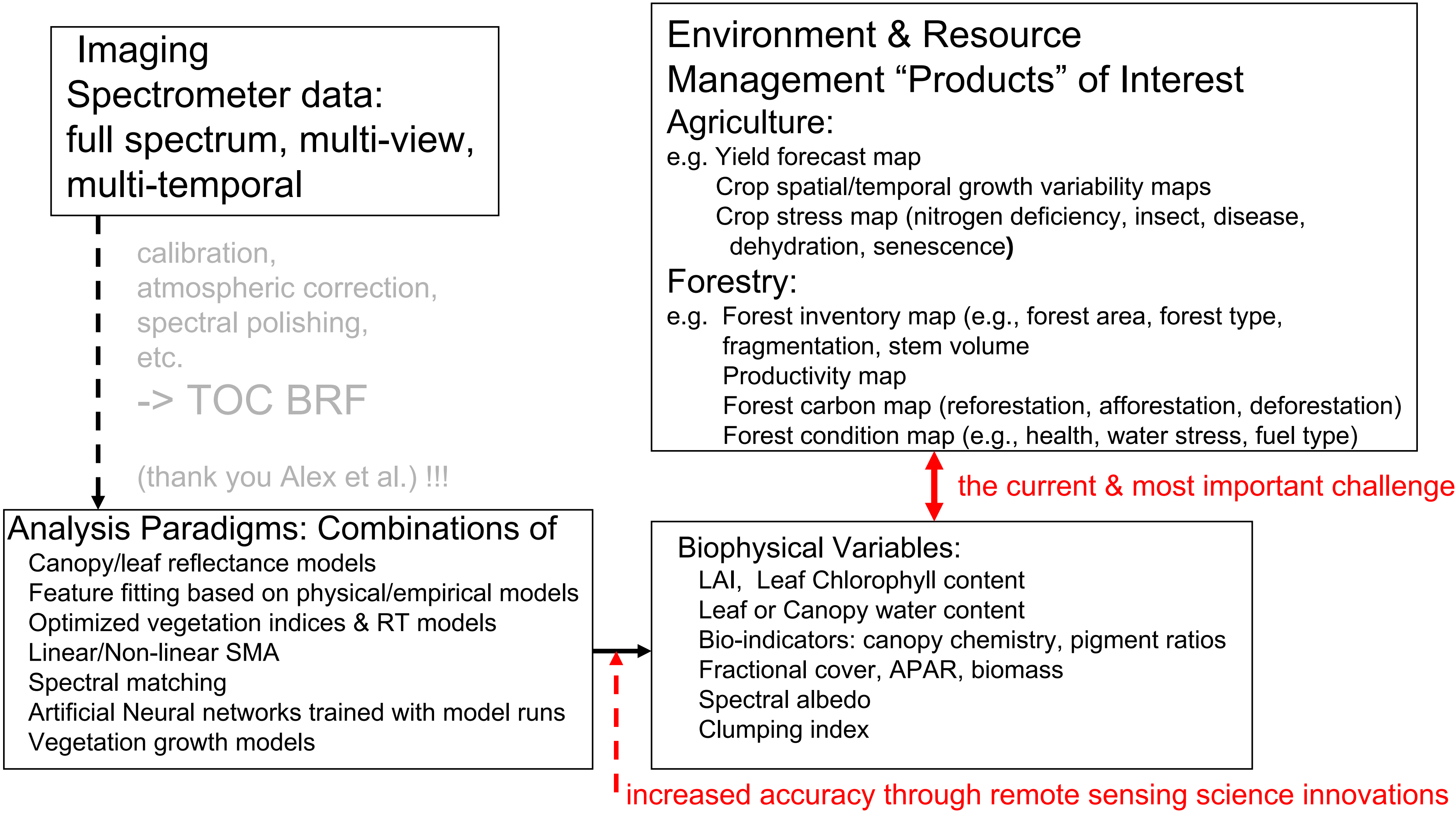
Retrieval of Biophysical/Structural Canopy Properties:
An evolving synthesis of imaging spectrometry data and models

J. Miller, P. Zarco-Tejada, D. Haboudane,
W. Verhoef, S. Jacquemoud, A. Gitelson,
I. Moorthy, H. Bach, D. Riaño,
G. Schaepman-Strub, E. Chuvieco
Canada, Spain, France, Netherlands, USA, Germany

Outline - 2

1. Earth Observations and Analysis Approaches - A perspective
2. Analysis Approach Selection: Rationale and Challenges
3. Analysis Paradigm Development and Assessment
4. Variable Retrieval Maps: Forestry, Agriculture, Landscape
5. New Developments
6. Suggested Next Steps

Perspective – toward a HIS Satellite Mission?



Imaging Spectrometer data:
full spectrum, multi-view, multi-temporal

calibration,
atmospheric correction,
spectral polishing,
etc.
-> TOC BRF

(thank you Alex et al.) !!!

Analysis Paradigms: Combinations of
- Canopy/leaf reflectance models
- Feature fitting based on physical/empirical models
- Optimized vegetation indices & RT models
- Linear/Non-linear SMA
- Spectral matching
- Artificial Neural networks trained with model runs
- Vegetation growth models

Environment & Resource Management "Products" of Interest

Agriculture:
e.g. Yield forecast map
  Crop spatial/temporal growth variability maps
  Crop stress map (nitrogen deficiency, insect, disease, dehydration, senescence)

Forestry:
e.g. Forest inventory map (e.g., forest area, forest type, fragmentation, stem volume
  Productivity map
  Forest carbon map (reforestation, afforestation, deforestation)
  Forest condition map (e.g., health, water stress, fuel type)

the current & most important challenge

Biophysical Variables:
- LAI, Leaf Chlorophyll content
- Leaf or Canopy water content
- Bio-indicators: canopy chemistry, pigment ratios
- Fractional cover, APAR, biomass
- Spectral albedo
- Clumping index

increased accuracy through remote sensing science innovations

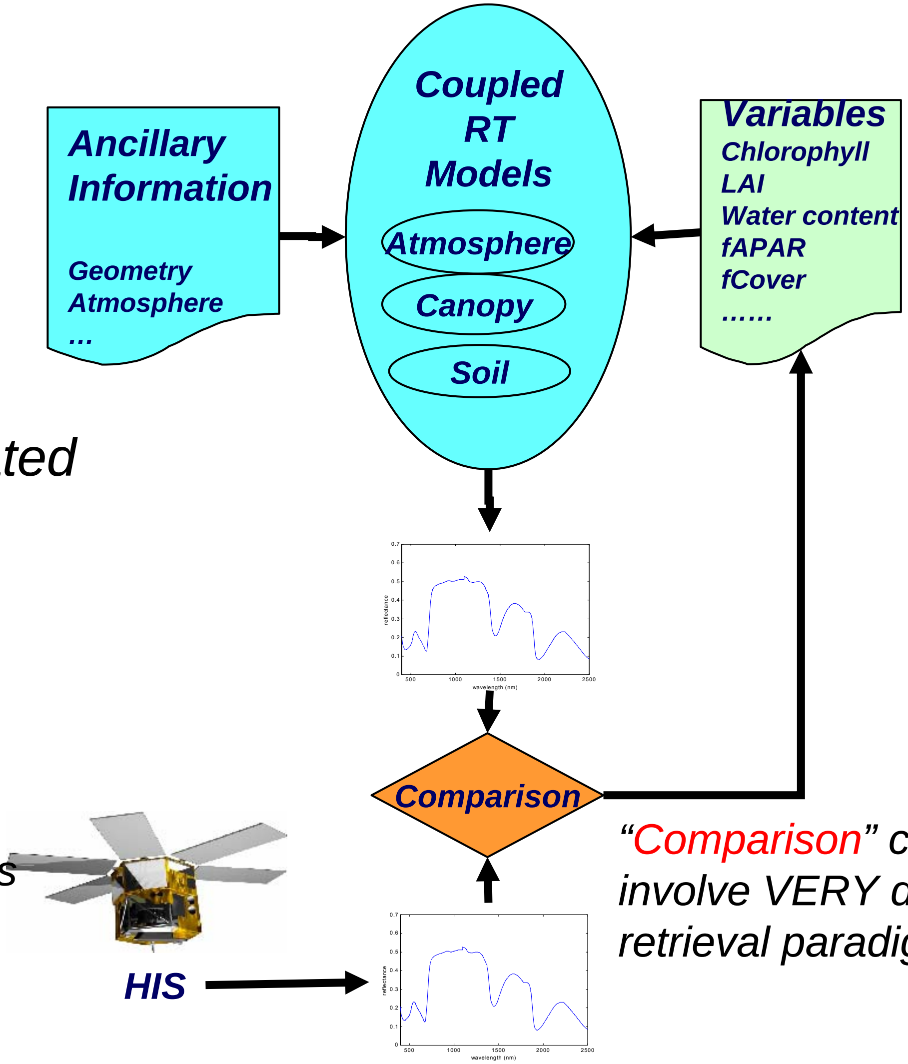
Physical Modelling Approach - Rationale

Implicit Assumptions

- hyperspectral and/or selected narrow band multispectral image data available at required time resolution
- appropriate/validated RT models across spatial scales of target pixel

Potential Advantages Demonstrated

- yields quantitative estimates of target variables that are inherent surface properties, insensitive to location and time of observation
- ground truth ‘calibration” not essential
- rapid delivery of product maps feasible
- responsive to worldwide scientific efforts to develop and improve appropriate RT models and techniques for variable(s) retrieval (i.e. can exploit remote sensing science advances)



“Comparison” can involve VERY different retrieval paradigms

Physical Modelling Approach – Challenges: Target Complexity

Forest Canopies

(Numbered in order of difficulty:
-1 to 3 tackled
-4, 5 underway)

Closed canopies

- Negligible background influence, only shadowing

Sparse canopies

-background influence throughout, with spectral distinctiveness of background critical

Clumped canopies

-background influence between crown, with spectral distinctiveness of background critical

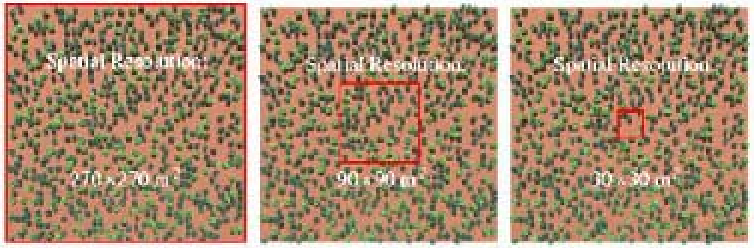
Agriculture Canopies

Physical Modelling Approach – Challenges: Appropriate Models

Numerous canopy models under development and intercomparisons for specific configurations are available

(a) - Side view

(b) - Top view



Pinty et al., 2004. Radiation Transfer Model Intercomparison (RAMI) exercise

Specific canopy/biome/ecosystem conditions allow a judicious choice of RT model for quantitative variable retrieval – authors have experience with

- *SAILH, SAIL++, 4-SAIL, Kuusk-Nilson*
- *FLIM, GeoSAIL, rowSAIL, SPRINT, FLIGHT*

(each coupled with the PROSPECT leaf model)

- chosen as appropriate to canopy closure, density, clumping, closure, background contrast, etc.

Analysis Paradigm Development - Strategy

1. Utilize Airborne Hyperspectral Imagery Collection for Forestry and Precision Agriculture Tests

~ 2 to 4 m spatial resolution hyperspectral imagery - to evaluate spatial heterogeneity
~ <1 m resolution with selected narrow bands - scale of relevance to “users”
nadir view & possible multi-angle imagery potential & measure background R
- multi-temporal (3 or 4 campaigns per season, varying SZA) – evaluate t/s robustness
- multi-year (2 or 3 successive years) – evaluate stability

