Possibilities and limitations of plant nitrogen retrieval from spaceborne imaging spectroscopy

(few thoughts regarding crop nitrogen retrieval)

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Motivation

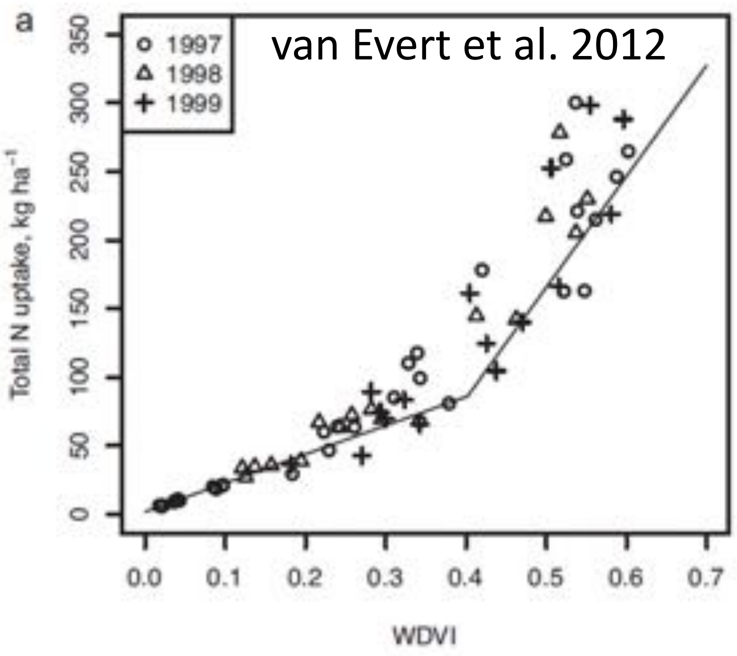
Canopy nitrogen content (CNC) has been identified as one of the CHIME High Priority Products. However, there are still open aspects and questions to be discussed:

1. First, a clear definition of remotely sensed N quantities is missing.
2. Different methods are available for estimating crop CNC from VNIR/SWIR hyperspectral satellite (and other sensor) systems
3. Efficient crop N monitoring requires remote sensing time series
   A. Adequate revisit frequency comes mainly from multispectral systems
   B. Hyperspectral (HS) systems are needed for protein-related crop N
4. Are satellite-based N products provided at the right time to support agronomists?
5. Often, CNC alone doesn't help. For instance, under drought, the plant cannot take up the fertiliser that was applied based on a CNC map

Definition of N quantities in plants

Level	Variable	Definition	Unit
Leaf	Concentration or N%	Mass of N per mass dry matter	%
	Content (LNC) or N_{area}	Mass of N per leaf area	mg / cm2
Canopy	Concentration or N%	Mass of N per mass dry matter	%
	Content (CNC) or N_{area} or N Uptake	Mass of N per ground area	g / m2 kg / ha
Plant tissue or whole plant	N Uptake	Dynamic process	g per time
Plant to field	Nitrogen use efficiency	Output / input (e.g. grain yield per unit of nitrogen available from the soil	unitless

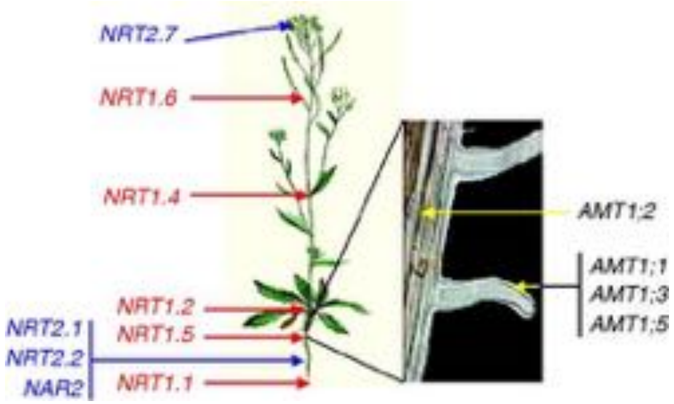
Nitrogen quantities; marked yellow= open to RS



$$WDVI = R_{v,810} - \left(\frac{R_{s,810}}{R_{s,560}}\right) R_{v,560}$$

Weighted Difference Vegetation Index (WDVI) (Clevers, 1989)

Nsidedress = Ntarget − Ncrop



Nitrate uptake occurs at the root level and is the transport process to take up nitrate from the soil solution and distribute it within the whole plant (Masclaux-Daubresse et al 2010)

Available plant trait retrieval methods

Parametric

- Narrowband vegetation indices (NB-VI), using discrete selected bands to formulate simple ratio or normalized difference, e.g. Glenn et al. (2008)
- Spectral positions (red edge inflection point, REIP), e.g. Cho et al. (2008)
- Spectral derivates, e.g., le Maire et al. (2004)
- Spectral integrals, e.g. Pasqualotto et al. (2018)
- Continuum removal, e.g. Malenovsky et al. (2013)
- Wavelet transform, e.g. Blackburn & Ferwerda (2008)

