MuSLI Canopy Chlorophyll Content Prototypes
for Assessment of Vegetation Function and Productivity

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Project Goal and Objectives

Leaf chlorophyll content is arguably the most important driver of photosynthesis and a key characteristic of vegetation function. It has become critical to understand the dynamics in vegetation function, as ecosystems respond to variable environmental conditions and cycle through seasonal changes.

Goal: produce consistent medium resolution (30m) Chl product prototypes and algorithms that can reliably be scaled to regional and continental scales.

Objectives

- produce high density time series of VIs and canopy Chl for regionally important species, (e.g., higher Chl accuracy than it can be produced with either L-8 or S-2 alone)
- provide a multisystem approach, for using L-8 OLI and S-2 MSI images and for improved detection of physiological changes
- generate dense seasonal Chl time series and 'function/stress maps' as the difference between optimal vs. observed Chl

Tasks and Project Status

Tasks (T)

T1: Field and lab measurements

- *collected 2018-20, to process 2019-20*

T2: Assembly of field and satellite data

- *2016-2018 TS ready for US and Lz*

T3: HLS and VHR Chl Vis

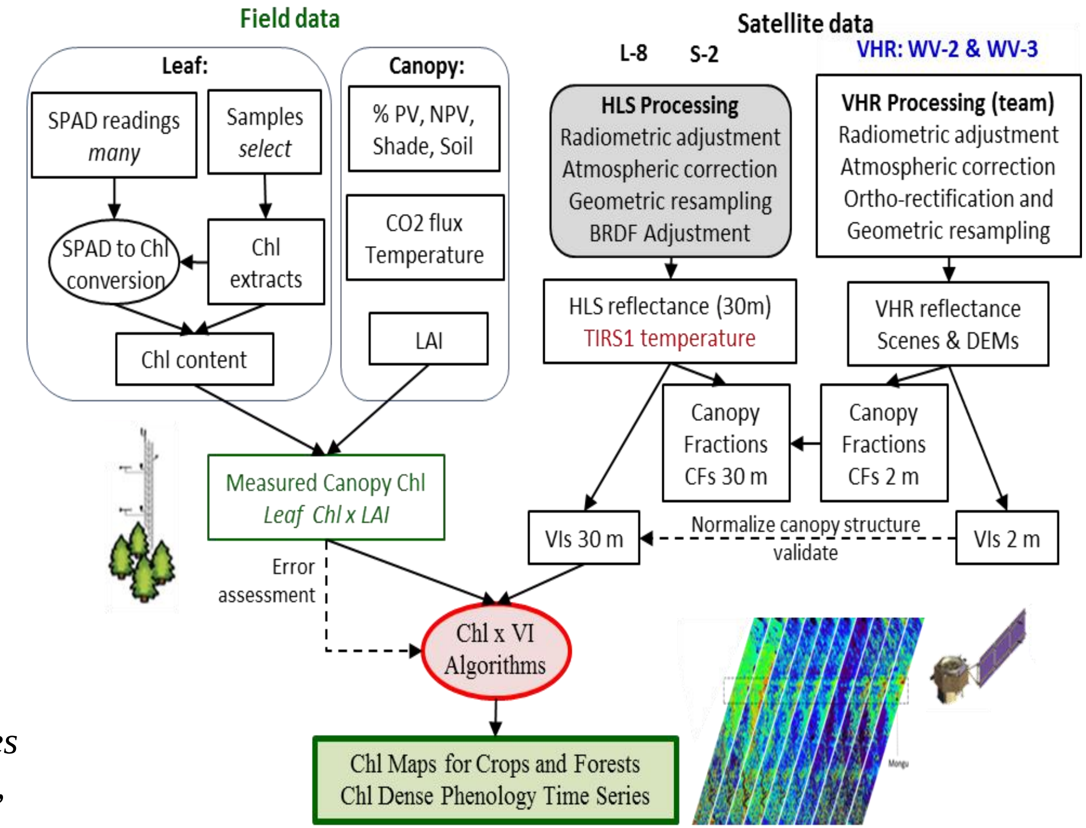
- *working with HLS 2020*

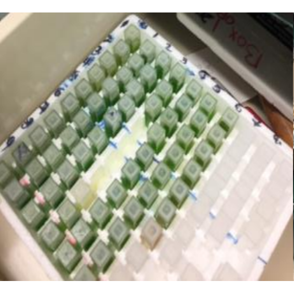
T4: Algorithms - development of relationships between VIs and field Chl

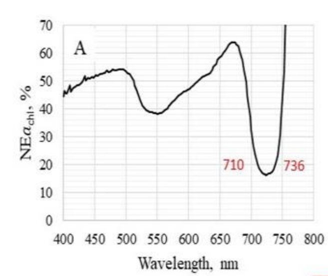
T5: Importance of S-2 Red Edge (RE) bands for Chl estimation

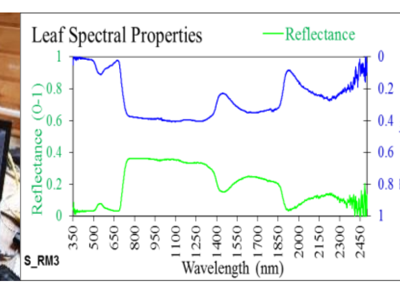
T6: Scientific use of the Chl time series

- *Chl time series across seasons, sites and species*
- *Improved detection of stress (rain fed/irrigated, drought)*