2. Select (or manipulate) sites for a wide range of biophysical variable values

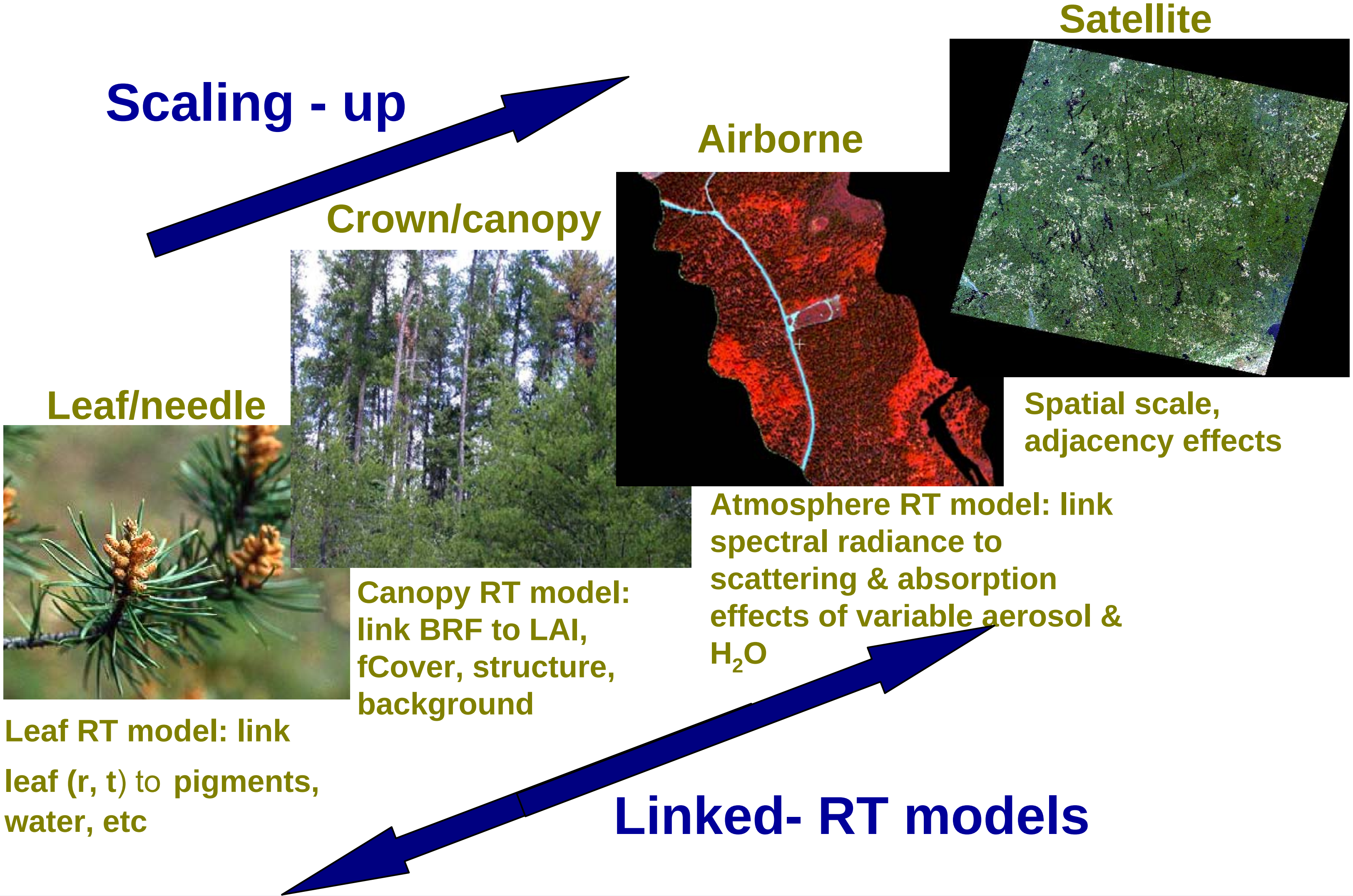
3. Field measurements by Collaborators (AAFC, OFRI) at each scale to Validate/Evaluate RT Models at leaf, canopy, airborne and satellite scales including:

- **top-of-canopy leaf sampling**
- **leaf biochemistry (pigments, water, etc) (AAFC, OFRI) , and optical r, t (York) for leaf RT model characterization/evaluation**
- **atmospheric characterization - AOD (Aeronet)**
- **structural, fCover & understory: LAI, LIDF, fCover, R_b(l), height, clumping**

4. Generate maps of predicted canopy variables for assessment, evaluation, and use and feedback by collaborators to demonstrate robustness, accuracy, temporal/spatial stability

Evaluate effect of Model Assumptions and Real World Canopies

Physical Modelling Approach – Challenges: Linking Scales



Scaling - up

Satellite

Airborne

Crown/canopy

Leaf/needle

Spatial scale, adjacency effects

Atmosphere RT model: link spectral radiance to scattering & absorption effects of variable aerosol & H_2O

Canopy RT model: link BRF to LAI, fCover, structure, background

Leaf RT model: link

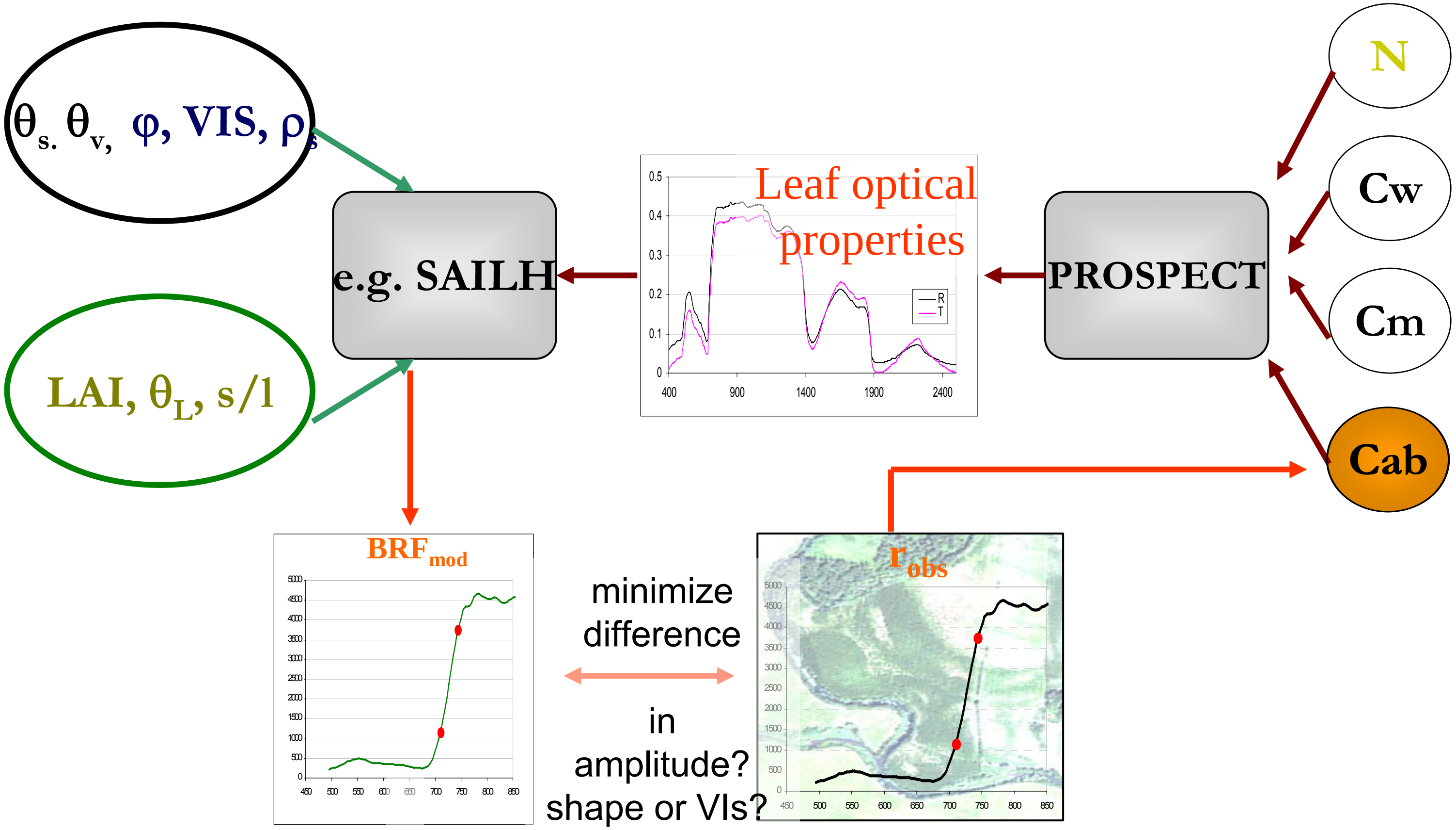
leaf (r, t) to **pigments, water, etc**

Linked- RT models

Canopy Physical Modeling Approach – Variable Retrieval through Inversion

Canopy **BRF** simulation

Leaf **ρ & τ** simulation



θ_s, θ_v, **φ, VIS, ρ_s**

LAI, θ_L, s/l

e.g. SAILH

Leaf optical properties

PROSPECT

N

Cw

Cm

Cab

BRF_{mod}

r_{obs}

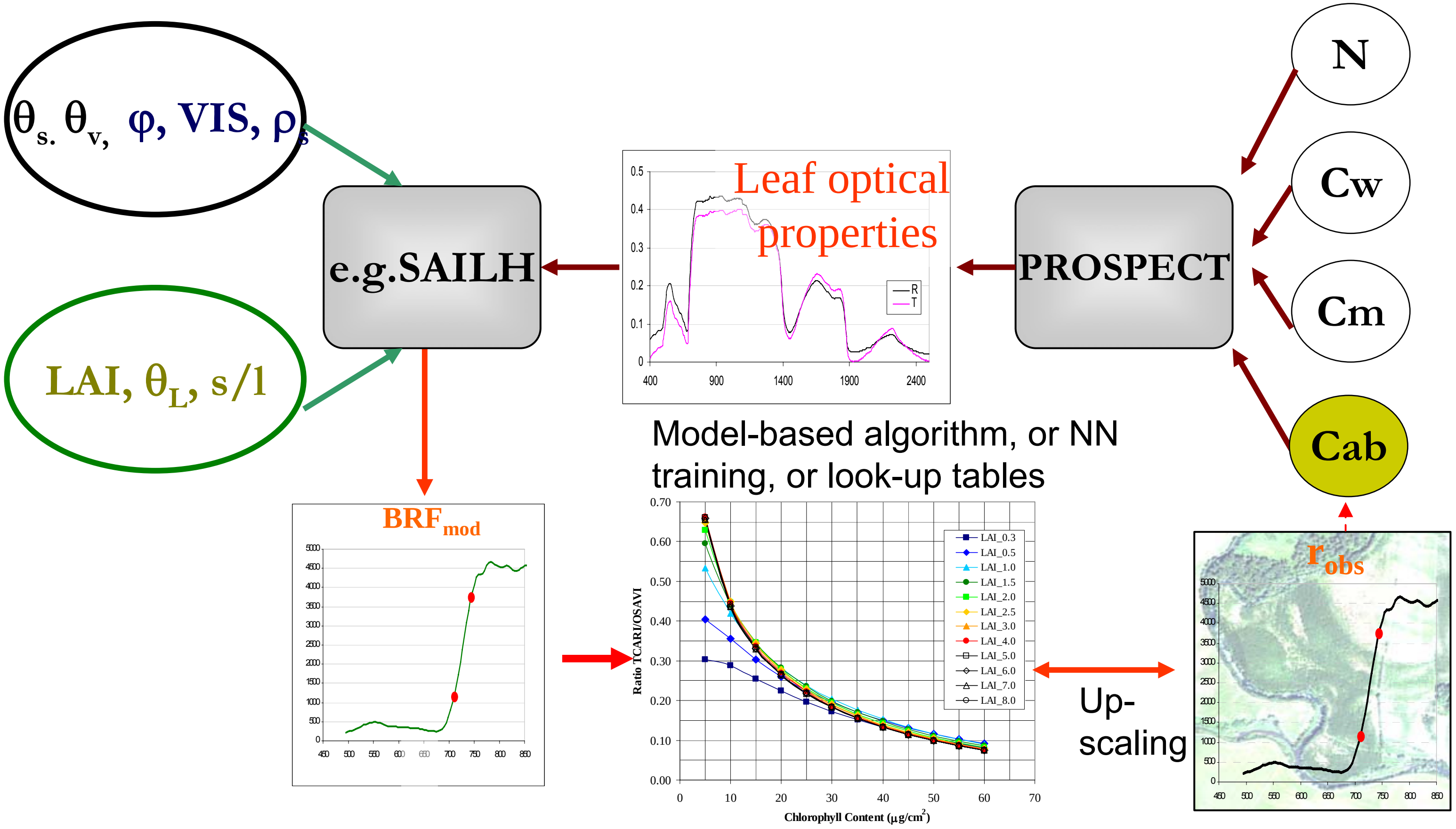
minimize difference

in amplitude?
shape or VIs?
at specific λ s?

Canopy Physical Modeling Approach – Retrieval through Up-Scaling (eg Cab)

Canopy **BRF** simulation

Leaf **ρ & τ** simulation



θ_{s}, θ_{v}, φ, VIS, ρ_{s}

LAI, θ_{L}, s/l

e.g.SAILH

Leaf optical properties

PROSPECT

N

Cw

Cm

Cab

Model-based algorithm, or NN training, or look-up tables

BRF_{mod}

r_{obs}

Up-scaling

Algorithm Evaluation Completed or Underway:

Uniform, extended, dense, closed canopies

- deciduous forests
- cereal crops near maturity

Extended, thin, open canopies

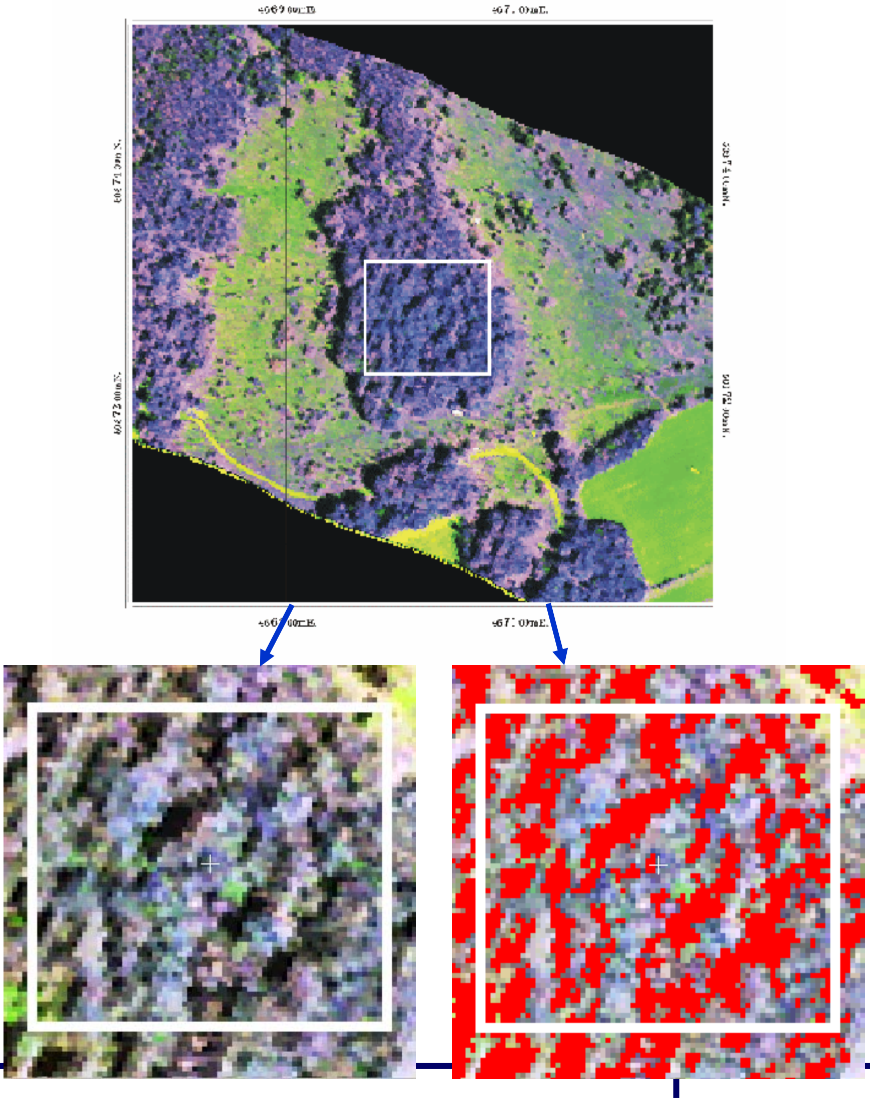
- cereal crops shortly after emergence
- sparse poplar forest stands