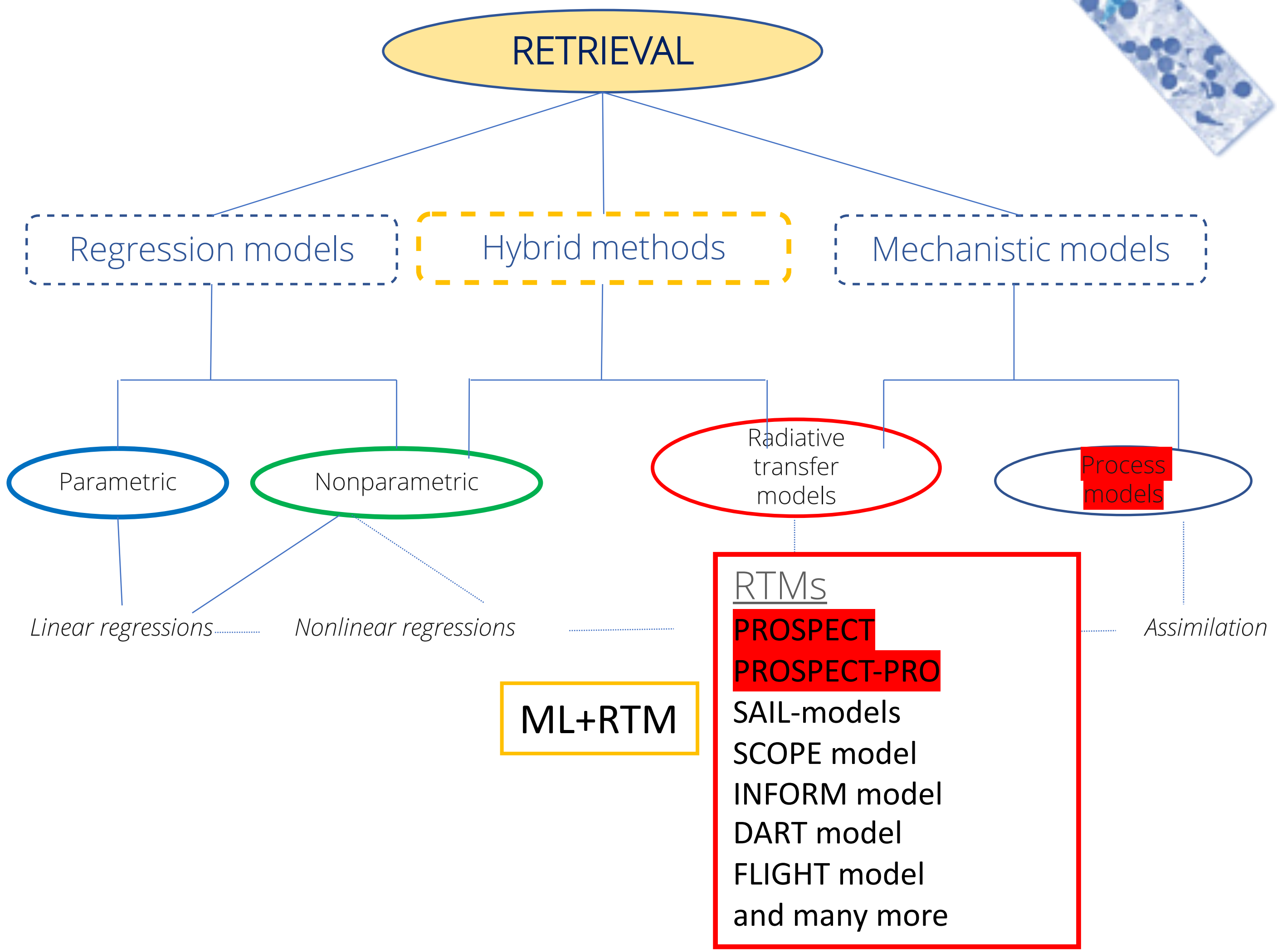
Non parametric linear

- Chemometrics, e.g. PLSR

Non-parametric non-linear (ML)

- Artificial neural networks
- Extreme learning machines
- Decision trees
- Bagging trees
- Boosting trees
- Kernel ridge regression
- Support vector regression

