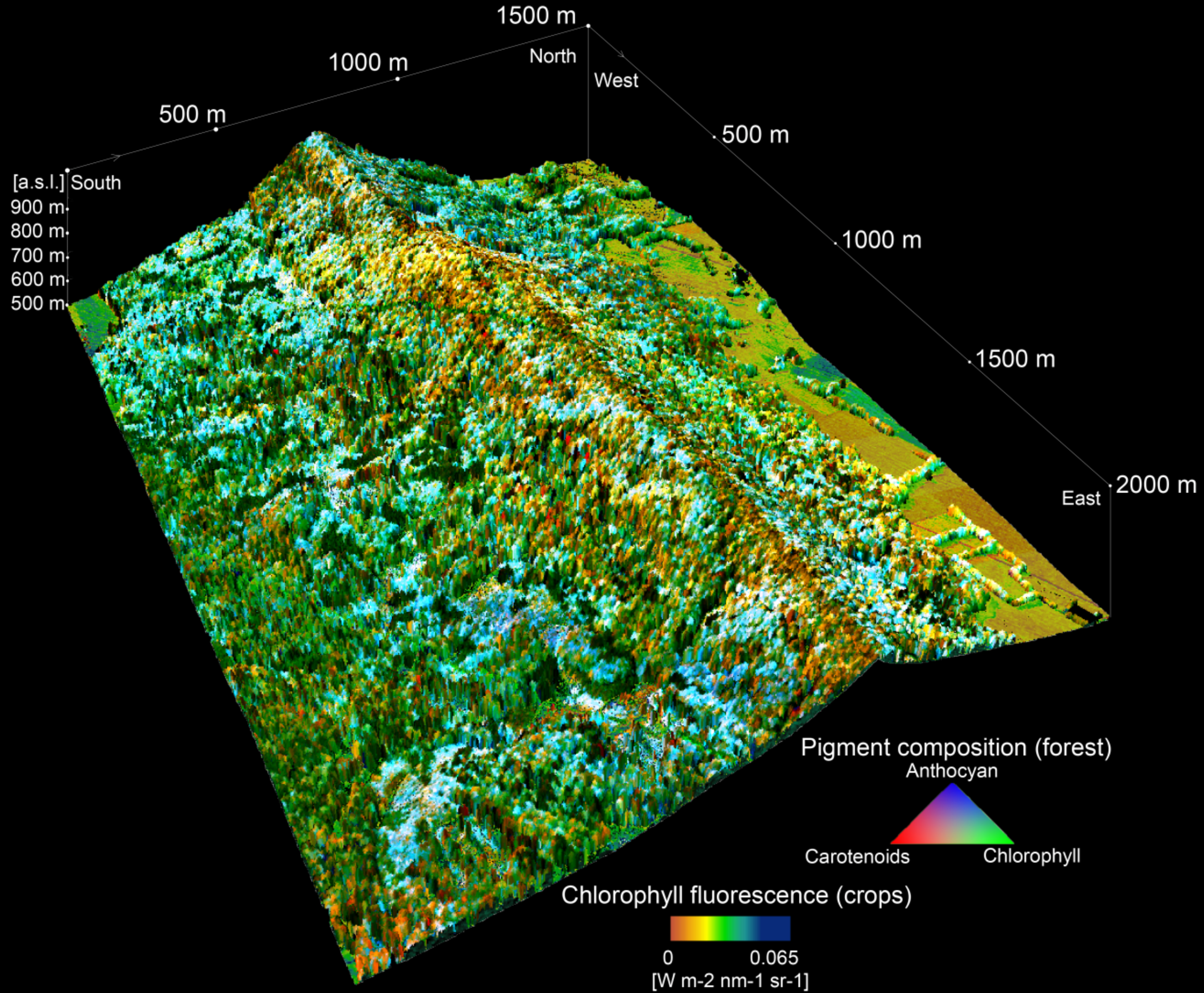


Canopy structure models based on laser scanning

Tree structure characterization based on ALS (leaf-off/-on, 300 pts/m^2)