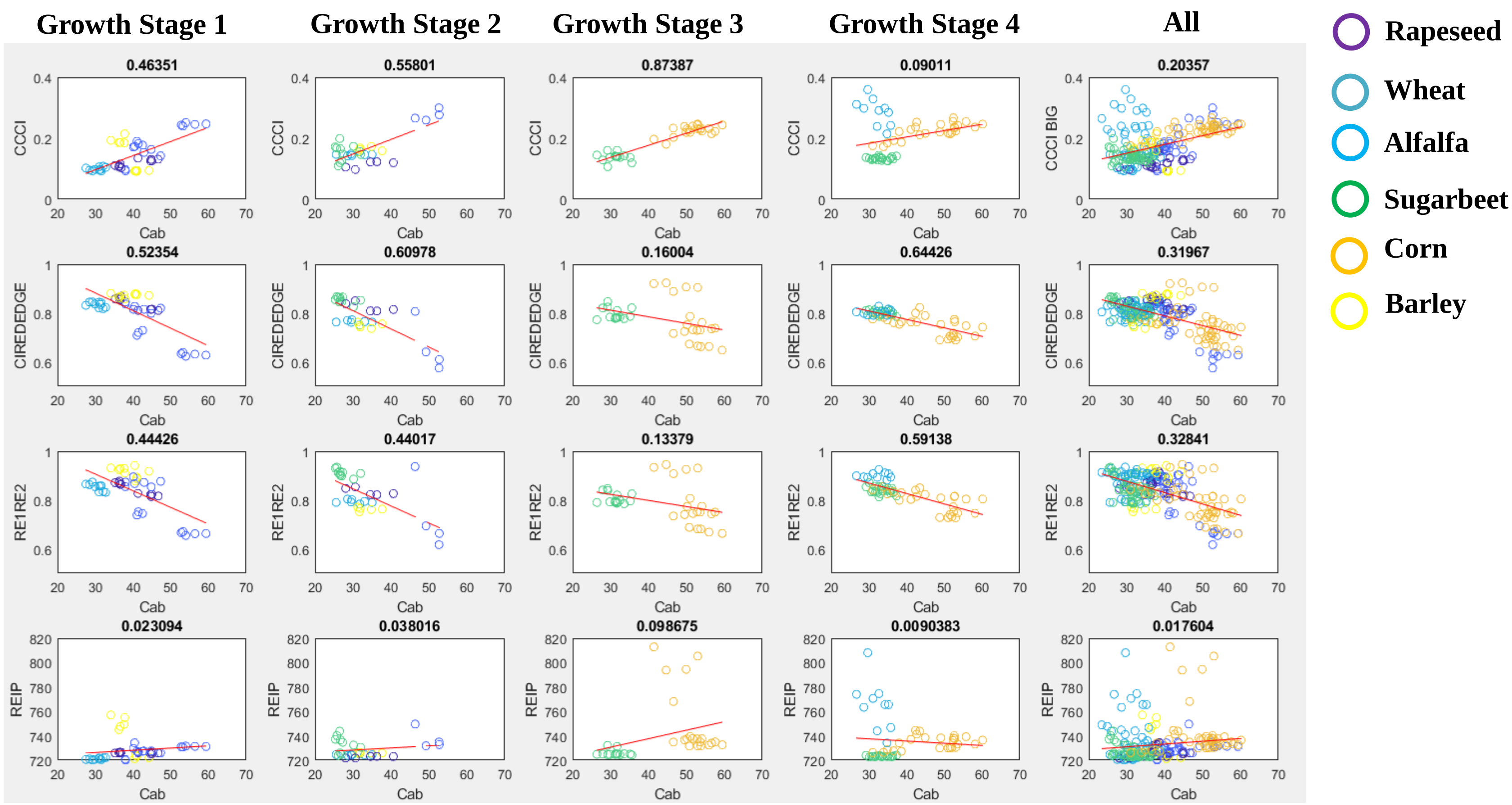








Relationships between VIs and field Canopy Chl, Crops

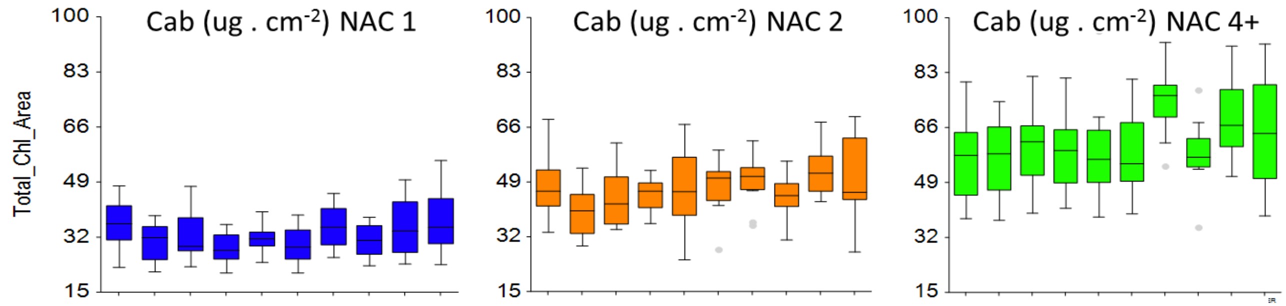


➢ **To predict reliably canopy chlorophyll content across the seasons, for crops and deciduous we need field and satellite data <u>representative of the key growth stages</u> and phonologic events.**

- Best-performing vegetation indices were those based on <u>red-edge (RE) bands</u> (r^2 up to 0.87)
- Lower Chl predictions using VIs were encountered for canopies with very low vegetation fraction

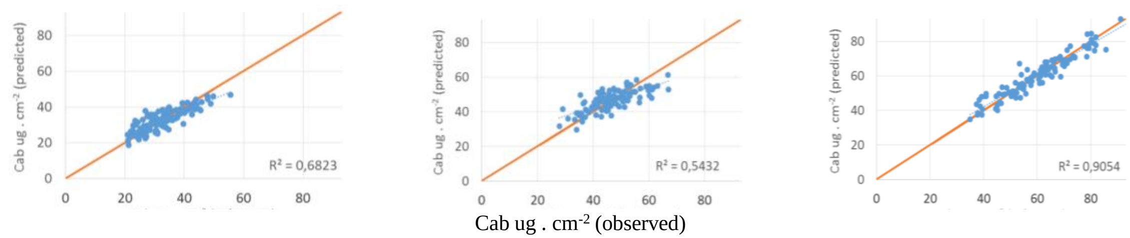
(Lukes, Lhotakova, Kupkova, Albrechtova)

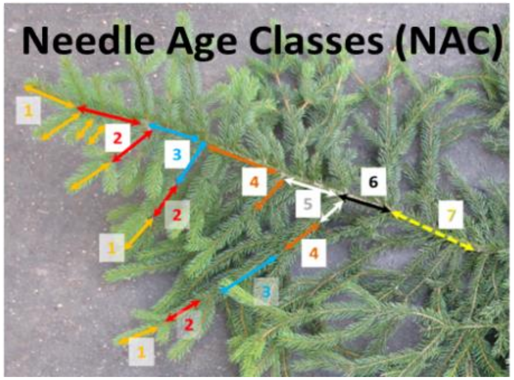
Relationships between VIs and field Canopy Chl, Conifers



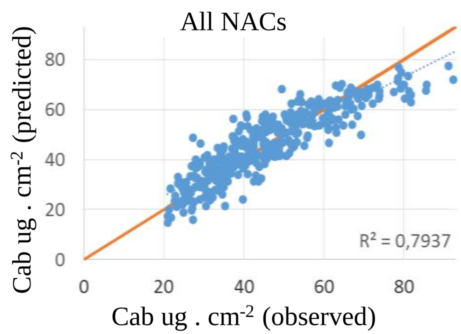
10 Sites (in order: LYS, PLB, NAZ, LIZ, ANE, SAL, POM, UDL, UHL, CER)

Cab PLSR Prediction Models





NAC = needle age class



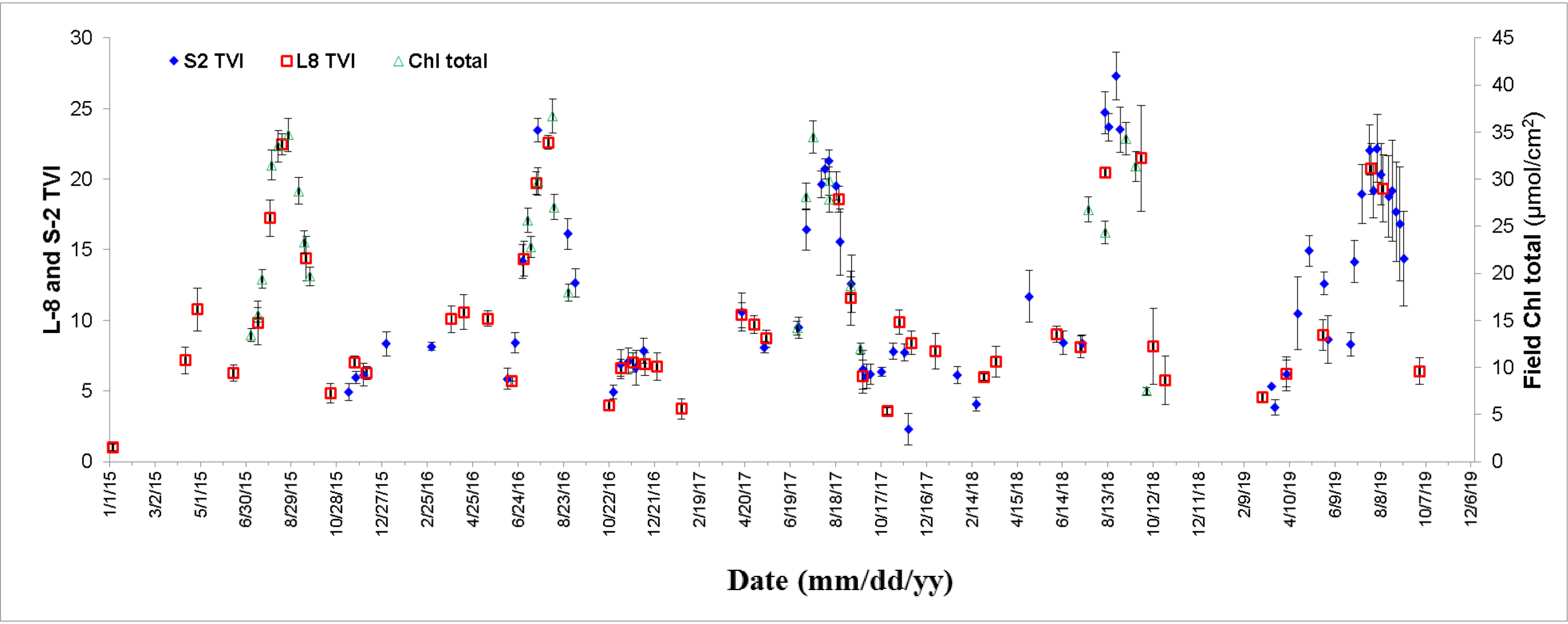
- Strong age-dependence of needle traits, which affects performance of canopy models and the Cab predictions

➢ **Calibration data from <u>3+ NACs</u> is needed for robust predictions**

(Albrechtova, Lhotakova, Lukes, Kupkova)