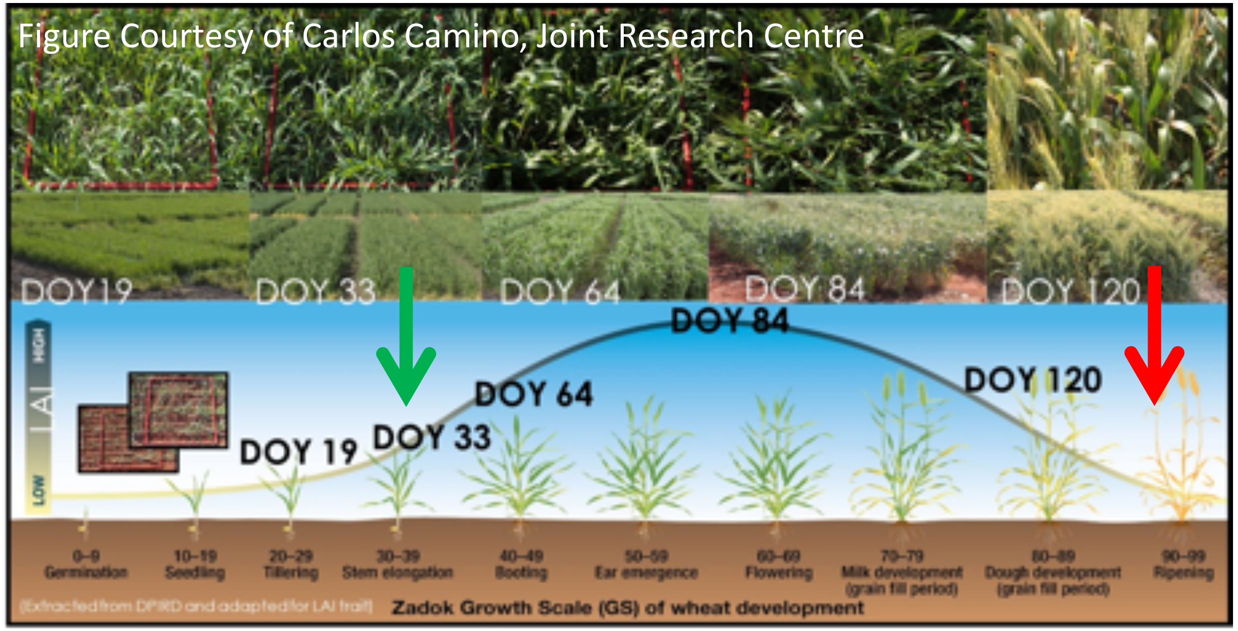
Adapted from Verrelst et al. (2019a)



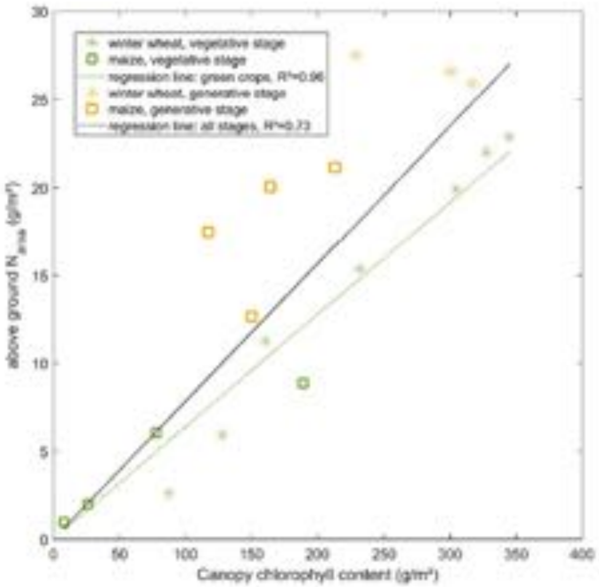
Available plant nitrogen retrieval methods

No.	Type	Principle	Example
1	Indirect via Cab-N link	CI_red-edge (800 nm and 705–740 nm bands) or narrowband VI, empirical (crop type dependent) relation to CCC or CNC	Clevers and Gitelson 2013 Inoue et al. 2012
2		Physically-based retrieval of LAI or CCC (LAI or GAI x Cab) and empirical LAI-CNC or CCC-CNC link	Delloye et al. 2018 Bossung, Schlerf, Machwitz 2022
3	Direct via protein features	Empirical relation between reflectance and N (protein, chlorophylls) using (non-) parametric regression	Summarized in Homolova et al. 2013
4		Physically-based via protein features using inversion of PROSPECT-PRO (leaf level) or PROSAIL-PRO (canopy level)	Féret et al., 2020 Berger et al. 2020

Cab-N (de-)correlation and timing of N assessment



Phenological stage: LAI, structural effect and soil properties



Relationship between field measured canopy chlorophyll content (i.e. leaf area index, LAI, multiplied with leaf chlorophyll content, Cab) and measured aboveground N content (Narea) as sum of measured N content of leaves, stalks and ears (Berger et al. 2020

The estimation of canopy nitrogen content (CNC, kg/ha) during **stages 30–39 (stem elongation)** provides crucial information that may allow for the adjustment of fertilization to the crops' needs (Delloye et al., 2018).