Height a.s.l. [m]
820
800
780
760
740
720
700
680
660
640
2.592
2.5915
2.591
2.5905
2.59
2.5895
x 10^5
Northing [m]
6.697
6.6975
6.698
6.6985
6.699
6.6995
x 10^5
Easting [m]
Vertical distribution of traits following: Niinemets (2007) Photosynthesis and resource distribution trough plant canopies. Plant, Cell, Env., 30, 1052-1071. to be applied


1500 m
1000 m
500 m
North
West
[a.s.l.] South
900 m
800 m
700 m
600 m
500 m
500 m
1000 m
1500 m
2000 m
East
Pigment composition (forest)
Anthocyan
Carotenoids
Chlorophyll
Chlorophyll fluorescence (crops)
0
0.065
[W m-2 nm-1 sr-1]

Level 3: Alpine ecosystem services (agronomic, cultural, pollination, soil C)

Idea

- Using plant functional traits to predict ecosystem services using spectroscopy (based on: Lavorel, S., Grigulis, K., Lamarque, P., Colace, M., Garden, D., Girel, J., Pellet, G., Douzet, R. Using plant functional traits to understand the landscape distribution of multiple ecosystem services (2011) Journal of Ecology, 99 (1), pp. 135-147.)

Methods

- Replacing modeled continuous traits and services (using GLM) by spectroscopy. Derive land cover in a continuous fashion from spectroscopy data

Results

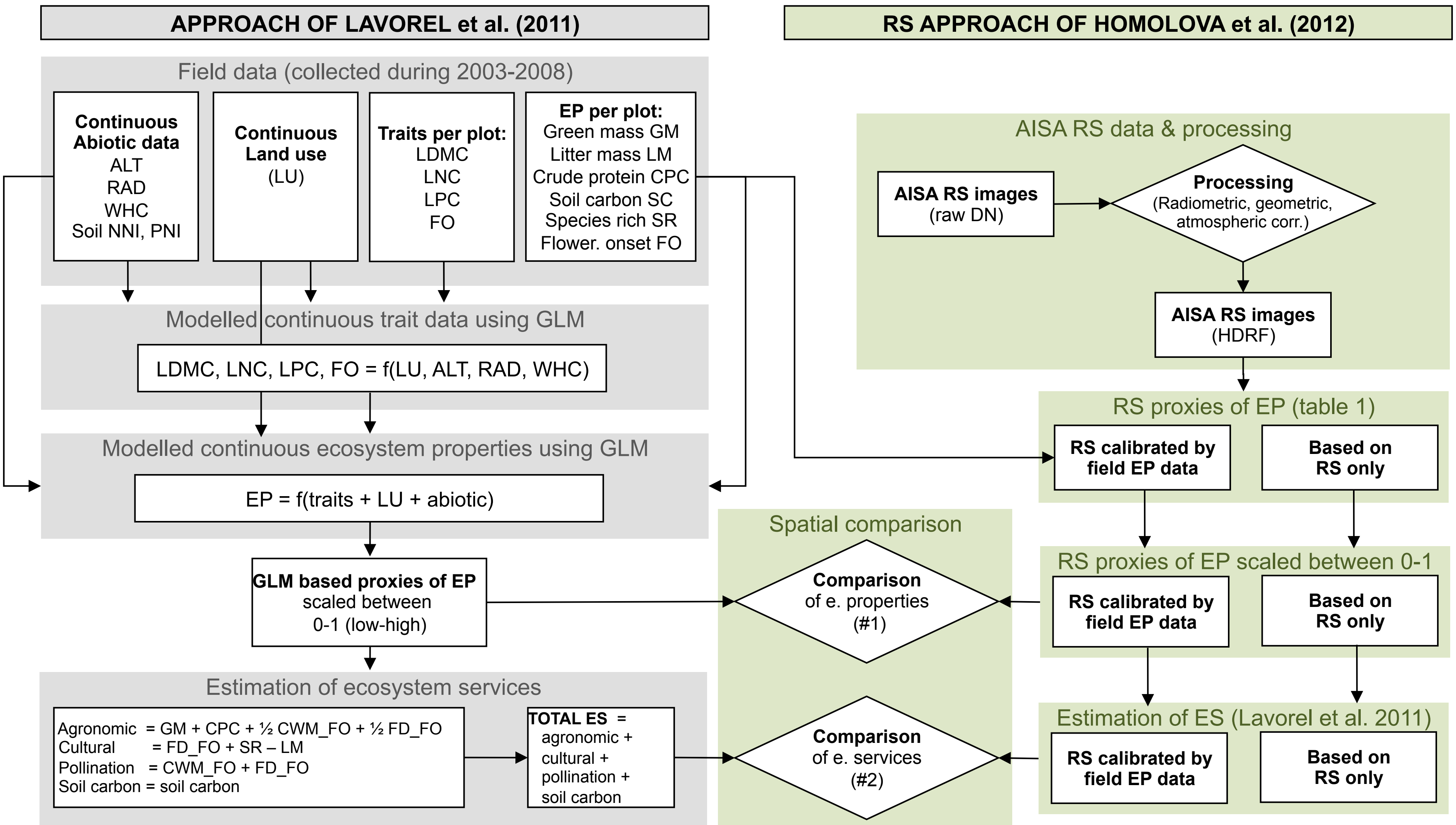
- Alpine ecosystem services (Homolova, Schaepman, Lavorel, et al. (2012). *J of Ecology*, in prep.)