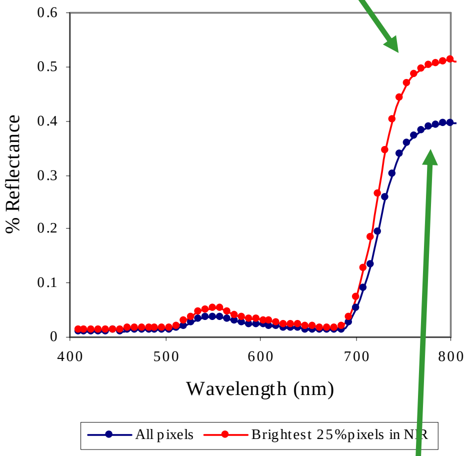
account for Δ background

Open, dense, clumped canopies

- olive groves, vineyards
- conifer forests

Dense-Closed Canopies - select analysis paradigm





brightest pixels targeting crowns

all pixels including shadows

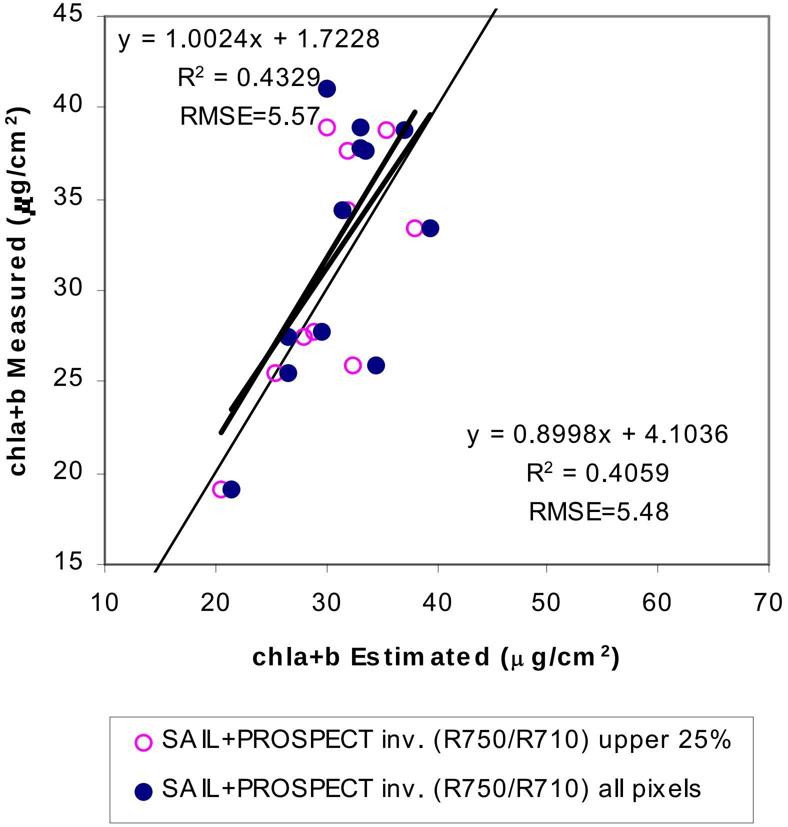
4a. Forestry Algorithm Development - high spatial/hyperspectral tests of model assumptions

Forestry – Leaf Chl from closed, dense deciduous canopies

Deciduous Sugar Maple closed canopy
- leaf chlorophyll retrieval (LAI > 3)
- widely separated individual sites
- canopy shadowing insensitive

<u>Paradigm:</u> inverse RT models
(PROSPECT-SAILH)
with VI (R750/R710) as “best”
merit function for Cab

<u>Application:</u> permits Cab mapping into
3 to 4 bio-indicator “stress” levels,
given known species maps



4b. Forestry Results: Zarco-Tejada et al (2001)

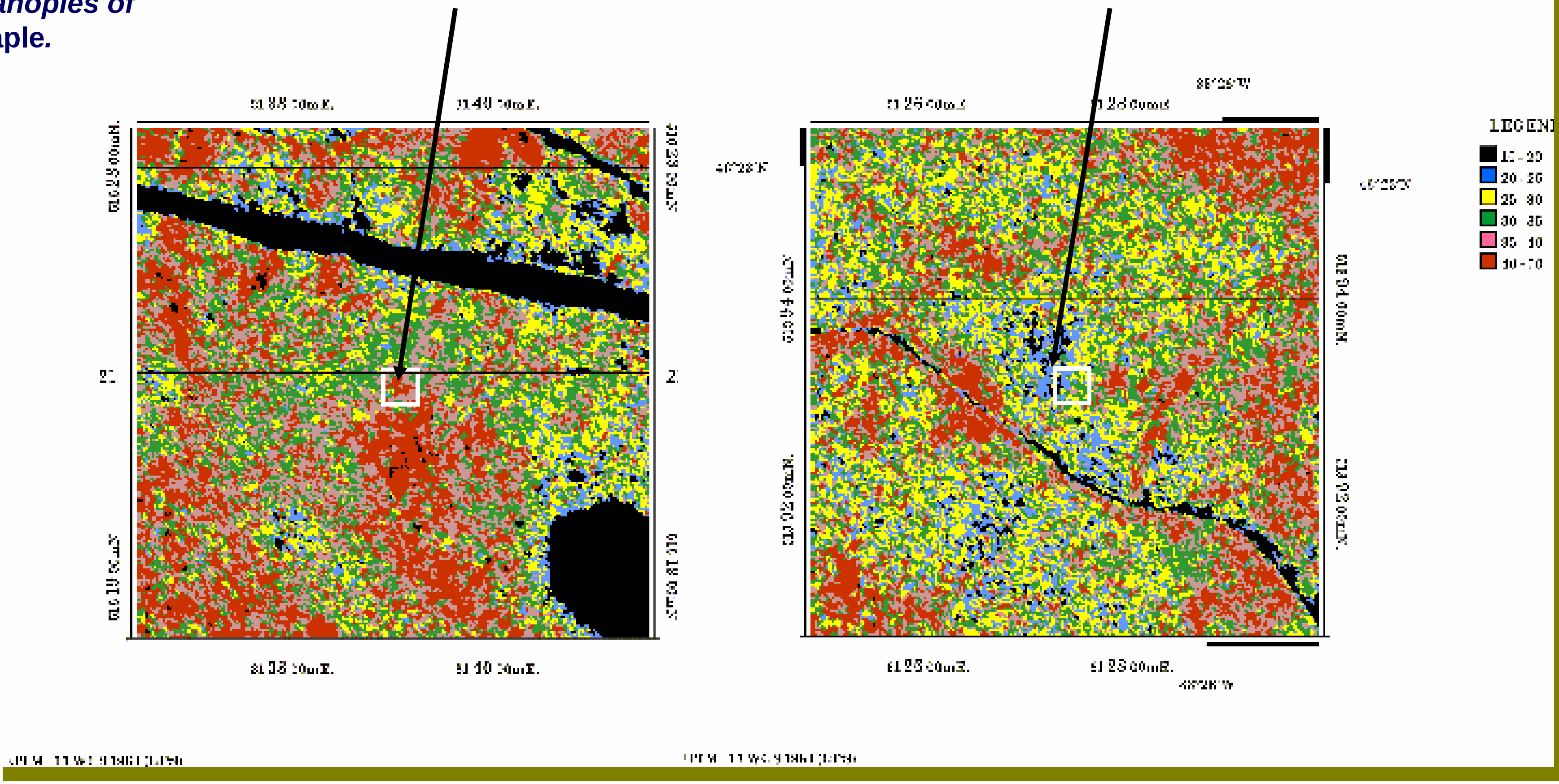
Forestry – Leaf Chl from closed, dense deciduous canopies

IGARSS 2006 &
27th CSRS

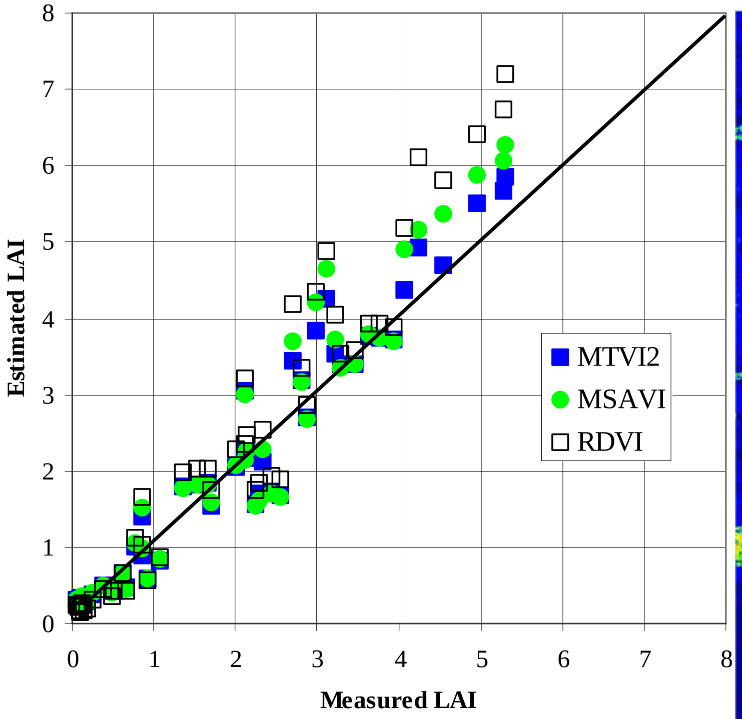
Leaf Chl$_{a+b}$ by numerical model Inversion (SAILH + PROSPECT) for closed canopies of sugar maple.

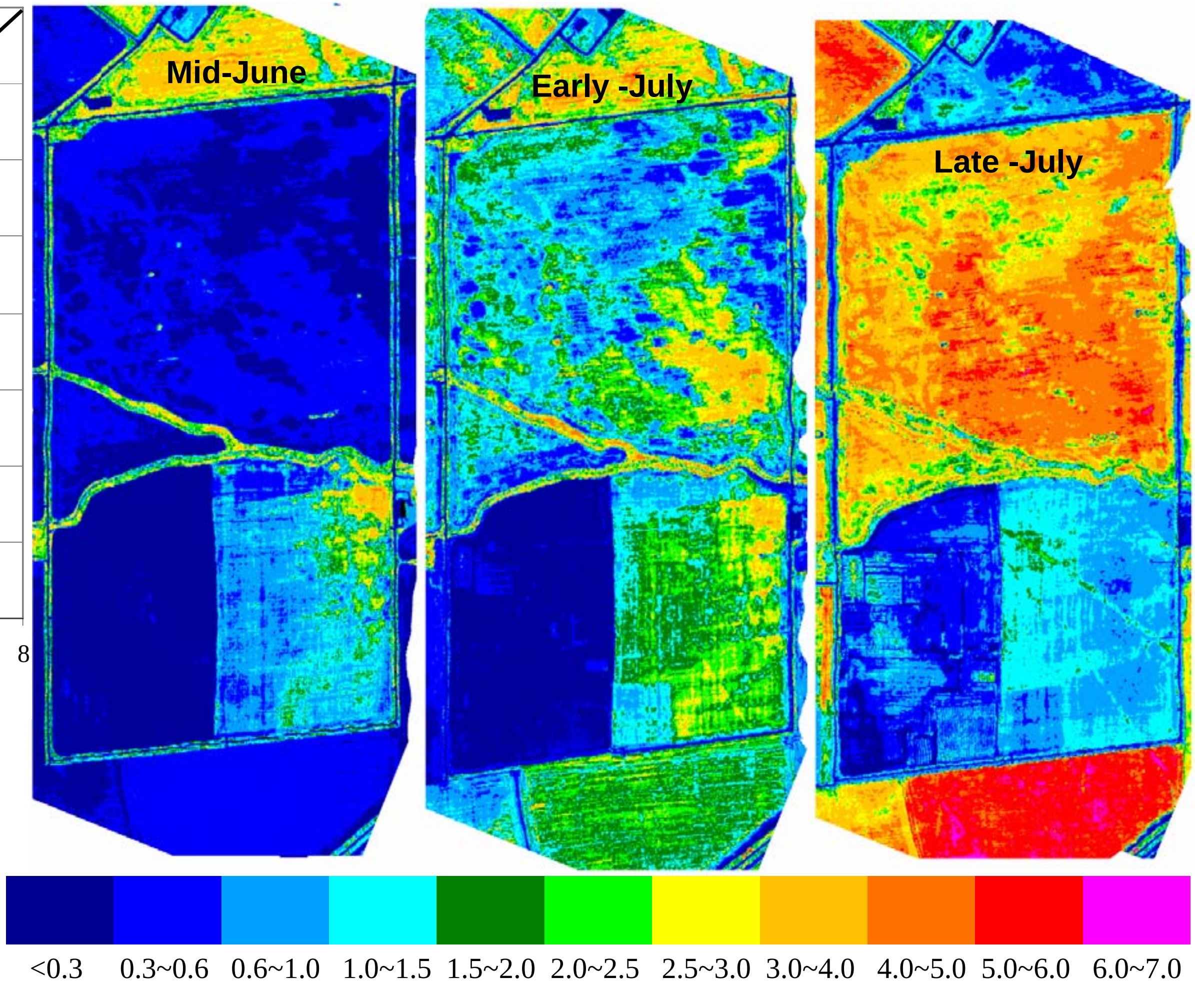
Low stressed site
Measured: 38.8 µg/cm^2
Estimated: 35.2 µg/cm^2