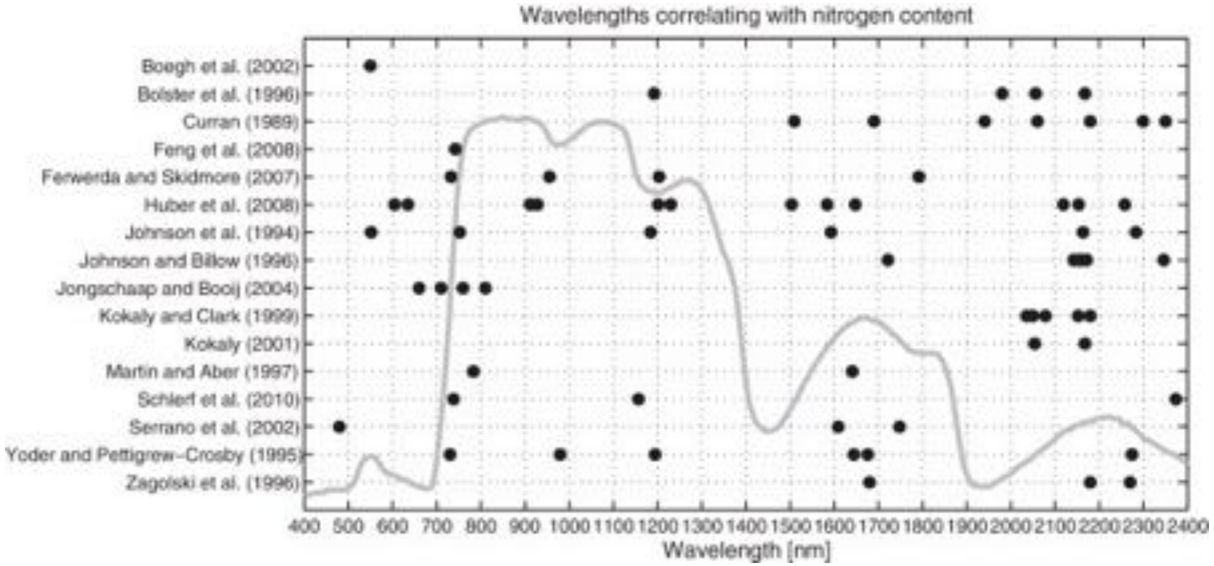
Assessment of N during **mature growth stages** provides valuable indication of expected yield quality (Berger et al. 2020).

moderately strong correlation between leaf N and Cab exists across different species (r = 0.65 ± 0.15) (Homolova et al. 2013)

LIST

Direct empirical N estimation via N-related features

- Direct reflectance – N link, only empirical methods
- 20 studies: R2 = 0.6-0.8, relative RMSE = 10-20% (Homolova et al. 2013)
- selected wavelength often relate to red edge region and protein absorption features, but vary between studies
- In principle not transferable to other datasets



Overview of spectral wavelengths used in scientific literature for estimation of nitrogen concentration and content in green and dry plant leaves (Homolova et al. 2013)

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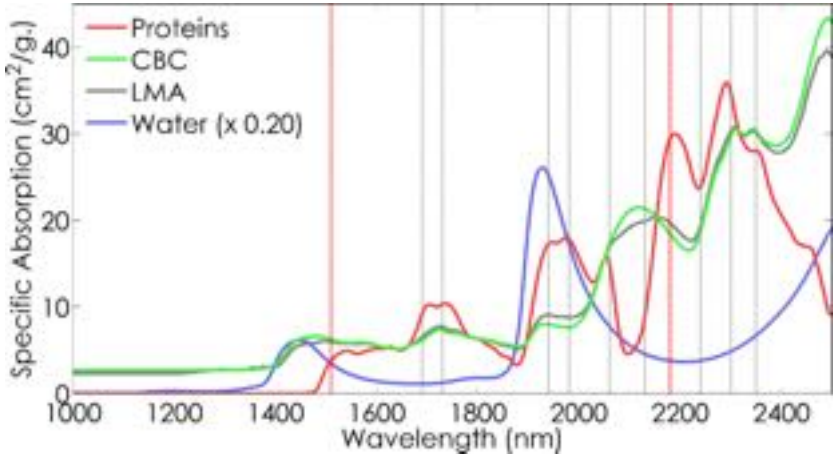
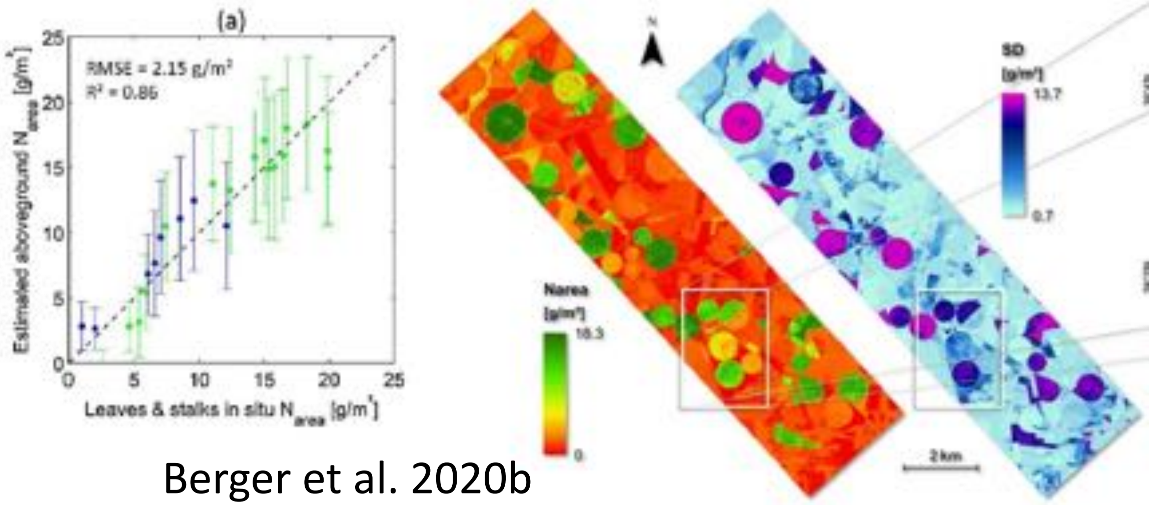
Direct physically-based via protein features