HLS Comparison of L-8 and S-2 Chl VIs, OPE3

TVI=0.5*[120*(R815-R555)-200*(R655-R555)]; L-8 vs S-2, R^2=0.97

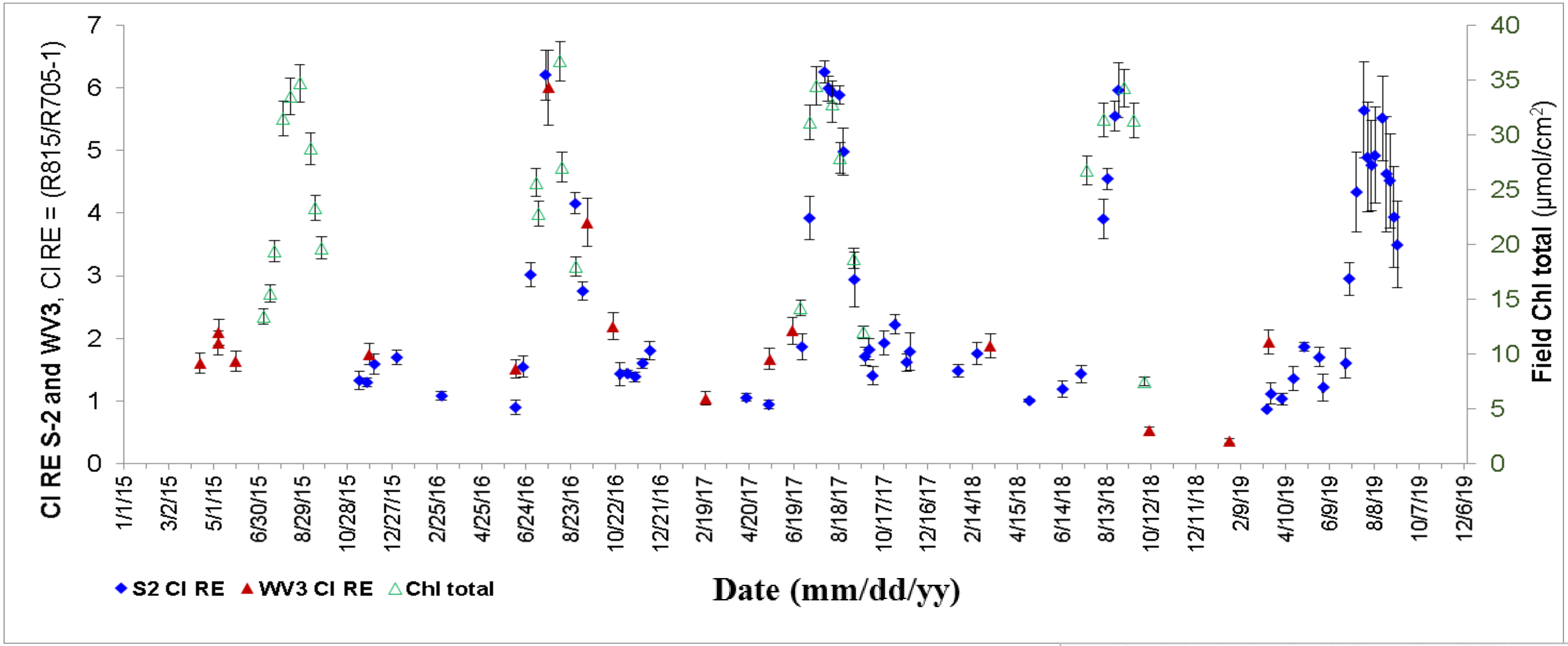


- **HLS TVI, SR and Cl_{705} performed optimal for both corn and soybean at OPE3**
- **The use of L-8 and S-2 provided <u>higher temporal frequency</u>, than using either L-8 or S-2 alone**

- The processing of leaf spectra and extraction of pigments from 2017-18 is completed, however 2019-20 pigments need to be processed. Prior collections are being added: 2015-17

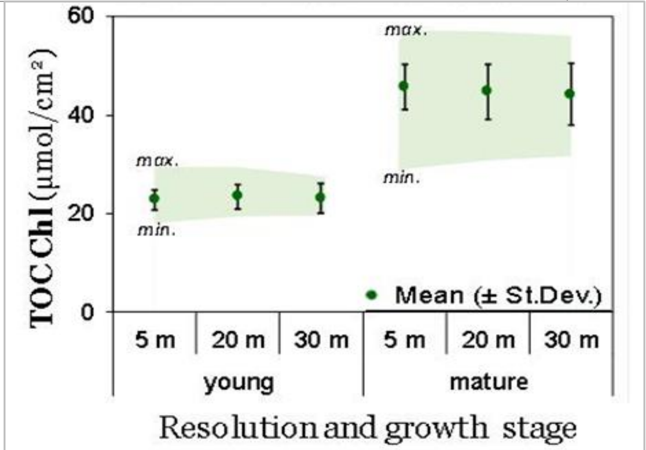
HLS S-2 and WV3 Chl VIs, OPE3

$CL_{RE} = (R_{nir}/R_{re} - 1)$; **S2** + WV, R^2=0.98



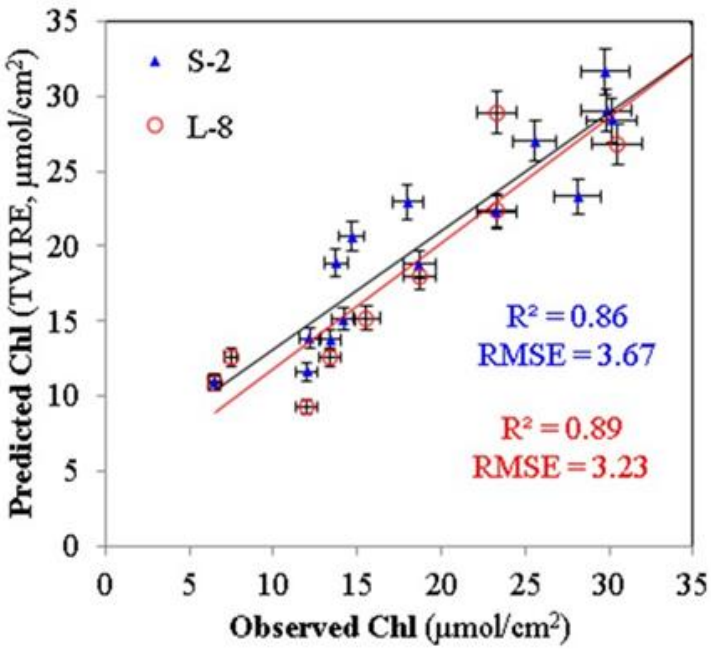
- ➢ **HLS S-2 and WV data both provide <u>RE VIs sensitive to changes in canopy Chl</u> which can be used together**

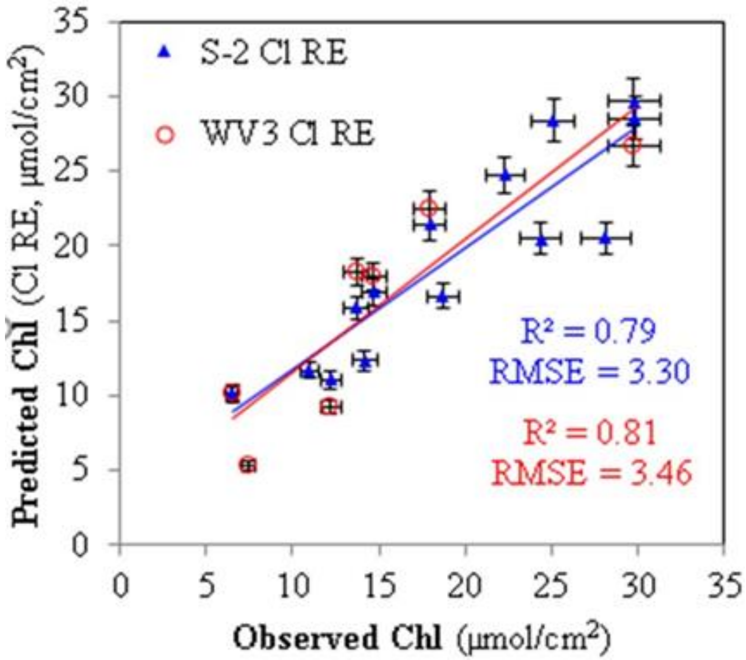
- However, spatial aggregation to 30 m is required