High stressed site
Measured: 19.1 µg/cm^2
Estimated: 20.2 µg/cm^2



Precision Agriculture: AAFC Ottawa Study site –2002: LAI estimation





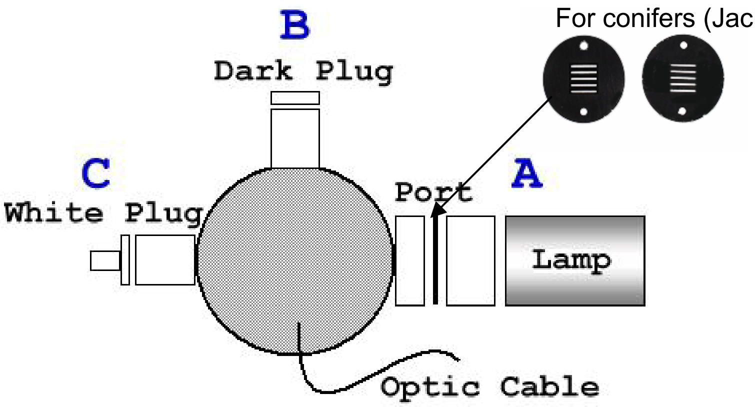
RMSE (and R^2) for LAI prediction were 0.28 (0.98), 0.46 (0.89), and 0.85 (0.74) for soybean, corn and wheat respectively

Paradigm: Up-scaling new VI: MTVI2 based on PROSPECT-SAILH simulations

Application: Seasonal progression of LAI development (< 1 week turnaround) for input into productivity estimates.

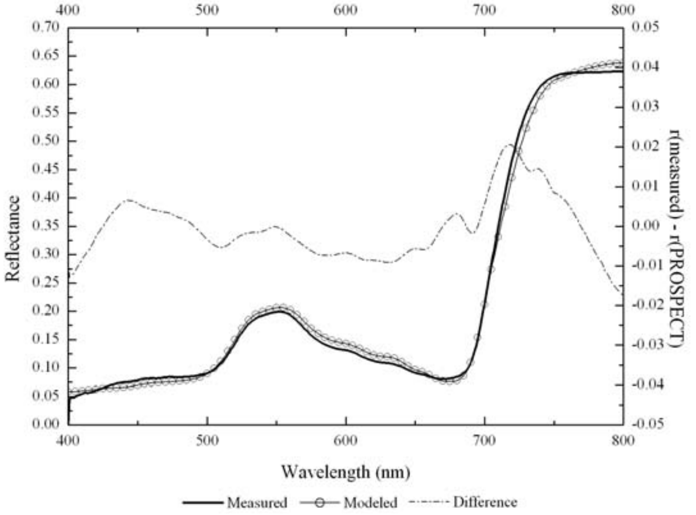
4d. Agriculture Results - Haboudane et al (2003)

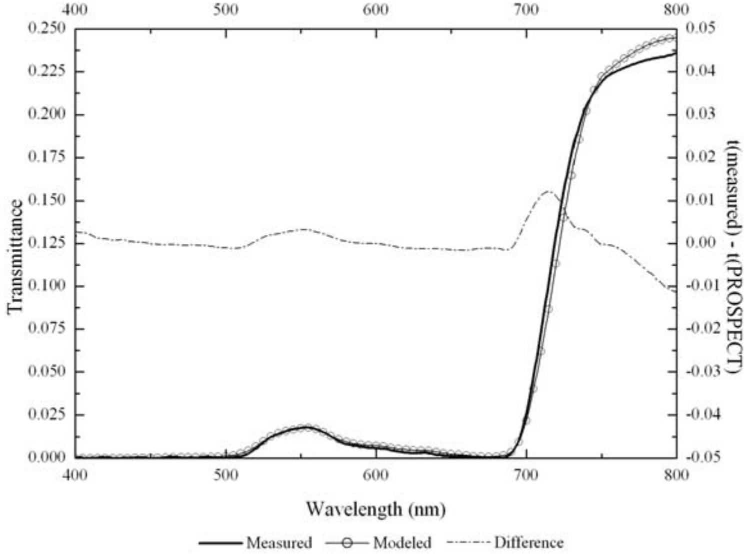
Clumped conifer forest canopies - adapt leaf level models Moorthy et al 2005



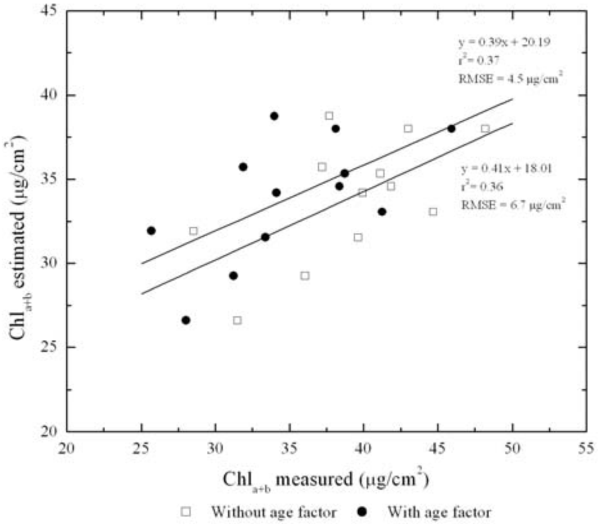
For conifers (Jack Pine needles)

-Note sig. difference in r, t cf broadleaves

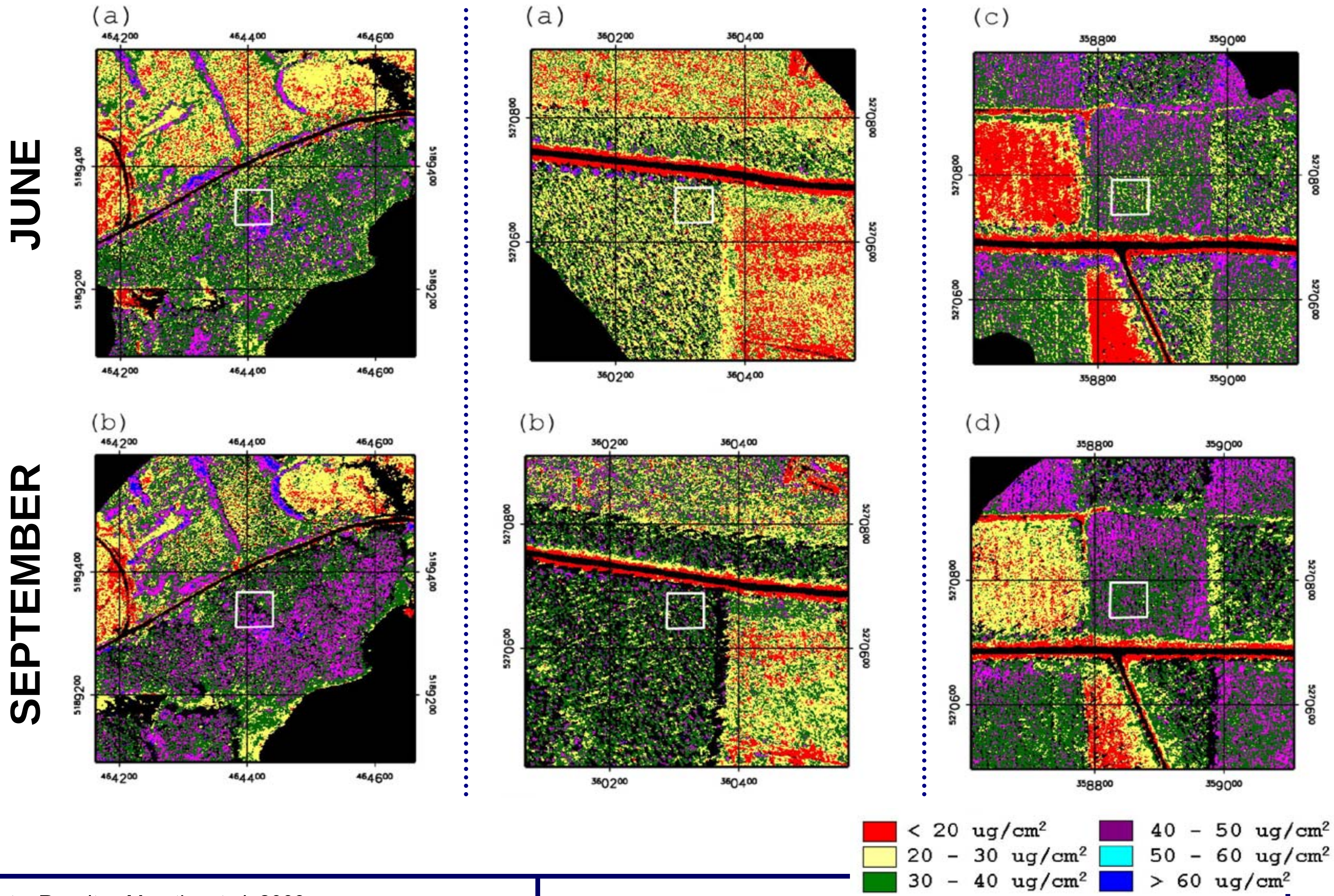




<u>Analysis Paradigm:</u> inverse RT models (PROSPECT-SAILH) for isolated tree crowns with VI (R750/R710) as merit function for Cab



Forestry: seasonal change in average needle Cab in conifer crowns



4f. Forestry Results: Moorthy et al, 2003

Precision Agriculture: clumped crops Chlorophyll & LAI retrievals

Extension of modeling approach to clumped canopies with soil understory - underway (Zarco-Tejada et al , RSE & Brugges, 2004)

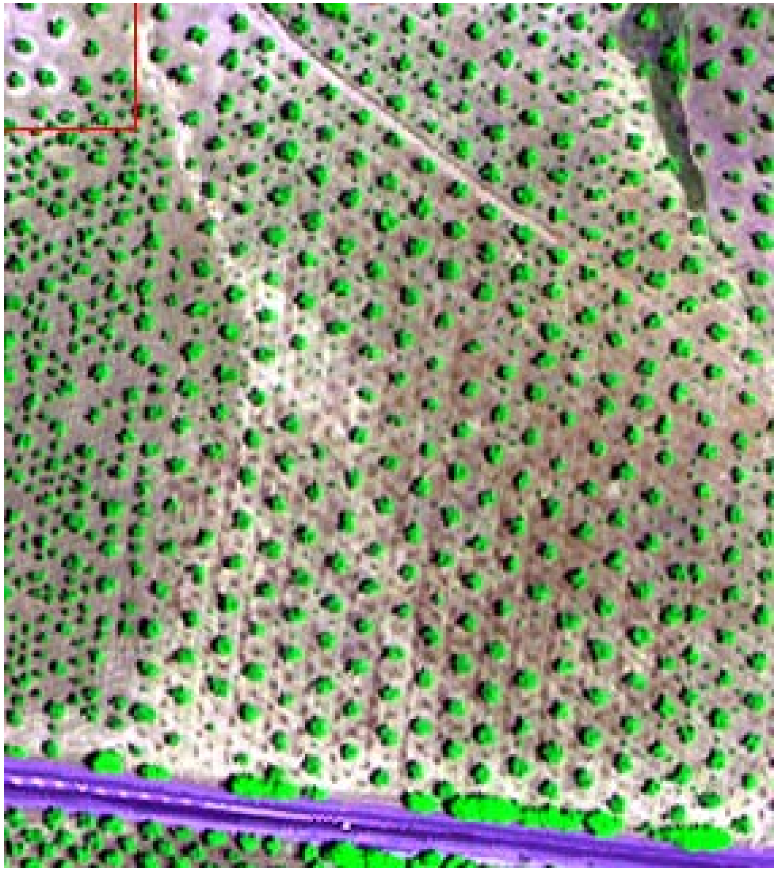
Olive groves in Andalucia, Spain

Vineyards in Castilla-Leon, Spain

4g. Clumped Crops: Zarco-Tejada et al (2004)