- Earlier attempts to incorporate N into PROSPECT were abandoned due to its strong covariance with other leaf compounds leading to inconsistent results (Jacquemoud et al., 1996).
- The idea has recently been revived by Feret et al. 2020 with the PROSPECT-PRO model
- PROSPECT-PRO was coupled with SAIL to PROSAIL-PRO and the hybrid inversion approach allows to map CNC, uncertainties and the relative contribution of important wavelengths (Berger et al. 2020)
- The approach could replace the empirical ones and has better generalisation potential; masking effect by leaf water in fresh leaves and confounding effects by cellulose and lignin?

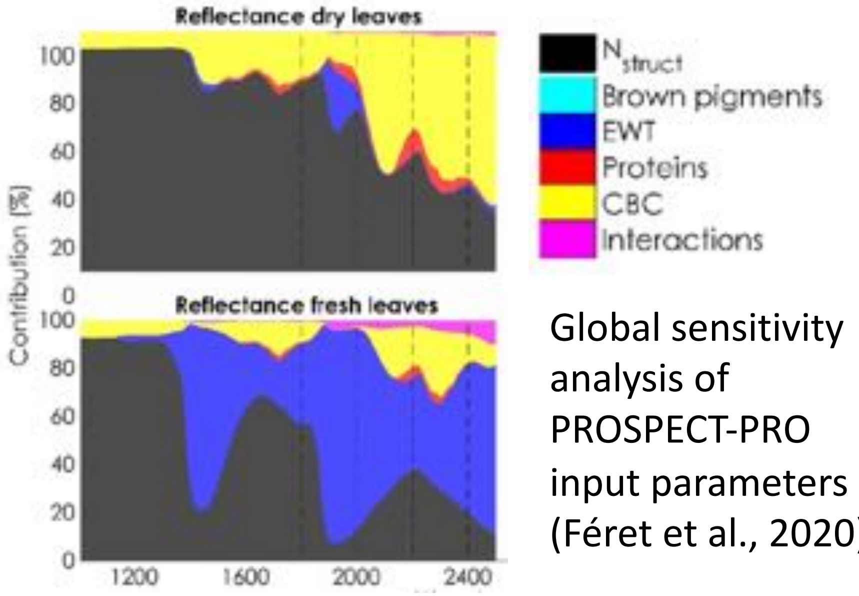


(Féret et al., 2020)