S-2, L-8 and WV3 - Predicted vs Observed Chl

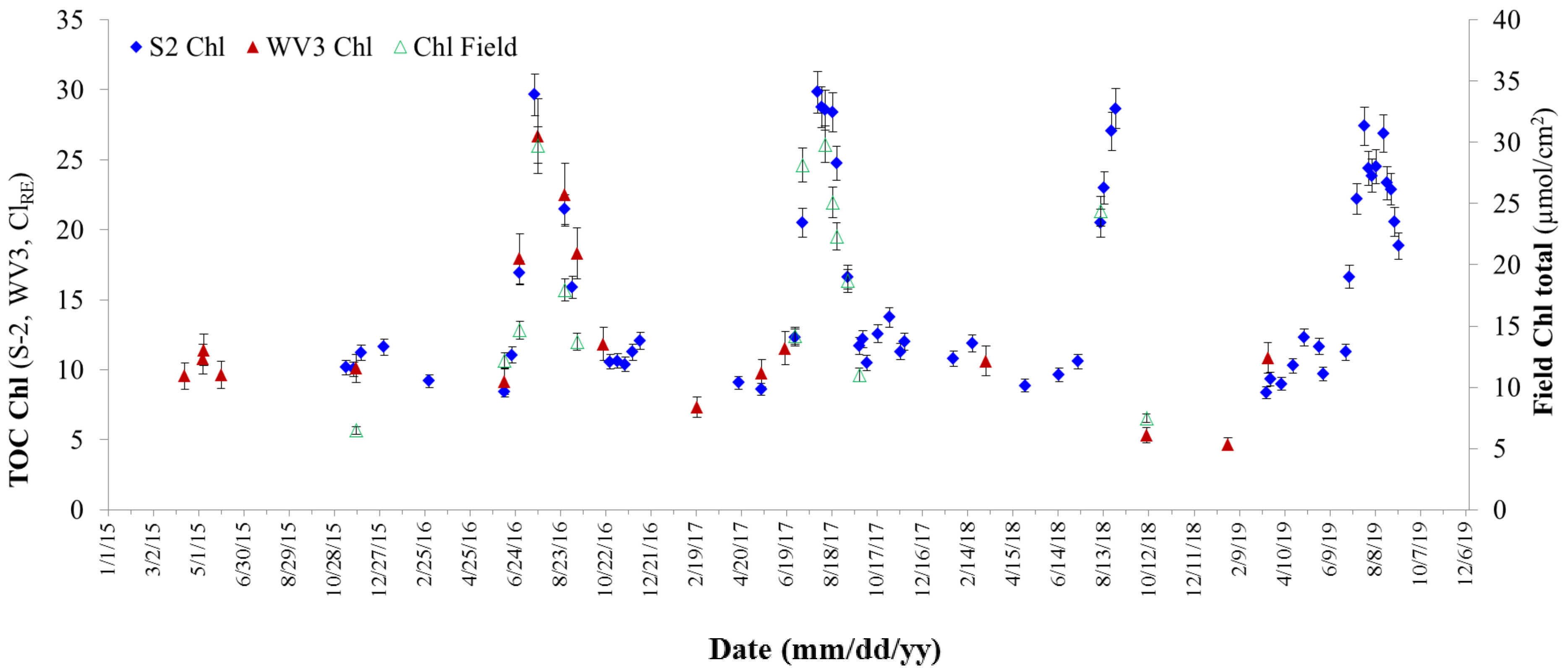
TVI using S-2 and L-8 (left), Cl_{RE} using S-2 and WV3 (right)
OPE3, data from 2015-2018 growing seasons





- The uncertainties of the TOC Chl predictions were within approximately 3-4% of the field measurements.
- Joint models, applicable to L-8, S-2, WV3 (e.g. TVI) were developed and tested for transferability across seasons.

Canopy Chlorophyll Time Series for OPE3



- TS based on CI_{re} using both S-2 and WV, provide consistent results with different uncertainty

To gap-fill the time series with satellite and field data from all growing seasons, the commercial Rapid Eye data offers RE band

Testing Published Canopy Chl Algorithms with HLS VIs

Soybean and Corn, Nebraska

Can we obtain comparable canopy Chl estimates using different HLS VIs?

Table 3. Algorithms, normalized root mean square error (NRMSE) in g·m^{-2} and determination coefficient (R^2) of canopy Chl estimation during the entire growing season in maize and soybean.

VI	Maize			Soybean		
	Algorithm	NRMSE	R^2	Algorithm	NRMSE	R^2
EVI	$y = 5.54x - 1.11$	0.112	0.89	$y = 2.51x - 0.59$	0.139	0.82
SR	$y = 0.14x + 0.30$	0.117	0.80	$y = 0.0653x + 0.0415$	0.093	0.87
CI_{green}	$y = 0.35x - 0.21$	0.103	0.85	$y = 0.182x - 0.168$	0.082	0.88
CI_{705}	$y = 0.36x + 0.15$	0.096	0.86	$y = 0.25x - 0.0778$	0.075	0.94
Red edge $NDVI_{740}$	$y = 18.8x - 1.06$	0.089	0.91	$y = 17.1x - 0.832$	0.093	0.92
MTCI	$y = 0.24x - 0.54$	0.087	0.89	$y = 0.202x - 0.473$	0.089	0.90
CI_{740}	$y = 6.68x - 0.67$	0.087	0.89	$y = 6.85x - 0.676$	0.089	0.92

The equations for EVI and SR were applied to the VIs to produce canopy Chl estimates.

Remote Sens. 2017, 9, 226; doi:10.3390/rs9030226 www.mdpi.com/journal/remotesensing

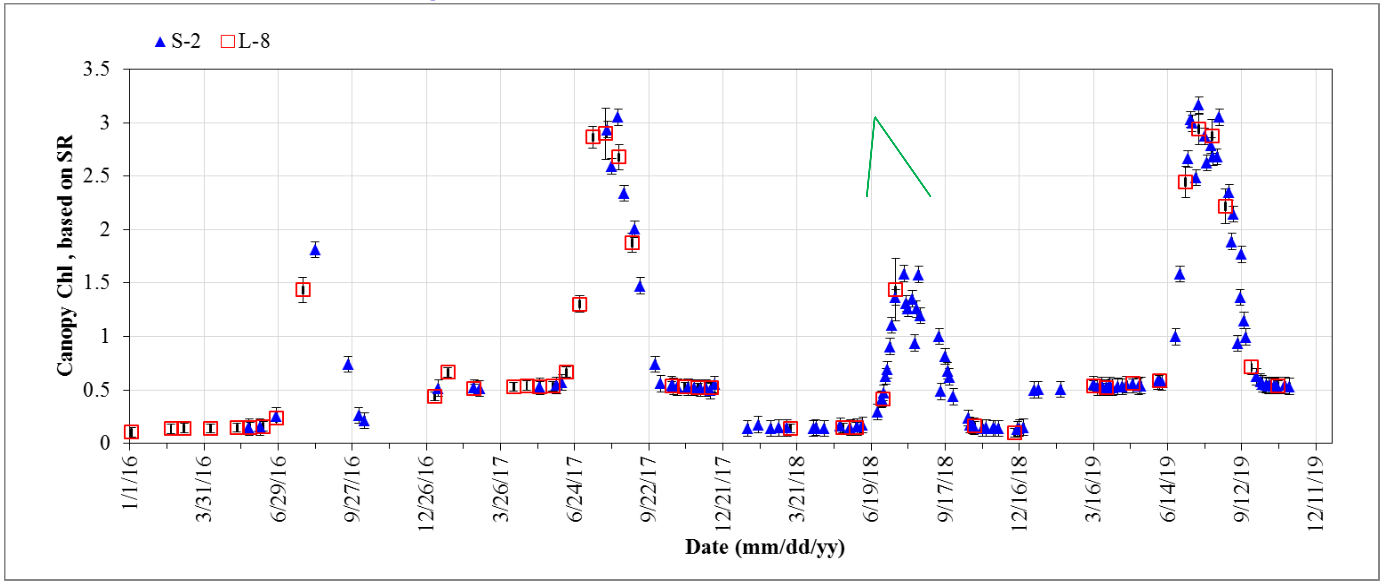
remote sensing MDPI

Article

Assessment of Canopy Chlorophyll Content Retrieval in Maize and Soybean: Implications of Hysteresis on the Development of Generic Algorithms

Yi Peng [1], Anthony Nguy-Robertson [2], Timothy Arkebauer [3] and Anatoly A. Gitelson [2,4,*]