CASI Airborne Images: Study Areas in Olive Groves & Vineyards

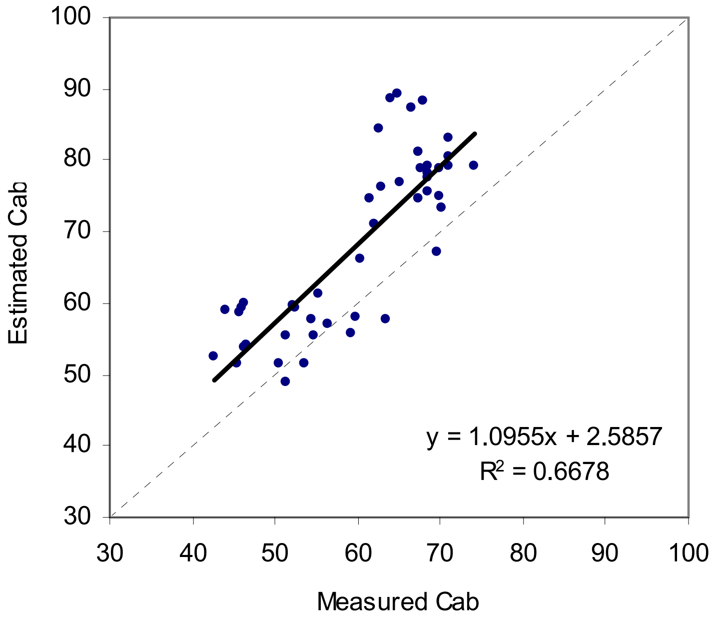
Olive Grove Study sites

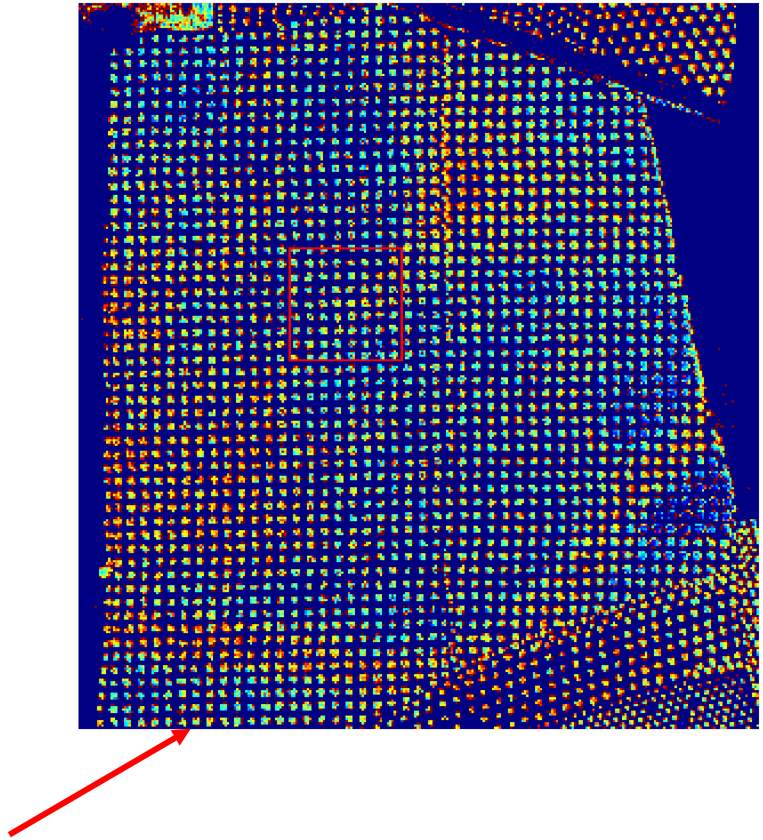


Vineyard Study sites

Zarco-Tejada et al , RSE& Brugges, 2004

Retrievals & Ouput Image: Open-clumped canopies -- Olive Groves





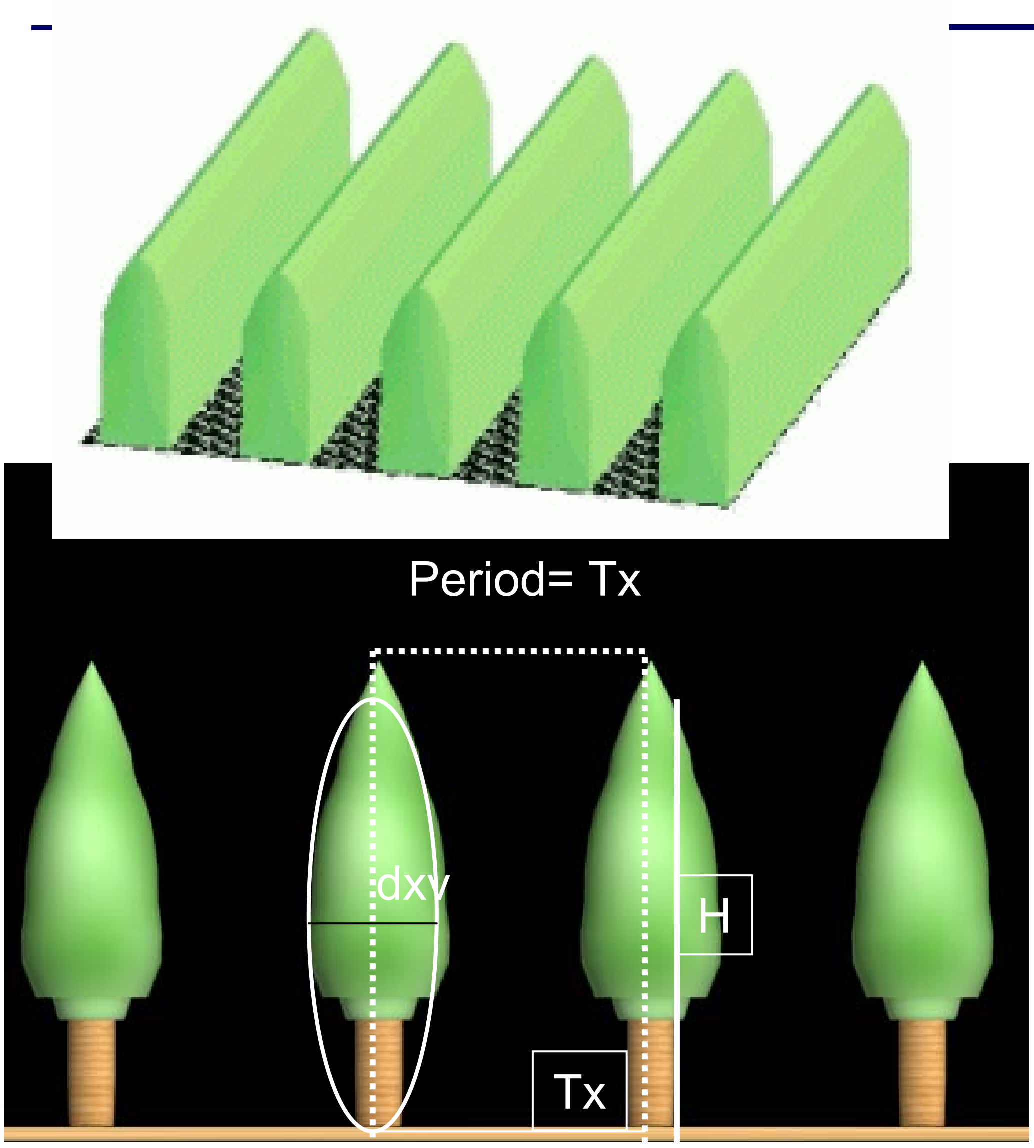
Analysis Paradigm: Cab estimation from crowns only using SAILH-PROSPECT simulation for MCARI/OSAVI VI prediction

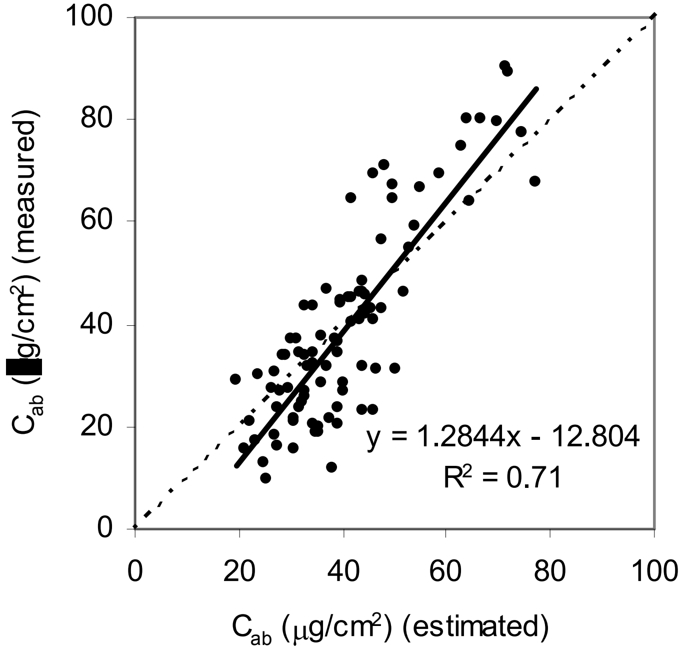
Note: For applicability to coarser spatial resolution sensors, clumped canopy predictions using FLIM and SPRINT also investigated

Application: Crown chlorophyll pigment image showing spatial patterns for precision agriculture management action or potential segregation by oil quality

4h. Clumped Crops (Olive Groves): Zarco-Tejada et al (2004)

Modeling Approach: Vineyards





Analysis Paradigm: Cab estimation at canopy level by scaling up TCARI/OSAVI through PROSPECT + rowMCRM model

Application: Cab variation as a potential surrogate for grapes segregation for wine quality

4i. Clumped Crops (Vineyards): Zarco-Tejada et al (2004)