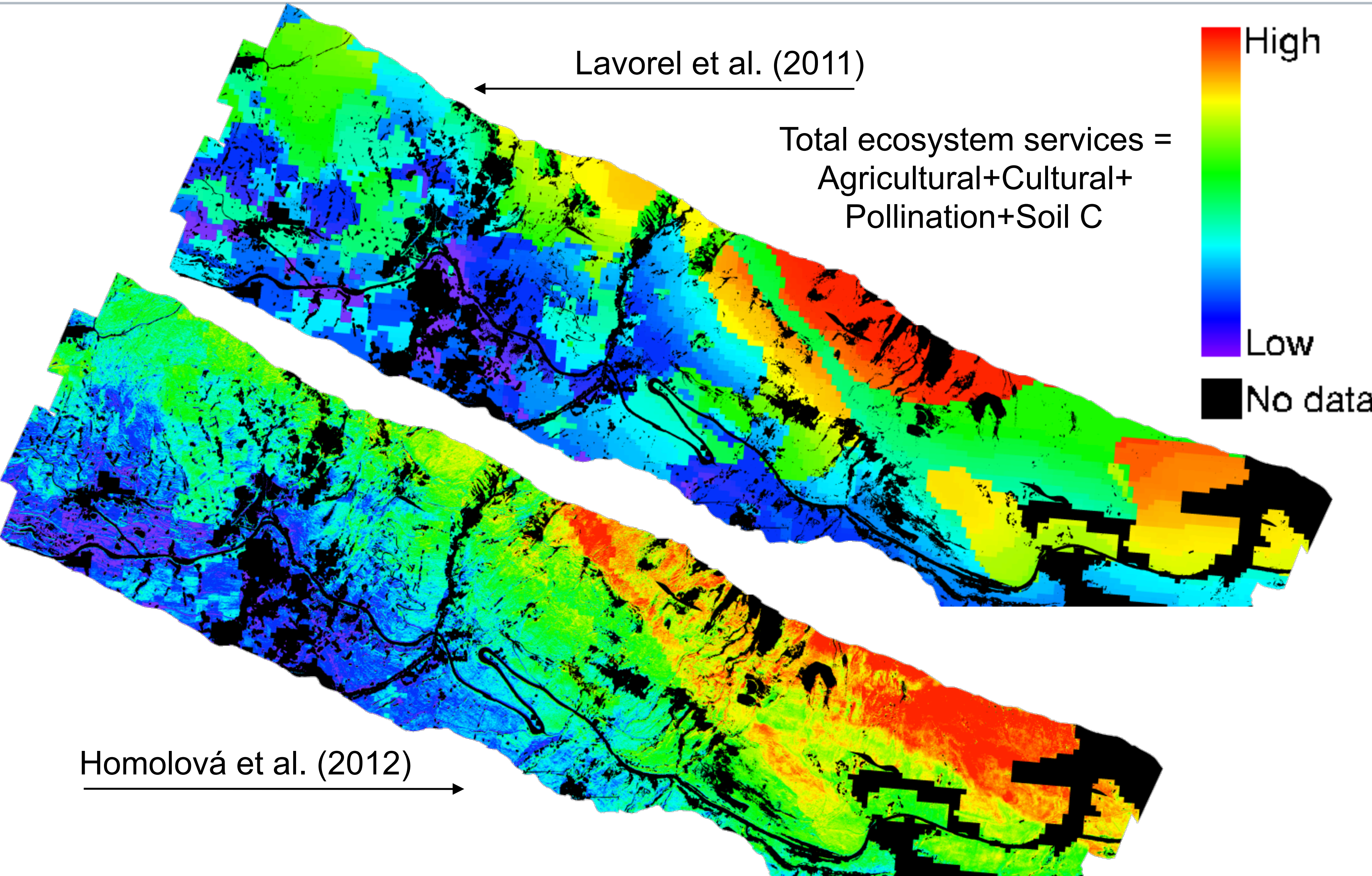
Outlook

- Improve pollination estimates by using multitemporal remote sensing data

French Alps – Ecosystem Services

Photos: L. Homolova


APPROACH OF LAVOREL et al. (2011)
RS APPROACH OF HOMOLOVA et al. (2012)
Field data (collected during 2003-2008)
Continuous Abiotic data
ALT
RAD
WHC
Soil NNI, PNI
Continuous Land use
(LU)
Traits per plot:
LDMC
LNC
LPC
FO
EP per plot:
Green mass GM
Litter mass LM
Crude protein CPC
Soil carbon SC
Species rich SR
Flower. onset FO
Modelled continuous trait data using GLM
LDMC, LNC, LPC, FO = f(LU, ALT, RAD, WHC)
Modelled continuous ecosystem properties using GLM
EP = f(traits + LU + abiotic)
GLM based proxies of EP
scaled between
0-1 (low-high)
Estimation of ecosystem services
Agronomic = GM + CPC + ½ CWM_FO + ½ FD_FO
Cultural = FD_FO + SR – LM
Pollination = CWM_FO + FD_FO
Soil carbon = soil carbon
TOTAL ES =
agronomic +
cultural +
pollination +
soil carbon
AISA RS data & processing
AISA RS images
(raw DN)
Processing
(Radiometric, geometric, atmospheric corr.)
AISA RS images
(HDRF)
RS proxies of EP (table 1)
RS calibrated by field EP data
Based on RS only
Spatial comparison
Comparison
of e. properties
(#1)
RS proxies of EP scaled between 0-1
RS calibrated by field EP data
Based on RS only
Comparison
of e. services
(#2)
Estimation of ES (Lavorel et al. 2011)
RS calibrated by field EP data
Based on RS only


Lavorel et al. (2011)
Total ecosystem services =
Agricultural+Cultural+
Pollination+Soil C
High
Low
No data
Homolová et al. (2012)

Level 3: Using NO_2 vertical column density for policy validation

Idea

- Use unbinned APEX acquisition for NO_2 vertical column density retrieval and policy validation

Methods

- Differential optical absorption spectroscopy (DOAS) and air mass factor calculations using radiative transfer approaches