Canopy Chl using SR and equations for soybean and corn, NE3

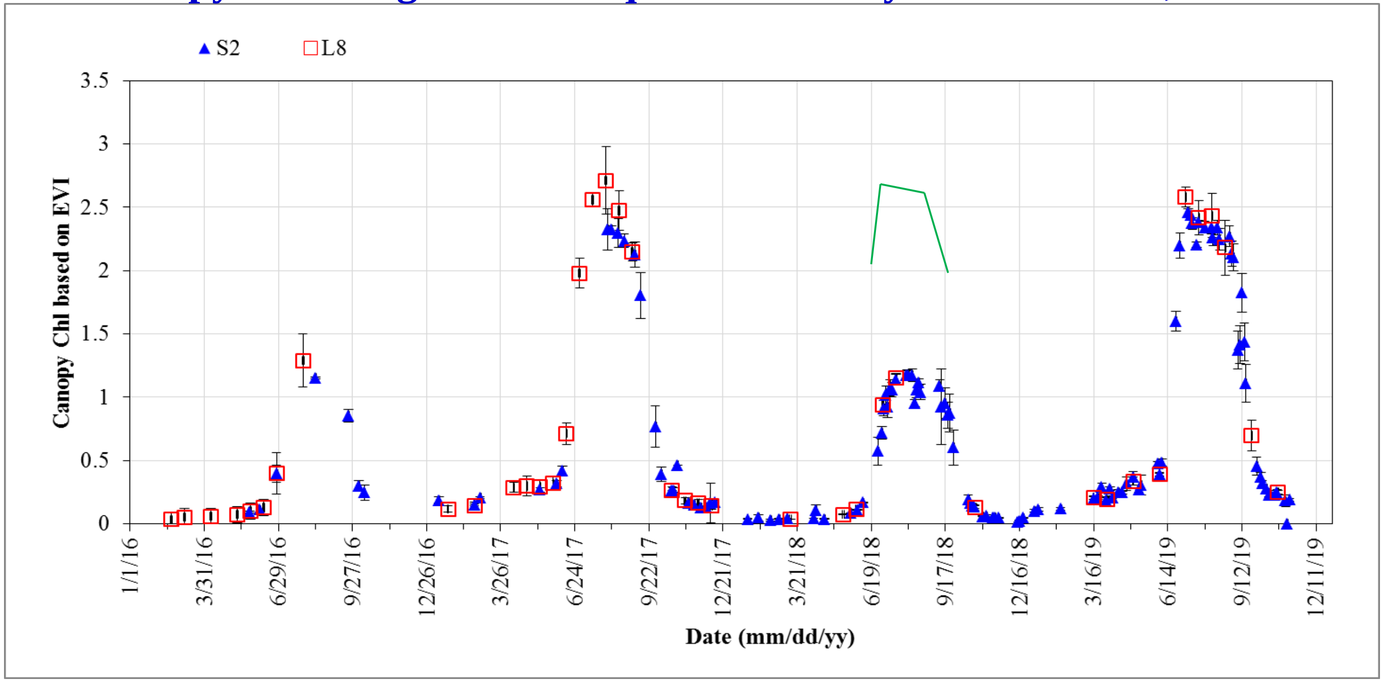


- The same canopy Chl algorithms can be used with S-2 and L-8 with <u>different uncertainty</u>

Maze
*Chl = 0.14*x+0.30*

Soybean
*Chl = 0.0653*x+0.0415*

Canopy Chl using EVI and equations for soybean and corn, NE3

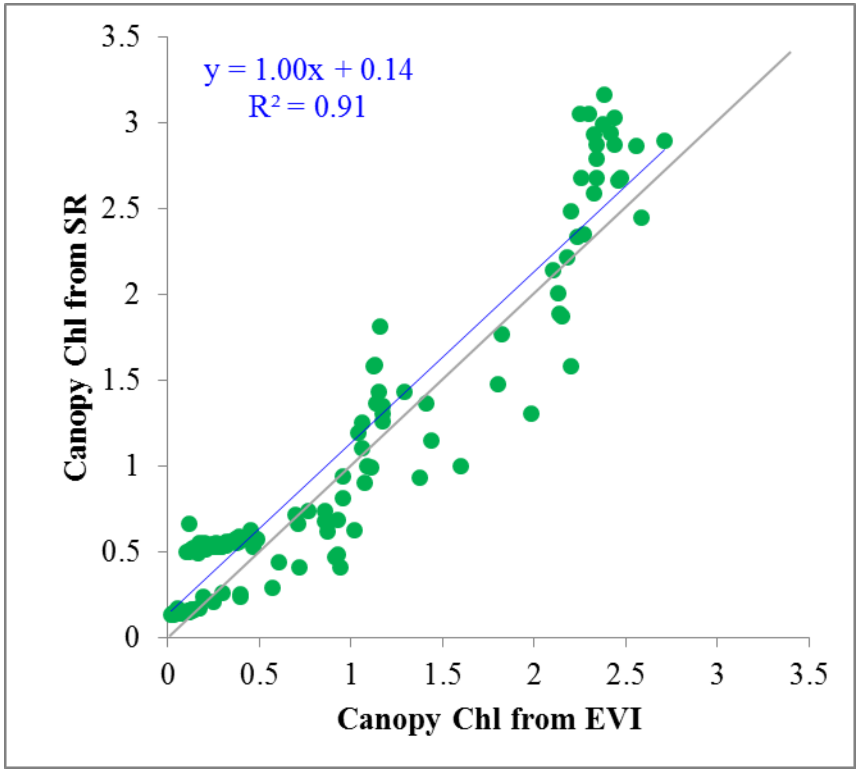


- The ranges in the estimates are comparable, however <u>differences in the sensitivity of the VIs are transferred to the derived canopy Chl</u>

Comparing Chl estimates based on EVI and SR, NE

- Similar magnitudes(slight offset) of Canopy Chl are derived using SR and EVI
- The derived Canopy Chl estimates are strongly correlated

- Next steps:
  - Confirm the equations to apply to the VIs
  - Validation with field data for Leaf Chl and LAI (Canopy Chl = leaf Chl * LAI)
  - Test the TVI and Clre equations that work well at OPE3

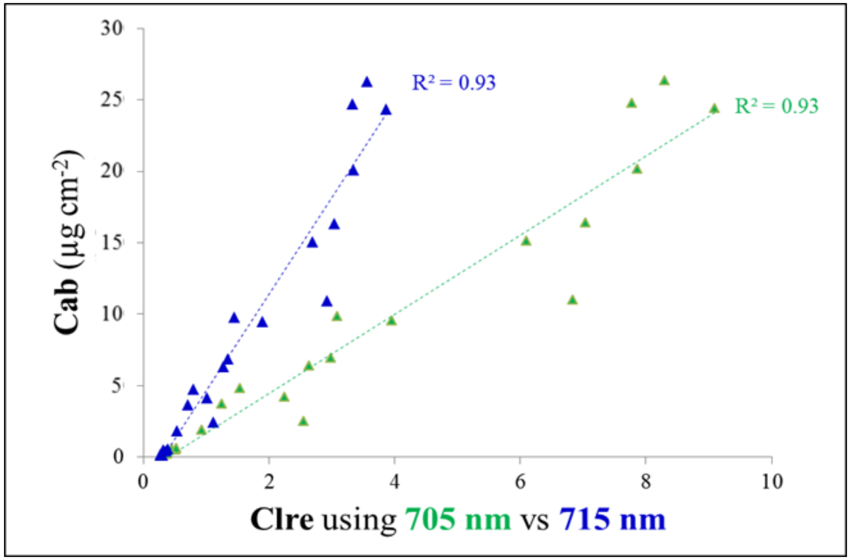


We have produced HLS VIs and canopy Chl time series for all sites in Nebraska (Ne 1 and Ne 2 for the same dates as for Ne 3), which are being validated.

Importance of RE Bands for Chl Detection with VIs

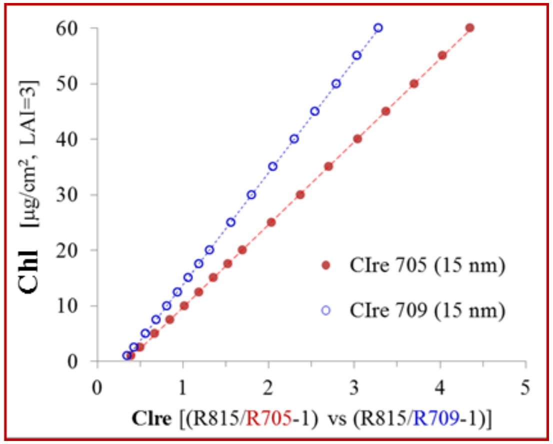
EO-1 Hyperion, OPE3

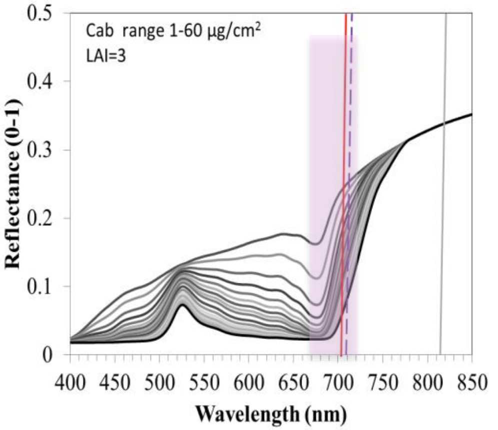
Cl_{re} = (R815/R705 - 1)