Validation of PROSAIL-PRO estimates of CNC from field spectrometer data



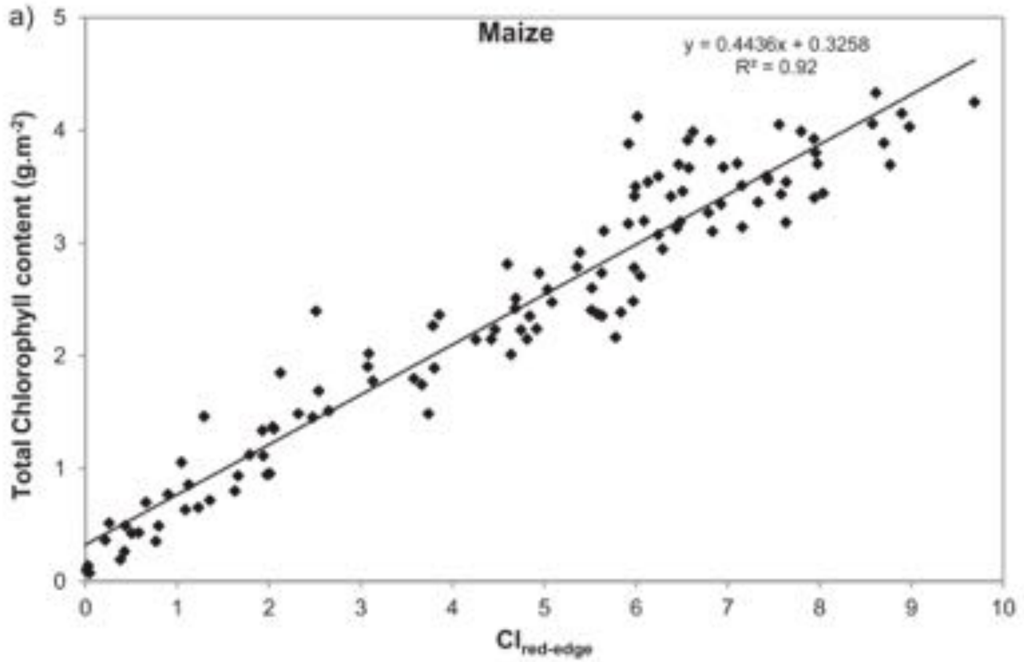
Berger et al. 2020b



Global sensitivity analysis of PROSPECT-PRO input parameters (Féret et al., 2020)

Indirect empirical N estimation through N-Cab link

- moderately strong correlation between leaf N and Cab exists across different species (r = 0.65 ± 0.15) (Homolova et al. 2013)
- Canopy chlorophyll content can be well retrieved from CIred-edge = R800/R710 − 1)



Clevers and Gitelson 2013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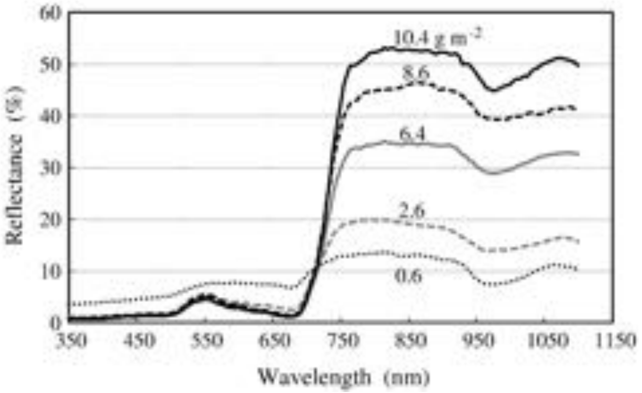
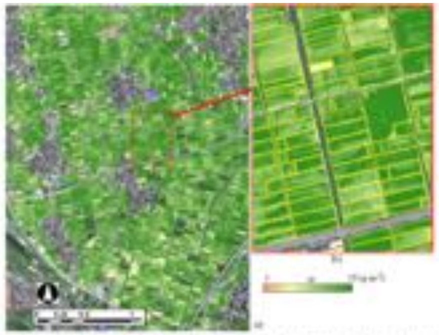
Diagnostic mapping of canopy nitrogen content in rice based on hyperspectral measurements

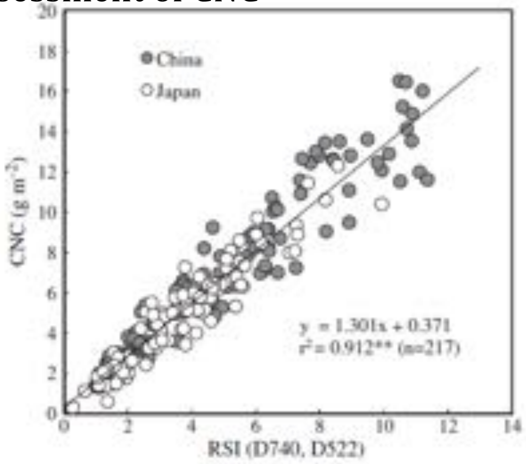
Yoshio Inoue, Eiji Sakaiya, Yan Zhu, Wataru Takahashi



Left: typical reflectance spectra of rice canopies from the ground-based dataset in Japan. Numbers indicate the CNC (g m⁻ ²) values.

Bottom: RSI (D740, D522) was the most significant and stable for assessment of CNC