1. Leaf/canopy model

Biochemical/structural properties

↓

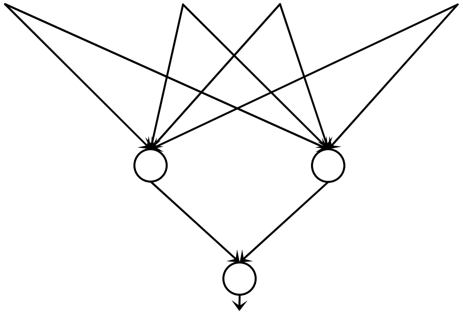
Model

↓

Spectral response

2. Training ANN

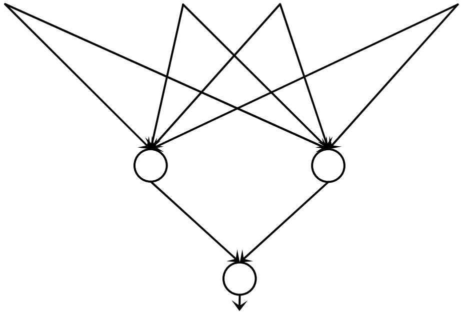
Modelled spectral response



Modelled Biochemical/structural properties

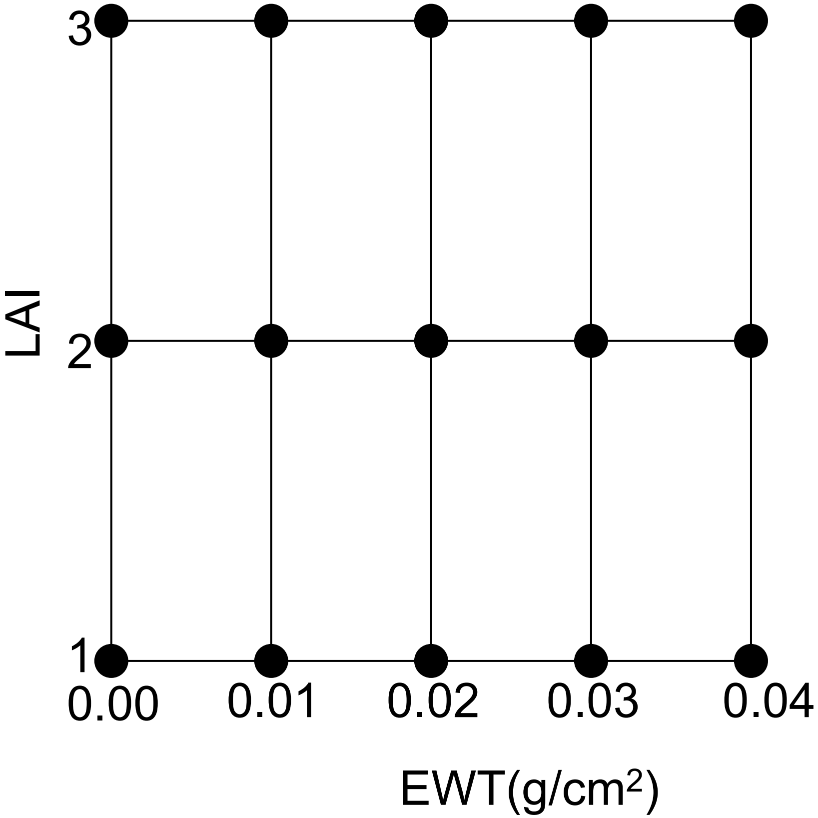
3. Application to image

Image spectral response



Estimated Biochemical/structural properties

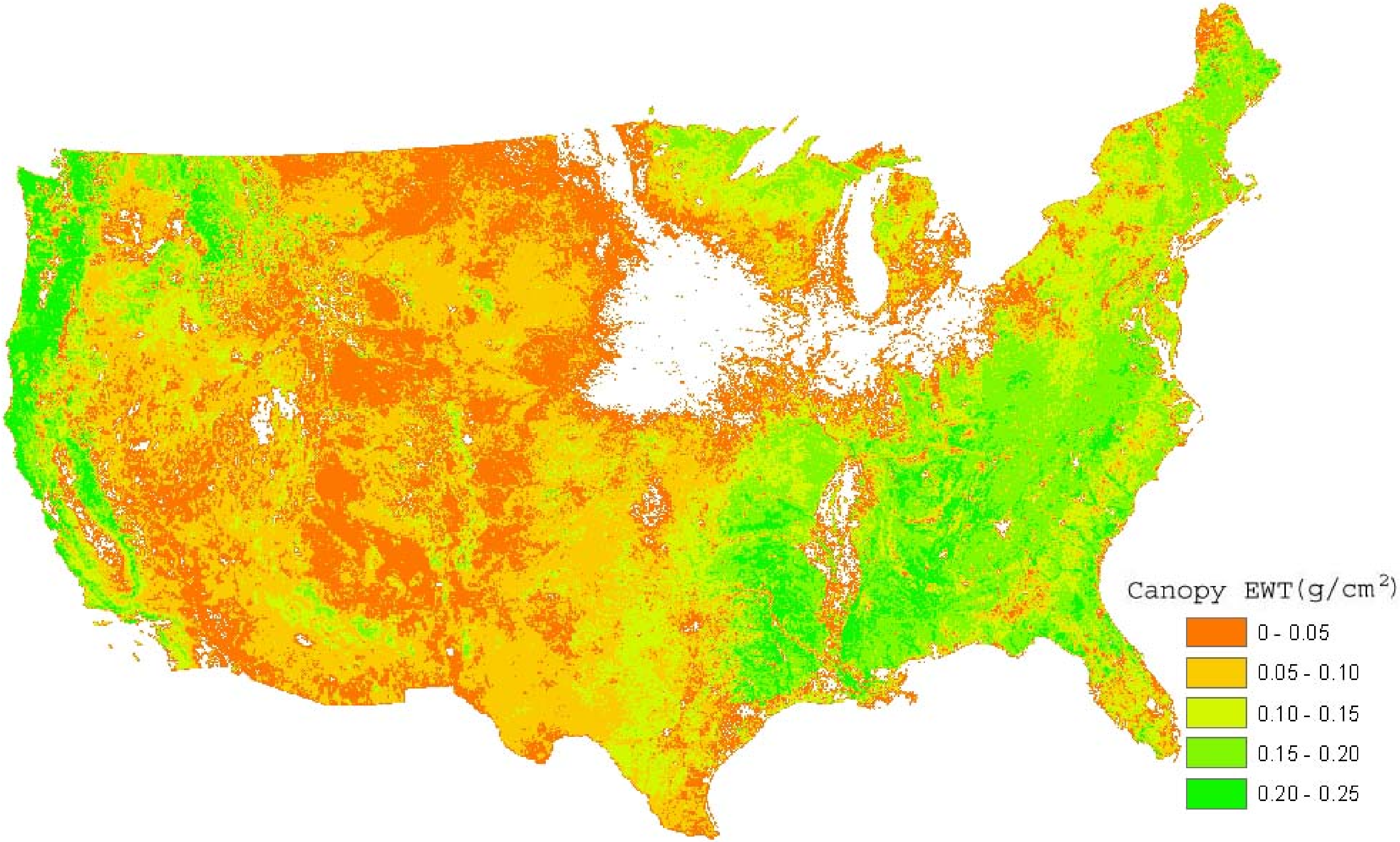
4j. Algorithm Development: Landscape EWT
Riaño et al 2006



Analysis Paradigm: Artificial Neural Network (ANN) trained with canopy reflectance spectra simulations with i) PROSPECT-SAILH, ii) PROSPECT-rowMCRM, and iii) PROSPECT-FLIM models, for grassland, row crop, forest cover types, respectively, for increments in Leaf EWT and canopy LAI.

4k. Landscape EWT estimations: Riaño et al 2006

Canopy EWT form trained ANN for USA landmass using MODIS



4I. Landscape EWT estimations: Riaño et al 2006

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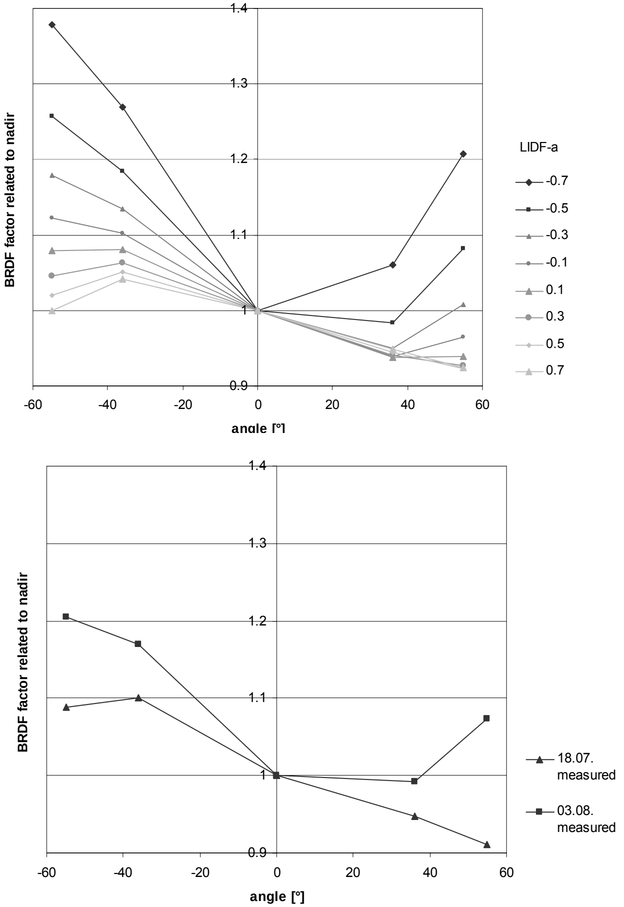
Incorporate multi-angle HIS data to characterize structure & improve retrieval accuracy – Bach & Verhoef

IGARSS 2006 & 27th CSRS

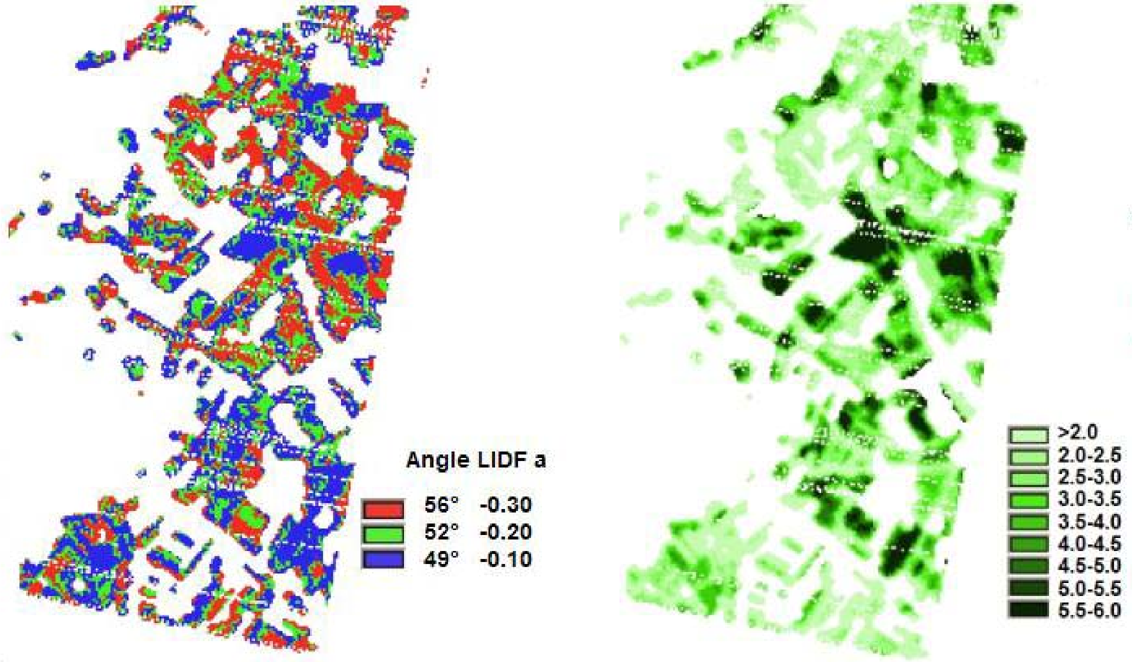
<u>Analysis Paradigm:</u> SLC (Soil-Leaf-Canopy) model *[4SAIL2 canopy model, PROSPECT leaf model, Hapke Soil model, vertical leaf greenness gradient as in GeoSAIL, clumping as in FLIM]* for simulation of surface bi-directional reflectances as seen with CHRIS from the PROBA satellite. Inversions with LUT on a pixel-by-pixel comparison of observed and modeled canopy reflectances with minimization of RMS error on full spectra (Bach et al., 2005).

<u>Applications:</u> Added retrieval of structural parameter LADF, expected to provide improved accuracy in LAI retrievals.



Simulated relative-BRDF factor at 773nm a maize field with LAI of 3.5 and its change with the canopy structure parameter LIDF (top), compared with two BRDF factors for maize measured by CHRIS on July 18 and August 03 (right)

CHRIS-Derived LIDF variation map and associated LAI map



Retrieval results using SLC and five angular CHRIS acquisitions on Jul 18; left: LIDF-a equivalent to average leaf angle; right: Leaf Area Index

Bach & Verhoef (2006)

New Developments: Spectral Albedo – G. Schaepman-Strub (2006)

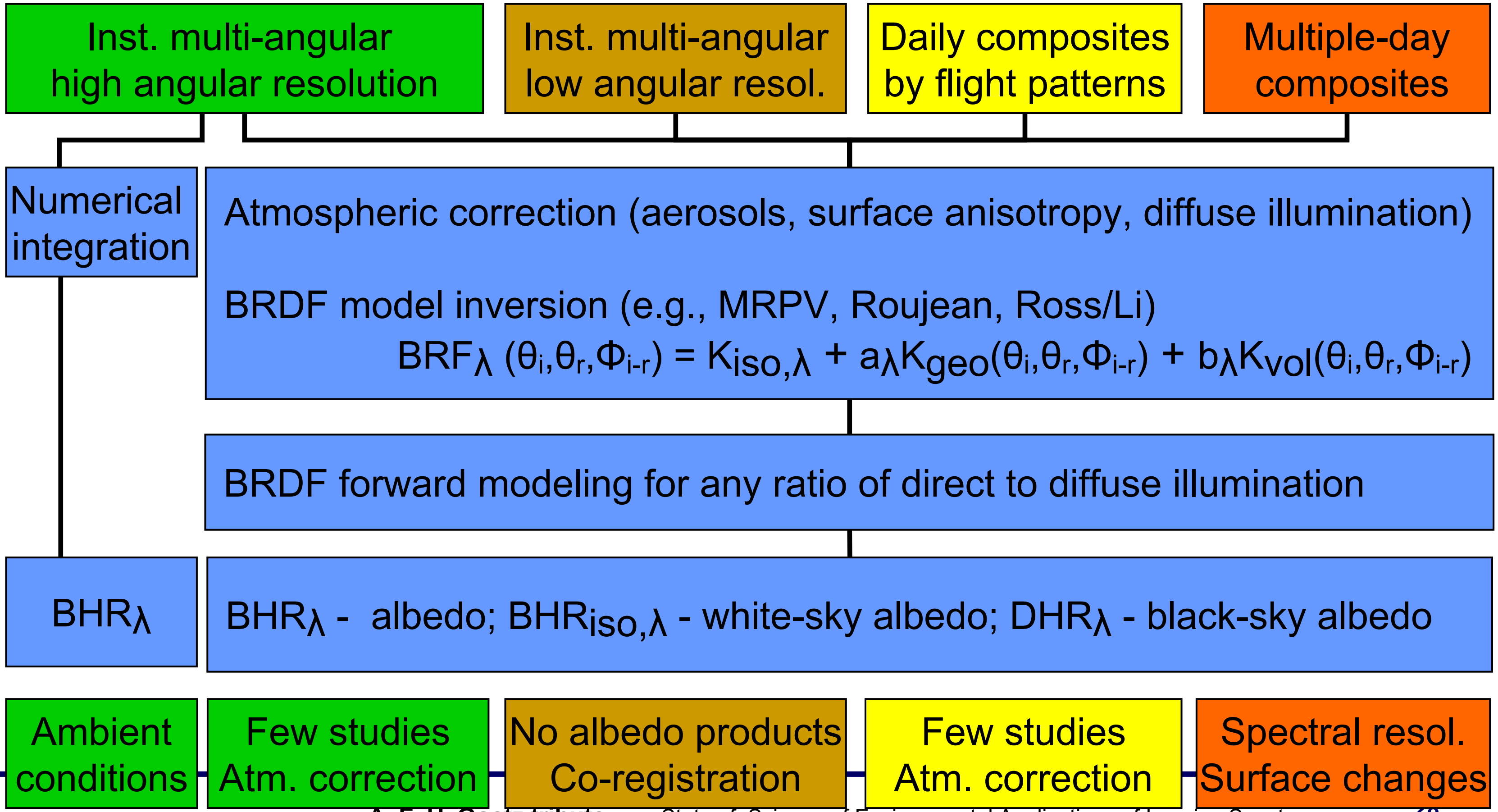
FIGOS

CHRIS

ASAS

HYMAP

MODIS



Inst. multi-angular high angular resolution

Inst. multi-angular low angular resol.