SCOPE Reflectance

Chl 1-60 µmol/cm², LAI = 3



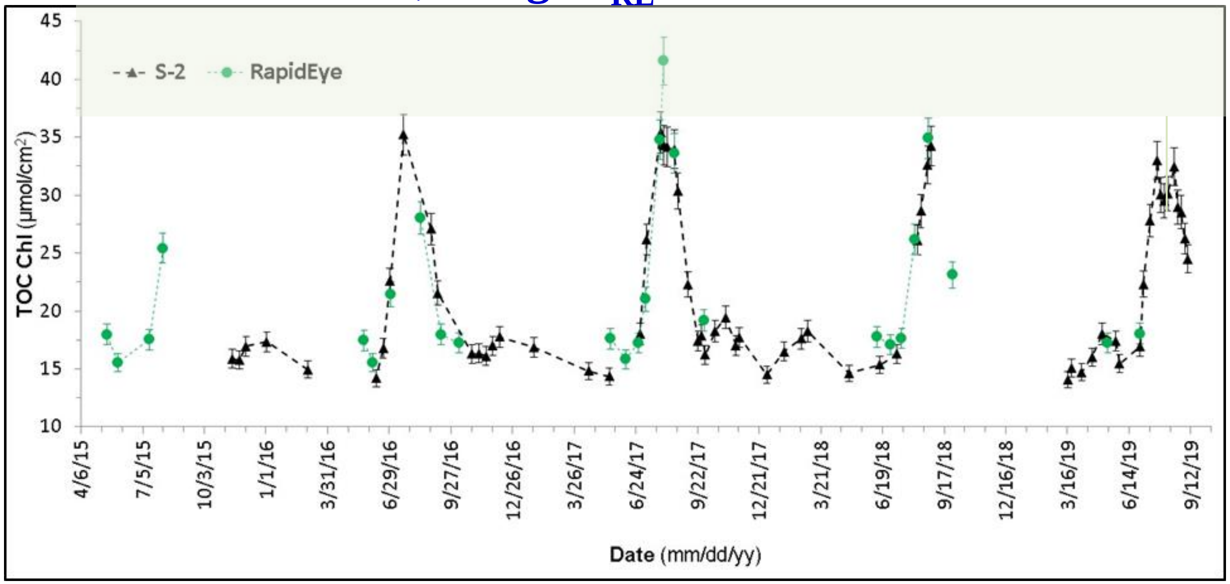


- Using R715 nm instead of R705nm reduces the sensitivity the chlorophyll VI, which is most pronounced at high chlorophyll levels. The result is reduced ability to detect the changes during initial senescence, when chlorophyll level is high.

The dynamic range of a VI is important **– using a red-edge band higher on the RE shoulder** (695-720 nm) **reduces the sensitivity of the VI.**

Importance of the HLS RE bands for Chl VIs

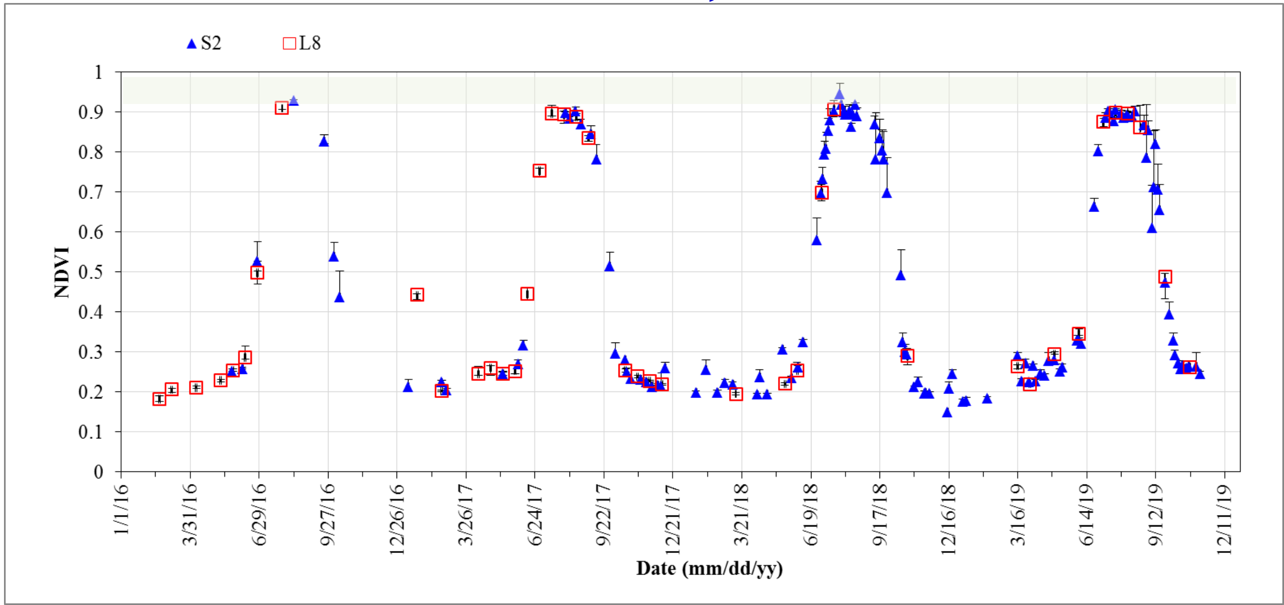
Chl, using CI_{RE} and OPE3



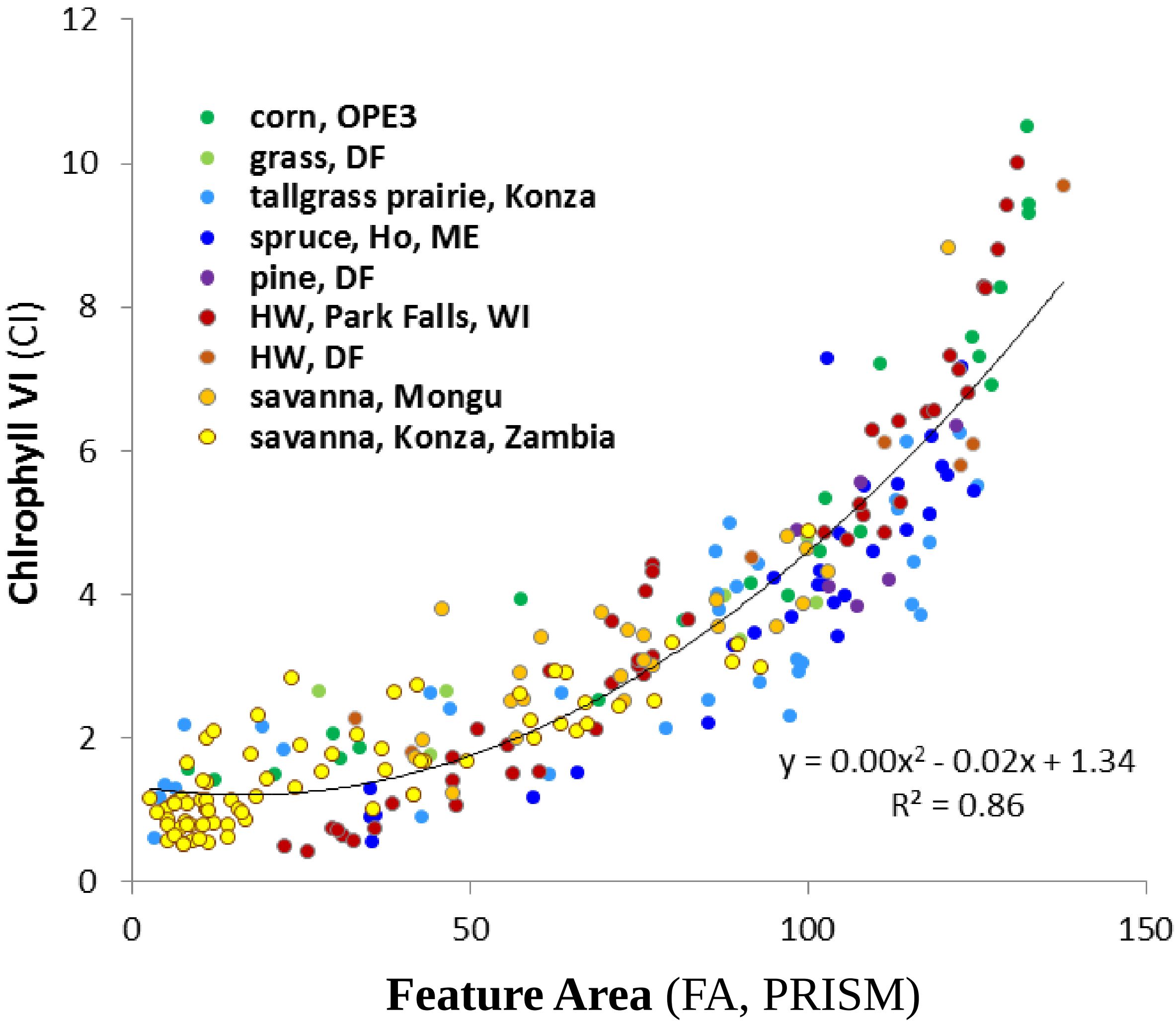
- Using RE bands, a clear maximum and a gradient in increase and decrease in canopy chlorophyll can be observed

HLS NDVI, Ne3

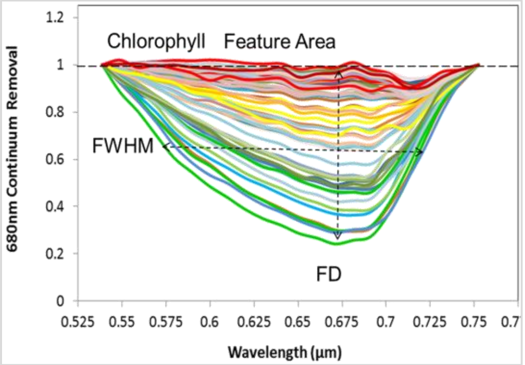
- NDVI increases sharply to maximal values which are maintained for 2-3 weeks at mid-growing season.