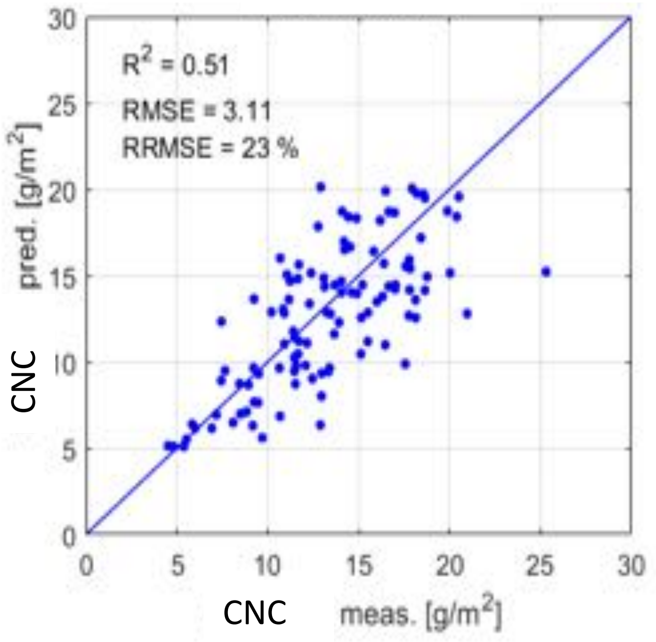




Indirect physically-based N estimation through LAI-CNC link

R (2017)	LAI	Cab	FM	DM	LNC	CNC	CCC
LAI	*1.00*						
Cab	0.31	*1.00*					
FM	0.86	0.34	*1.00*				
DM	0.73	0.38	0.92	*1.00*			
LNC	-0.32	**-0.08**	-0.58	-0.70	*1.00*		
CNC	**0.81**	0.44	0.84	0.81	**-0.23**	*1.00*	
CCC	0.90	0.68	0.81	0.74	-0.30	**0.81**	*1.00*

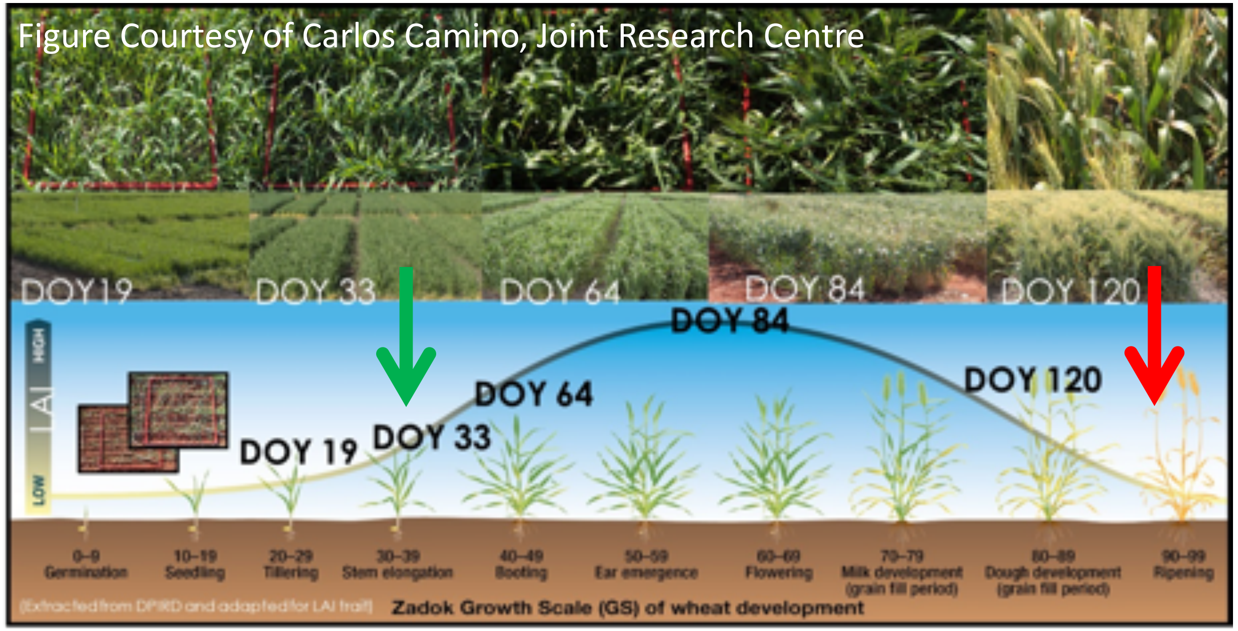
Data from n=181 wheat samples measured in 48 plots over 4 campaigns in 2017 in France and Belgium (Bossung, Schlerf, Machwitz 2022, Prec. Agric.)



CNC from Sentinel-2 vs measured CNC

- Leaf level: Cab and LNC are unrelated (r=-0.08)
- Canopy level: CCC and CNC are well correlated (r=0.81)
- To explain CNC variation, LNC is not important: CNC and LNC are only weakly correlated (r=-0.23)
- CNC variation is mostly correlated with variations in LAI (r=0.81), Fresh biomass (FM, r=0.84), Dry biomass (DM, r=0.81) and CCC (Cab x LAI, r=0.81)
- If canopy nitrogen content CNC (g/m2) is well linked to biomass (FM) and also to LAI, **and not linked to LNC**, we can use multi-spectral satellite data and common LAI retrieval methods plus empirical LAI-LNC relation to map CNC
- This may be the case on fertilised agricultural fields where LNC is typically at high levels with little spatial variation (But: dilution effect – LNC drops with increasing biomass during growth)

Timing of N fertilisation – need for high revisist time



Phenological stage: LAI, structural effect and soil properties

<u>Approximate length of stem elongation period:</u>
Center of DOY 19 and DOY 33 = DOY 26
Center of DOY 33 and DOY 64 = DOY 48.5
DOY 26 – DOY 48 = period of 18 days (2.5 weeks)