Daily composites by flight patterns

Multiple-day composites

Numerical integration

Atmospheric correction (aerosols, surface anisotropy, diffuse illumination)

BRDF model inversion (e.g., MRPV, Roujean, Ross/Li)

$$BRF_\lambda(\theta_i,\theta_r,\Phi_{i-r}) = K_{iso,\lambda} + a_\lambda K_{geo}(\theta_i,\theta_r,\Phi_{i-r}) + b_\lambda K_{vol}(\theta_i,\theta_r,\Phi_{i-r})$$

BRDF forward modeling for any ratio of direct to diffuse illumination

BHR_λ

BHR_λ - albedo; $BHR_{iso,\lambda}$ - white-sky albedo; DHR_λ - black-sky albedo

Ambient conditions

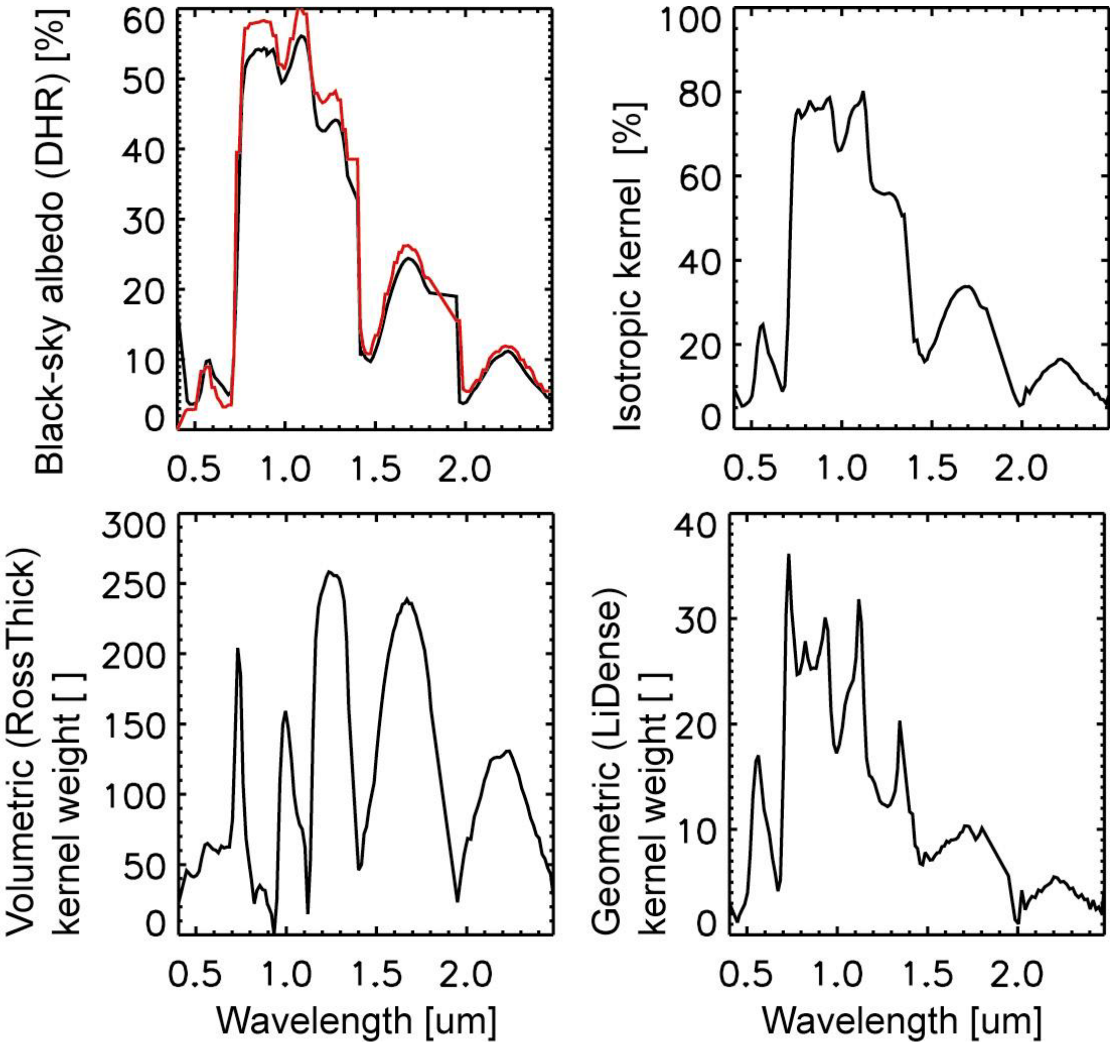
Few studies Atm. correction

No albedo products Co-registration

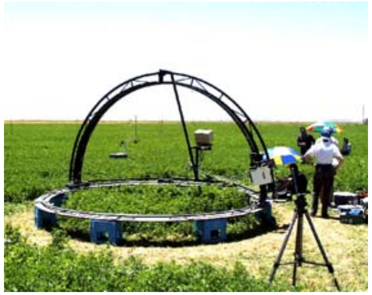
Few studies Atm. correction

Spectral resol. Surface changes

Spectral Albedo of Alfalfa Based on Imaging Spectrometer Data and BRDF Model Inversion



Spectral albedo (BHR) based on field goniometer measurements (numerical integration)



Spectral albedo (DHR) based on HyMap multi-angular flight pattern data and BRDF model

Isotropic kernel, geometric and volumetric kernel weights

-> spectral dependence!

Courtesy: U. Beisl, 2001

Recommendations – G. Schaepman-Strub (2006)

Status and Recommendations for Spectral Albedo Derivation based on Imaging Spectroscopy

- Spectral land surface albedo has a high potential for more detailed representation of vegetation dynamics in climate modeling, is used for validation purposes of broadband satellite albedo products and in meteorological studies.

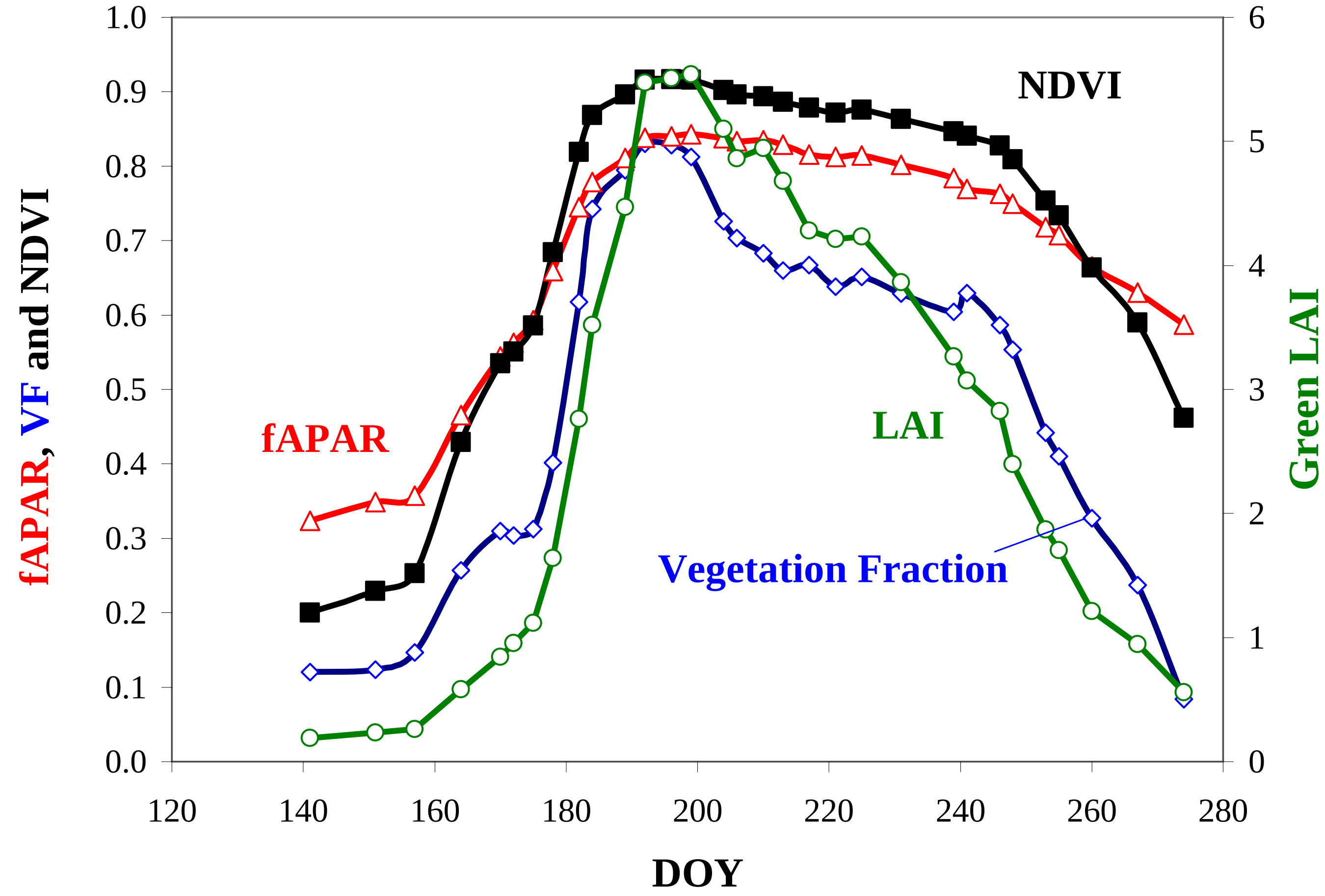
- No current spectral albedo product based on high spectral resolution (>7) and instantaneous multi-view-angular satellite data.

- Satellite, airborne and in-situ based spectrometer data have to be corrected for the diffuse irradiance!
  Neglecting the diffuse irradiance results in distortions of the derived BRDF, and thus in spectral albedo uncertainties (especially in blue spectral wavelengths).

- Spectral surface albedo databases have to be standardized in terms of description of the provided physical quantity, vegetation (e.g., LAI, LAD, stem density), solar angle, and atmospheric conditions.

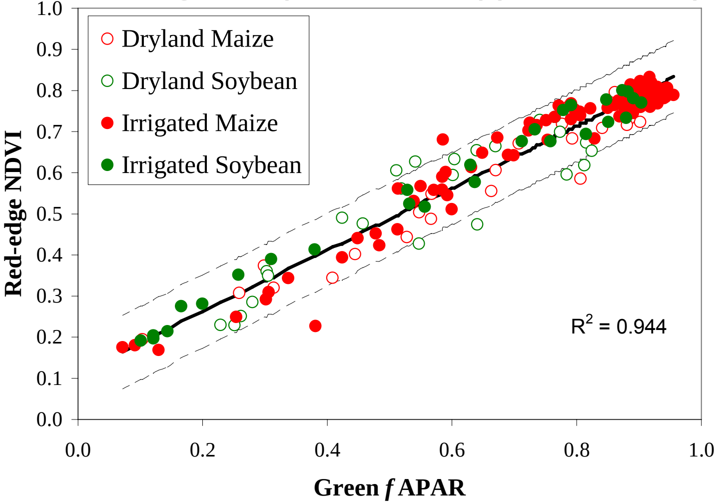
Continued development of VIs with potential to track crop temporal cycle of biophysical variables

Temporal behavior of maize biophysical characteristics from detailed field data - A. Gitelson

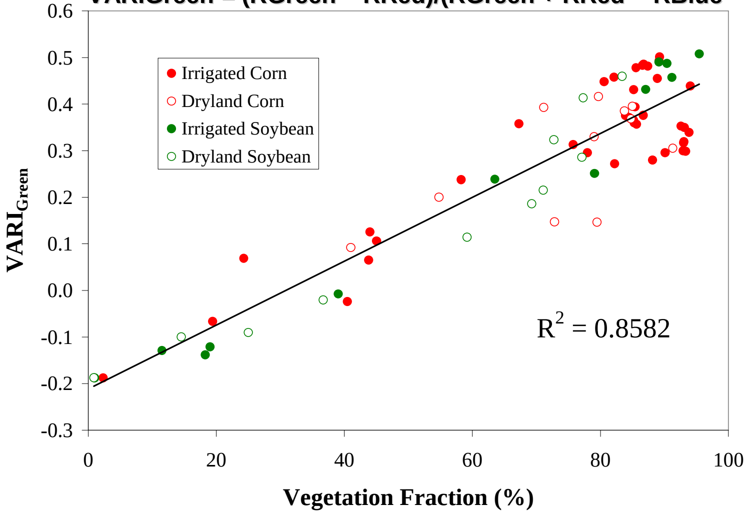


VIs with linear relationships to changes in biophysical variables – A. Gitelson

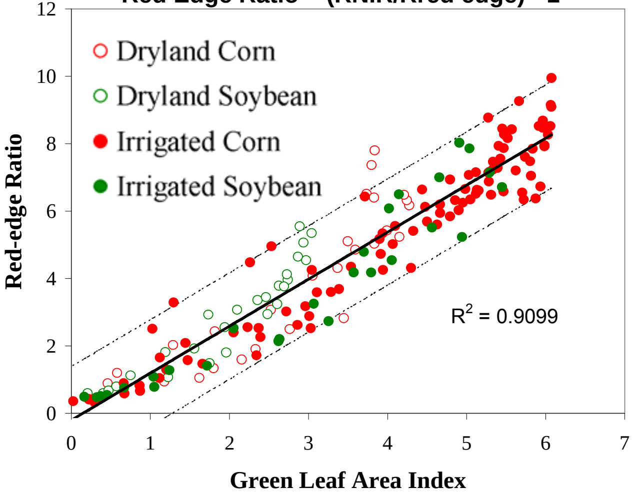
Red Edge ARI = (RNIR – R700-710)/(RNIR + R700-710)



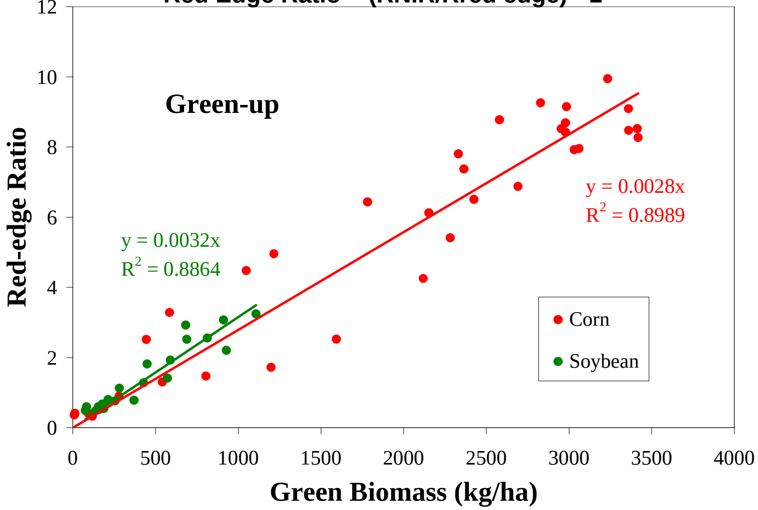
VARIGreen = (RGreen – RRed)/(RGreen + RRed - RBlue