Canopy Chlorophyll Detection Using HLS VI vs Spectra



Species	R^2
corn	0.96
grass + tallgrass prairie	0.87
spruce, ME	0.76
pine, DF	0.55
HW, DF and Park Falls	0.95
grassland savanna	0.88
wooded savanna	0.81



Conclusions & *Future Steps*

1) HLS (L-8 & S-2) provides temporarily dense and consistent VIs and Chl time series for assessment of canopy function

2) To produce canopy Chl estimates that scale reliably across species and seasons, we need satellite and field data representative of the key growth stages and needle-age categories

3) HLS Chl VIs (e.g., Cl_{re}, SR, EVI and TVI) can be used together to produce comparable Chl estimates in terms of magnitude, which differ in terms of sensitivity

4) We can scale Chl across seasons and species in crop canopies and are working on the transferability between crops and forests, both deciduous and coniferous

Future steps

- *Expand the dataset to include 2015-2020 - Chl from 2019&20 to be processed*
- *Improve transferability of HLSs Chl x VI algorithms*
  - improve the temporal extend & representativeness of the time series using:
    - VHR (WV & Rapid Eye) and hyperspectral (e.g., proximal, airborne, DESIS)
    - RTMo to add missing growth stages
  - improve VIs calibration & representativeness – forest shadow masks; $NAC_{1\text{-}3}$ data for coniferous
- *Evaluate the Cab time series ability for detection of stress*
  - compare rain-fed /irrigated for crops,
  - compare trends in canopy Chl to field measured productivity (GPP from towers)

Student Thesis

1. M. Abdulahi: Diurnal and Seasonal Course of Vegetation Reflectance and Indices: Physically based Analysis and Implication for Multisource Data Applications, Ph.D., PC/FH/BD UMBC, delayed
2. P. Bednář: Seasonal dynamics of physiological parameters of Norway spruce needles in mountain forest“, M.Sc., JA / ZL CUNI
3. Z. Češpírová: Seasonal dynamics of selected anatomical and physiological leaf traits in floodplain forest, M.Sc., ZL / JA CUNI, delayed
4. M. Horešovská: Seasonal dynamics of selected anatomical, physiological and spectral parameters of beech leaf in relation to drought, M.Sc., JA / ZL CUNI, gap year
5. L. Hunt: Dynamic structural, histochemical and optical changes in grass leaf protective mechanisms under changing environmental factors, Ph.D., JA/ZL CUNI
6. P. Mamula: Relationship between leaf biochemistry, physiology and specie´s competitiveness in selected grasses of relict tundra in Krkonoše Mts.“, 1st year of the M.Sc. study, ZL/JA CUNI
7. G. Pinlová: Determination of chlorophyll content in selected grass communities of the Krkonoše tundra based on field spectroscopy and aerial hyperspectral data, M.Sc, LC, CUNI
8. M. Roubalová: Classification and evaluation of the physiological state of vegetation of selected species heterogeneous ecosystems (tundra, Lanžhot forest) using laboratory and image spectroscopy , Ph.D. LK CUNI

Manuscripts and *Presentations*

- ✓ Yang, P.; van der Tol, C.; Campbell, P. K.E.; and Middleton, E. M. (2020). Fluorescence Correction Vegetation Index (FCVI): A physically based reflectance index to separate physiological and non-physiological information in far-red sun-induced chlorophyll fluorescence. Remote Sensing of Environment, Volume 240, 2020, 111676, ISSN 0034-4257, https://doi.org/10.1016/j.rse.2020.111676.
- ✓ Campbell, P.K.E.; Huemmrich, K.F.; Middleton, E.M.; Ward, L.A.; Julitta, T.; Daughtry, C.; Burcart, A.; Russ, A.L.; Kustas, W.P. (2019). Diurnal and Seasonal Variations in Chlorophyll Fluorescence Associated with Photosynthesis at Leaf and Canopy Scales. Remote Sens. 2019, Special Issue Quantifying and Validating Remote Sensing Measurements of Chlorophyll Fluorescence, 11(5), 488. DOI: 10.3390/rs11050488
- ○ P. Campbell, P, Lukes, F. Huemmrich, C. Neight, J. Albrechtova, E. Middleton and others. Comparing canopy chlorophyll algorithms and series for crops and deciduous forests. In progress, submit to RS “Remote Sensing for Estimating Leaf Chlorophyll Content in Plants”.
- ○ Z. Lhotakova, L. Kupkova, P. Lukes, E. Neuwirthová, L. Cervena, R. Janoutová, L. Homolová, M. Potuckova, P. Campbell, J. Albrechtova: Calibration model for different chlorophyll measurement instruments (SPAD-502, CCM-300, DualFlex) development based on laboratory chlorophyll estimations. In progress, submission: 2021.

P. Campbell, C. Neigh, F. Huemmrich, J. Albrechtova, E. Middleton, M. Abdulahi: Prospects for satellite monitoring of canopy chlorophyll content. Poster presentation by J. Albrechtová, 4th Open Science Meeting of the Global Land Programme. https://glp.earth/osm-2019

L. Červená, L. Kupková, M. Potůčková, J. Lysák, E. Neuwirthová, Z. Lhotáková, J. Albrechtová. Chlorophyll Content Estimations Based on CCM-300, Laboratory Measurements and Field Spectroscopy for Tundra Grass Species in The Krkonoše Mountains. Poster presentation at EARSeL SIG Imaging Spectroscopy, Brno, February 2019.

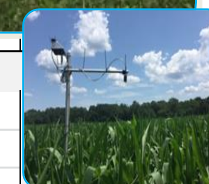
J. Albrechtova, P. Lukes, Z. Lhotakova, L. Kupkova, E. Neuwirthová, L. Cervena, R. Janoutová, L. Homolová, M. Potuckova, P. Campbell: Satellite monitoring of canopy chlorophyll content within the South Central and East European region (SCERIN). Oral presentation by J. Albrechtová, 4th Open Science Meeting of the Global Land Programme. https://glp.earth/osm-2019

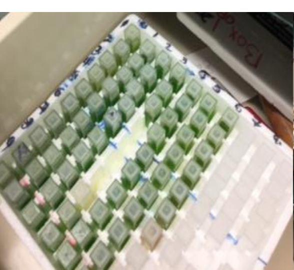
- BACKUP

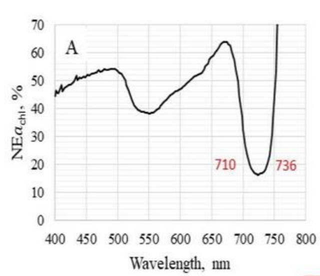
Status of Data Collections and Processing

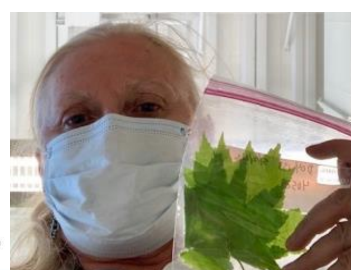
Site ID	OPE3 crops	NE (1, 2, 3) crops	SERC mixed deciduous	Stitna beech	PB crops	GEOMON mixed		
Season				***2017***				
Field Chl and LAI	processed	Chl*LAI in prog.	processed	processed	processed	processed		
HLS Data	VIs, algorithms, TS	VIs, algorithms, TS	VIs, TS	VIs, algorithms	VIs, algorithms	to do		
To do	stress detection	stress detection	PAR/LAI, algorithms	stress detection	stress detection	validate		
Additional Data	leaf R/T, *canopy R*		leaf R/T, canopy R	canopy R	canopy R	leaf R/T, chl		
Season				***2018***				
Field Chl and LAI	processed	Chl*LAI in prog.	processed	processed	processed			
HLS Data	VIs, algorithms	VIs, algorithms	VIs, algorithms	VIs, algorithms	VIs, algorithms			
To do	stress detection	validate	stress detection	stress detection	stress detection			
Additional Data	leaf R/T, *canopy R*			canopy spectra	canopy R			
Season				***2019***	**Lanzhot** beech		**Tundra**	
Field Chl and LAI	collected	LAI ready	collected		processed	collected	processed	
HLS Data	VIs, algorithms	VIs, algorithms	VIs, algorithms		VIs	in progress	in progress	
To do	extract Chl	assemble	extract Chl		stress detection	Chl x LAI	LAI in prog.	
Additional Data	leaf R/T, *canopy R*	collected	leaf R/T		leaf R/T, canopy R	leaf R/T, chl	leaf R/T, canopy R	
Season				***2020***				**Bily Kriz** spruce
Field Chl and LAI	-	collected	collected	collected	collected	collected	collected	collected
HLS Data	VIs, algorithms	VIs, algorithms	in progress	VIs	VIs	in progress	in progress	VIs
To do	model Chl, LAI	assemble	extract Chl	extract Chl	extract Chl	extract Chl	extract Chl	extract Chl
Additional Data	*canopy R*	collected	leaf R/T, *canopy R*	leaf R/T, canopy R	leaf R/T, canopy R	leaf R/T, chl	leaf R/T, canopy R	leaf R/T, canopy R