Extract of wheat growth stages in Kentucky and timing of N fertilisation (C. A. Knott, Univ. of Kentucky, https://mccracken.ca.uky.edu/files/identifying_wheat_growth_stages_agr224.pdf)

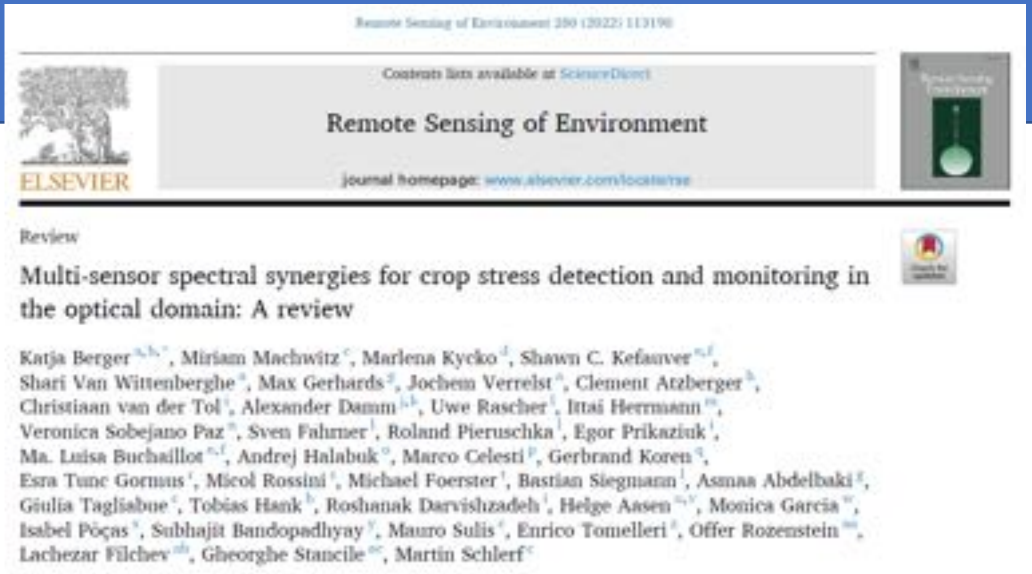
3 Green-Up	mid Feb early March	Wheat begins actively growing, "breaking" dormancy, at green-up in the spring. The first nitrogen application, of a split nitrogen application, is recommended at this stage. Often leaves appear to be twisting spirally and the plants will be prostrate: growing along the soil surface.
5	mid to late March	Wheat has elongated and become erect. The second nitrogen application, of a split nitrogen application, is recommended. If applying nitrogen as single application, apply at this stage. Herbicides and insecticides commonly applied at this stage. The growing point is still below the soil surface. The leaf closest to the soil surface on the pseudostem is about 1-inch from the soil surface.

First N application: mid-Feb to early March
Second N application: mid to late March

<u>For the Kentucky fertilisation example:</u>
One cloud free observation in second half of Feb
One cloud free observation in second half of March

Recommendations / Questions

- For crop N sensing, observations from hyperspectral should be preferred over multispectral sensors (especially when N is retrieved via protein-N linkage)
- Powerful generic recent methods (e.g. PROSPECT-PRO+4SAIL + GPR) allow routine delivery of CNC
- Fertiliser management requires CNC maps during stem elongation phase (within approx. 2.5 weeks), so crop N products should be harmonized for HS sensors (CHIME + SBG+…)
- Harmonisation with CNC retrievals from S-2 (lower accuracy than HS, only via Cab-N link, but higher temporal frequency)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Review

Multi-sensor spectral synergies for crop stress detection and monitoring in the optical domain: A review

Katja Berger, Miriam Machwitz, Marlena Kycko, Shawn C. Kefauver, Shari Van Wittenberghe, Max Gerhards, Jochem Verrelst, Clement Atzberger, Christiaan van der Tol, Alexander Damm, Uwe Rascher, Ittai Herrmann, Veronica Sobejano Paz, Sven Fahrner, Roland Pieruschka, Egor Prikaziuk, Ma. Luisa Buchaillot, Andrej Halabuk, Marco Celesti, Gerbrand Koren, Esra Tunc Gormus, Micol Rossini, Michael Foerster, Bastian Siegmann, Asmaa Abdelbaki, Giulia Tagliabue, Tobias Hank, Roshanak Darvishzadeh, Helge Aasen, Monica Garcia, Isabel Pôças, Subhajit Bandopadhyay, Mauro Sulis, Enrico Tomelleri, Offer Rozenstein, Lachezar Filchev, Gheorghe Stancile, Martin Schlerf

<u>Comprehensive study</u>

- Using many available datasets of HS imagery + ground CNC measurements for different crop types
- Systematically compare different CNC retrieval methods incl. indirect and direct ones
- For different N applications (fertiliser management, yield quality assessment)
- quantify the decrease in N estimation accuracy from frequently available Sentinel-2 compared to recent spaceborne hyperspectral systems

Thank you!