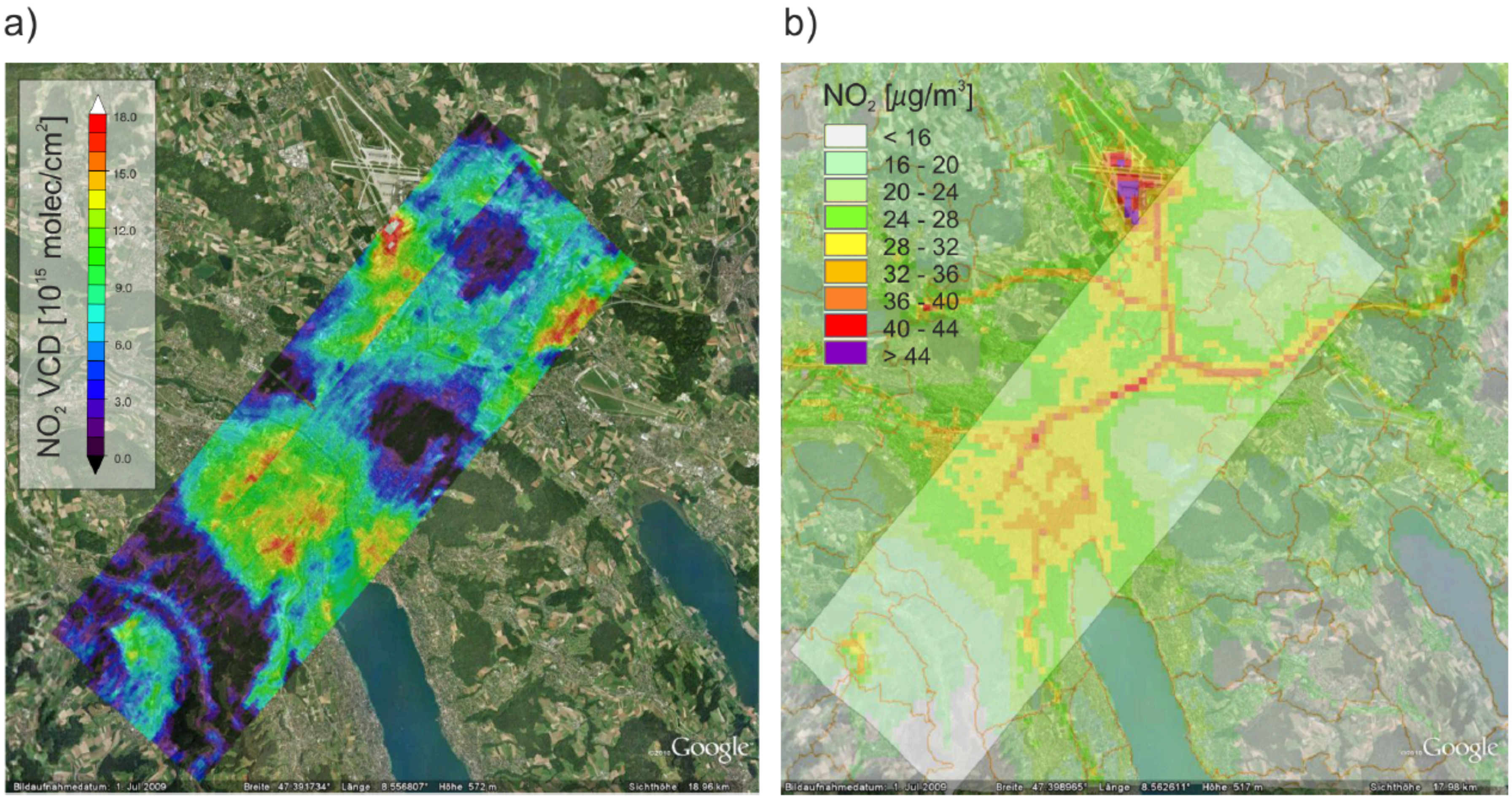
Results

- Detection of NO_2 emission sources, NO_2 emission modelling, and linking in-situ and satellite observations (Popp et al. (2012) AMT).

Outlook

- Combined estimates of NO_2 emission/deposition using transport models

Measurements and policy implementation



Popp, C., Brunner, D., Damm, A., Van Roozendael, M., Fayt, C., and Buchmann, B. (2012). High-resolution NO2 remote sensing from the APEX imaging spectrometer. Atmos. Meas. Tech., 5, 2211-2225.

Conclusions

Pushing the limits: 4th generation spectroscopy pushes much of the current models and technology to a higher level.

We move from predominantly observational & empirical approaches to

- radiance based approaches (instead of reflectance based) using coupled models
- coupling the physics of the observations to the physics of the environment
- implementing spectral databases providing ‘informative priors’ allowing the prediction of spectral signatures representing the dynamics of the process observed
- direct radiance data assimilation into process models (of photosynthesis)

Combined suborbital and orbital spectroscopy is the only way assessing **many** relevant processes of the Earth system **simultaneously** and at **unprecedented** accuracy!

Thank you for your attention!