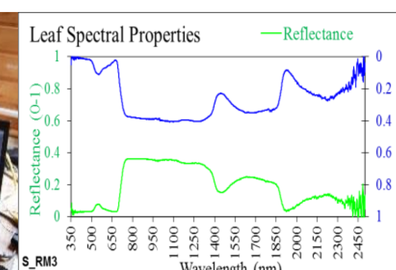
ready = collected and processed
leaf R/T = leaf reflectance/transmittance
in progress = started processing but stopped due to COVID
canopy R = proximal/FLoX, airborne, DESIS, Ven µs



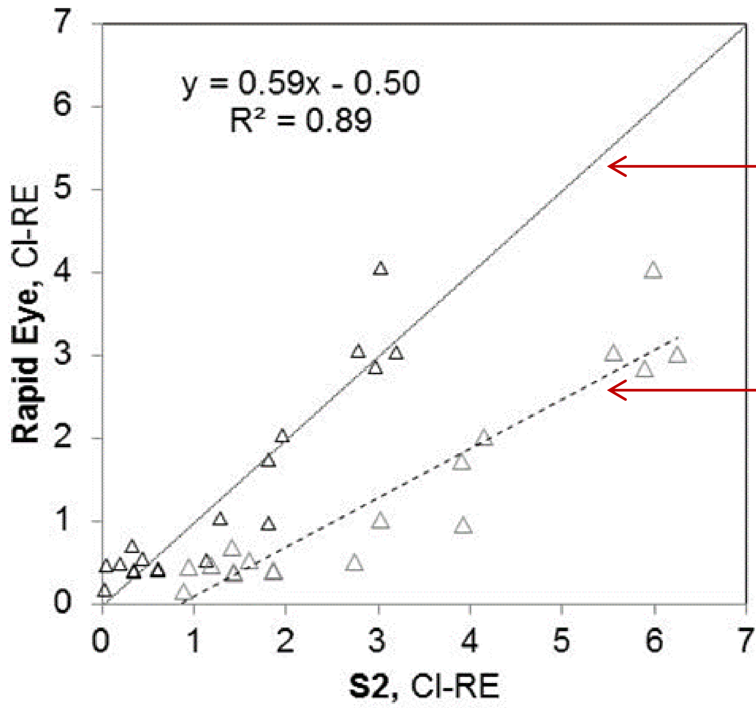








Comparison of Cl-RE from S-2 and Rapid Eye



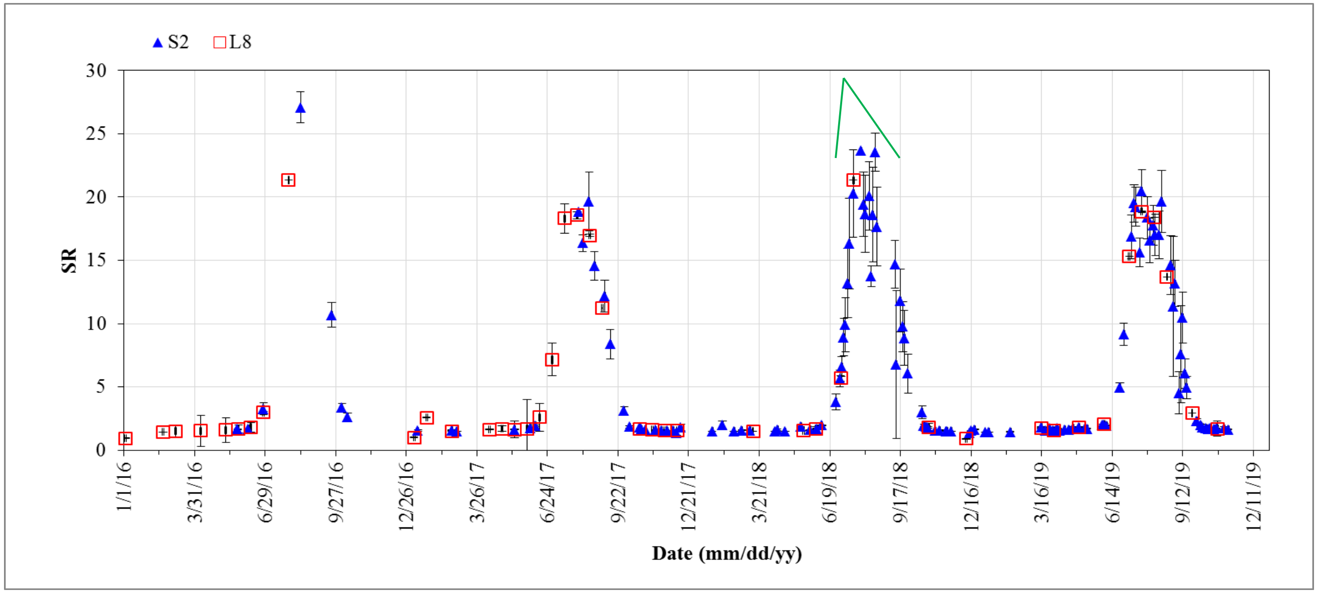
(2) Rapid Eye Cl-RE after calibration to S-2

(1) Rapid Eye underestimated Cl-RE from S-2

- The VIs from S-2 and Rapid Eye are strongly correlated, however Cl_{RE} from Rapid Eye had consistently lower values (1)

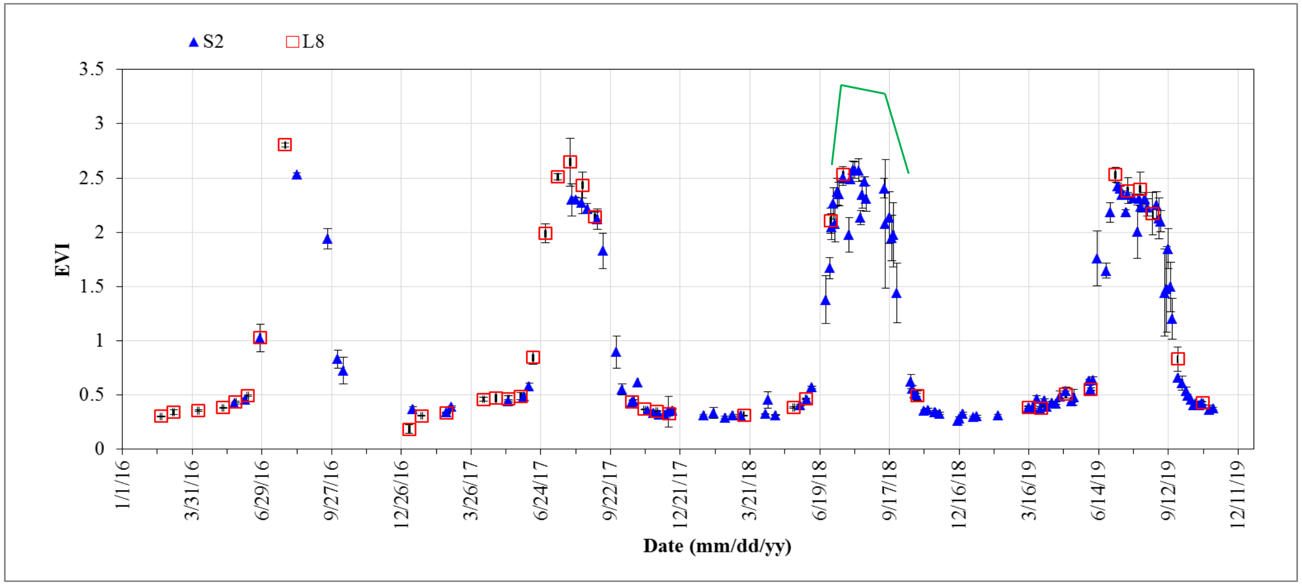
- After calibration of the Rapid Eye data, the Cl_{RE} VI provides the magnitudes obtained from S-2 (2)

SR, NE3; HLS SR = Rnir/Rred



EVI for NE3

HLS EVI = 2.5 (RNIR - Rred)/(RNIR + 6 Rred - 7.5 Rblue + 1)



- The combined L-8 and S-2 VIs time series provide **higher temporal frequency**
- However, the VIs have different sensitivity during the growing season