Red Edge Ratio = (RNIR/Rred edge) - 1



Red Edge Ratio = (RNIR/Rred edge) - 1



5e. New Developments: VI development to track biophysical variable phenology

Conclusions

•Through model-based approaches repetitive hyperspectral images over vegetated targets can predict canopy-leaf variables (specifically Leaf Cab, LAI, Leaf EWT, fCover) with sufficient accuracy to track seasonal, spatial, species-dependent changes measured in the field

•Maps of such variables have been shown to provide valuable information in forestry and precision agriculture applications, often indirectly related but correlated to desired products: inventory, speciation, land cover, stress (condition) maps, productivity/yield prediction/potential maps

•Multi-temporal retrieved variable maps have significant potential for model-based product retrieval through crop growth models: eg. crop biomass & yield prediction

Suggested Next Steps

- Increase emphasis on multi-angle imaging spectroscopy data because of new variables for retrieval (eg. spectral albedo, LIDF), and increased retrieval accuracy for primary biophysical variables

- assess new vegetation indices related to crop growth parameters (APAR, fCover, biomass) through leaf-canopy model simulations and refine such VIs for use in rapid variable map production through scaling up

- Improvements to PROSPECT to (i) provide Ca/Cb ratios, and (ii) better represent needle leaves, would open a significant new range of applications and potential

- Exploit and continue development of FluorMOD (a version of PROSPECT and 4SAIL which simulates TOC and TOA reflected radiances as well as fluorescence emissions) due to (i) potential to affect observed radiance in red and NIR regions and thus affect retrievals, and (ii) potential complimentary information – vegetation photosynthetic functioning

Thank you for your attention!

Canopy Physical Modeling Approach – Variable Retrieval Paradigms

Paradigms for deriving bio- geophysical variables from above-canopy bi-directional reflectance :

I. Canopy-Leaf model inversions: biophysical variables are retrieved by

(i) inverting RT models and matching complete spectra in the merit function (e.g Bach & Verhoef, 2006)

(ii) inverting RT models using key optical indices in the merit function for inversion (eg. Zarco-Tejada et al (2001) for deciduous closed canopy forests; Moorthy et al (2003) for boreal conifer forests; Zarco-Tejada et al (2004) for olive groves, vineyards)

Merit Function

$$\Delta^2 = \sum_{i=1}^{n} \left[r_{obs}(\lambda_i) - r_{\mathrm{mod}}(\lambda_i, P) \right]^2$$

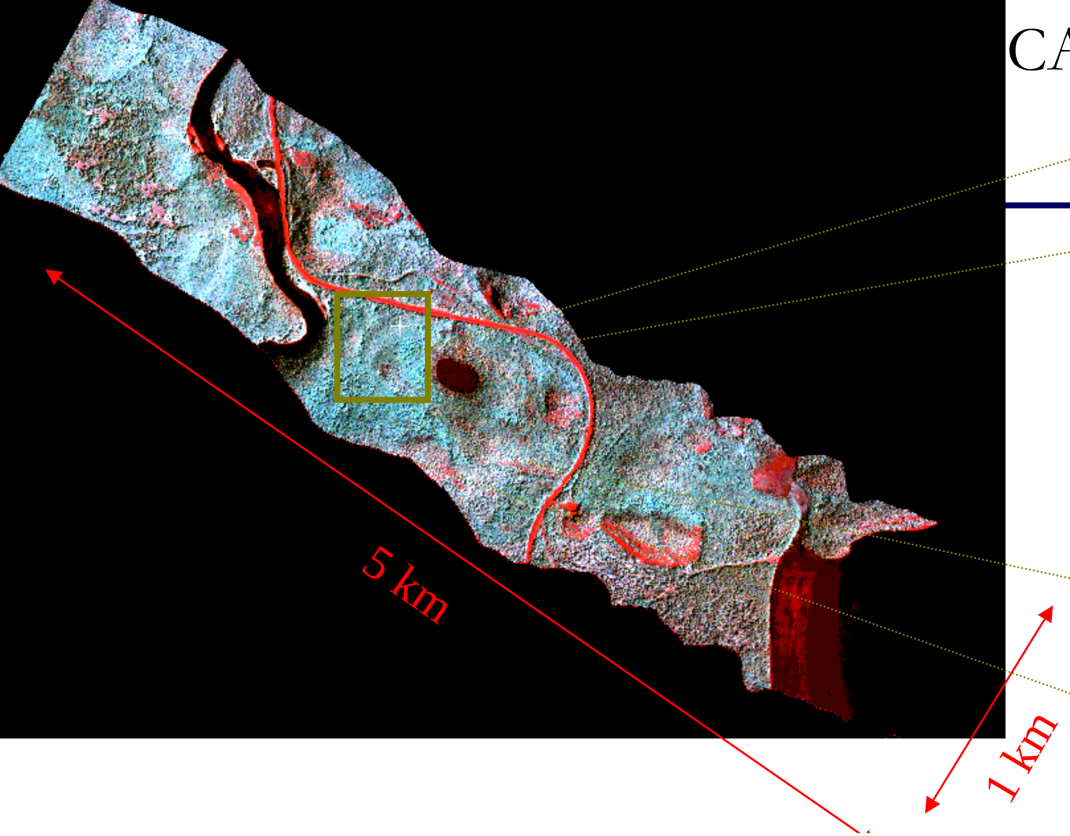
•V I

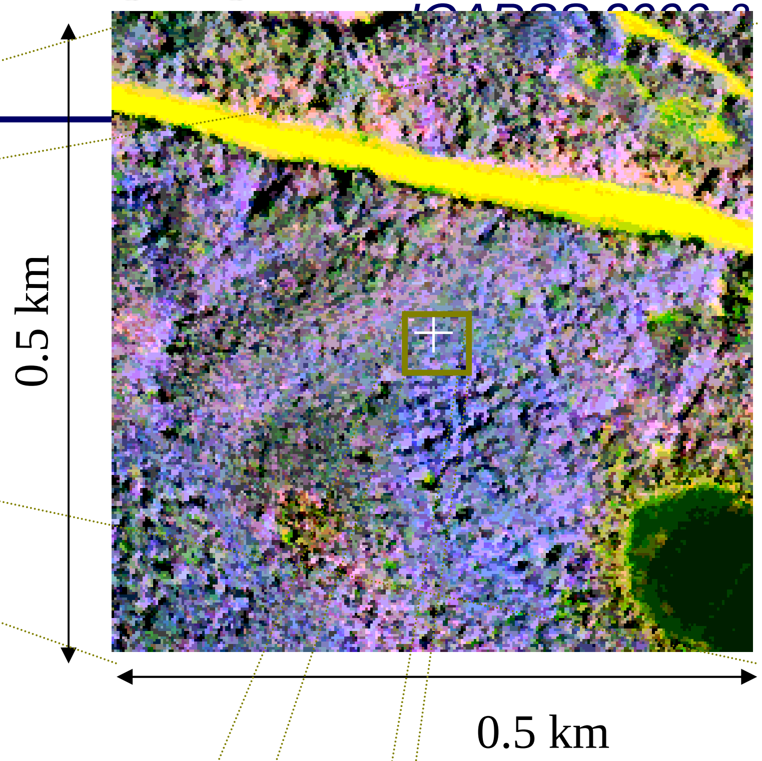
•Full Spectra

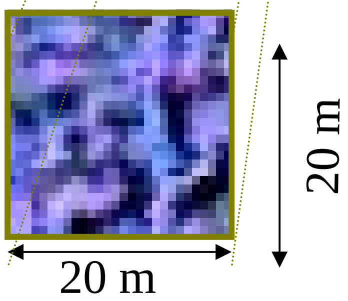
P= set of parameters: **Cab, LAI, θL…**

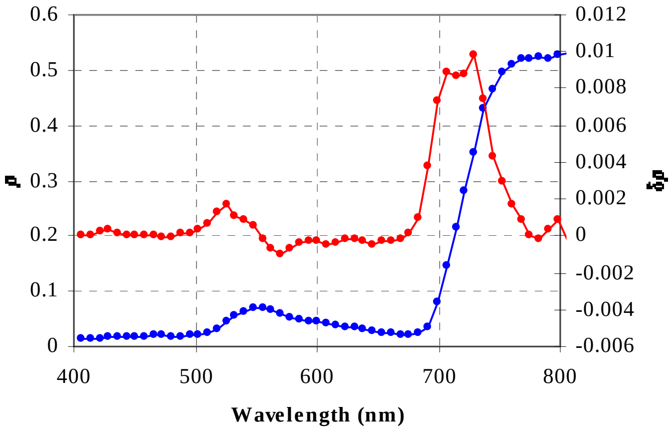
II. Upscaling through RT models simulations: new optical indices (eg. TCARI/OSAVI, MTVI, etc) sensitive to **specific biophysical variables** (with minimal sensitivity to other variables) are **simulated at above-canopy level** (e.g. Haboudane et al 2002, 2003, for agriculture crops) forming the basis of a retrieval algorithm

CASI Hyperspectral Data Collection



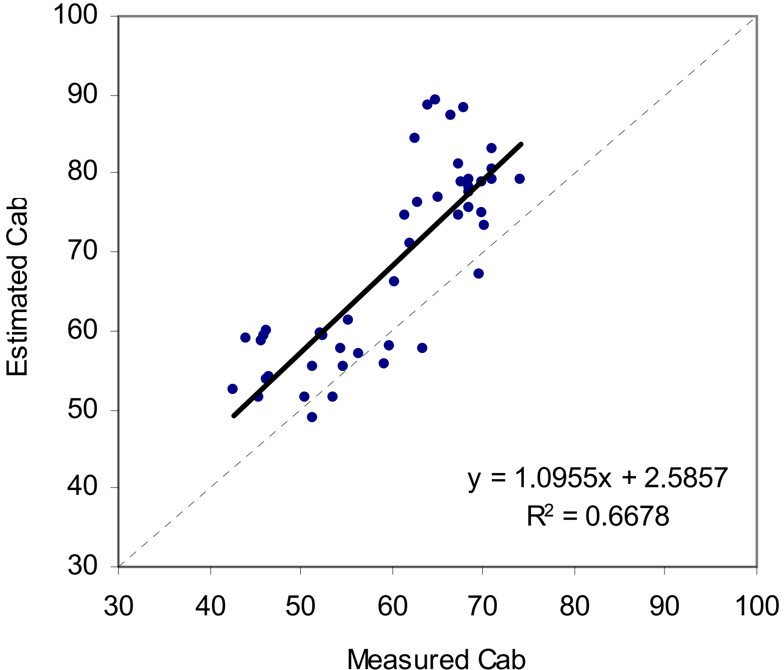




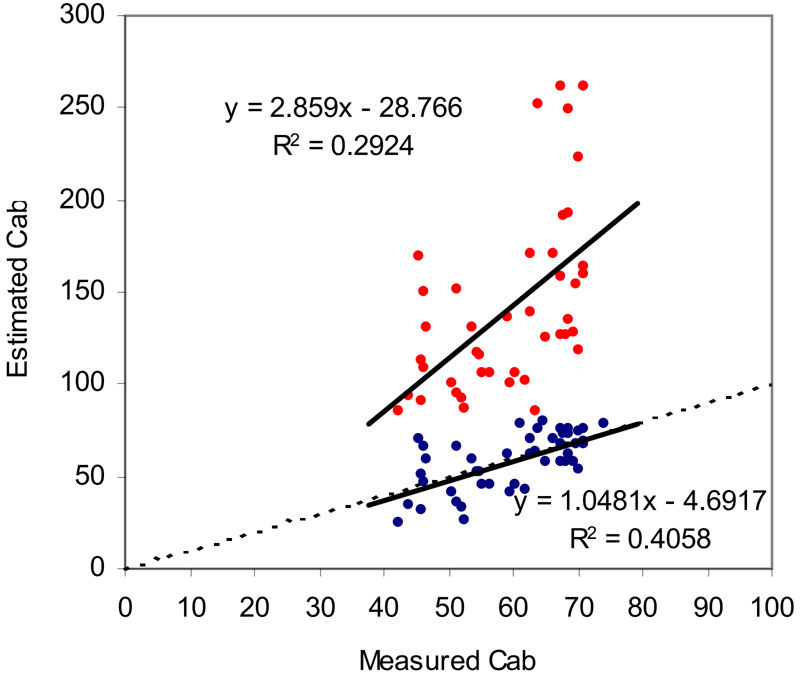


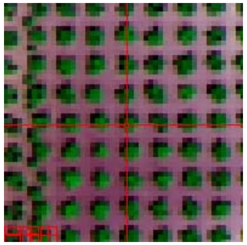
Retrievals: Olive Groves

C_{ab} estimation from ROSIS crowns using MCARI/OSAVI prediction

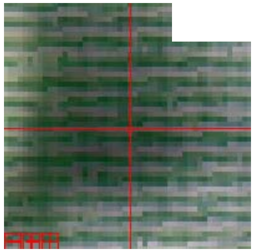


C_{ab} estimation from aggregated pixels (C+Sh+So) using MCARI/OSAVI





Crowns
PROSPECT-SAILH



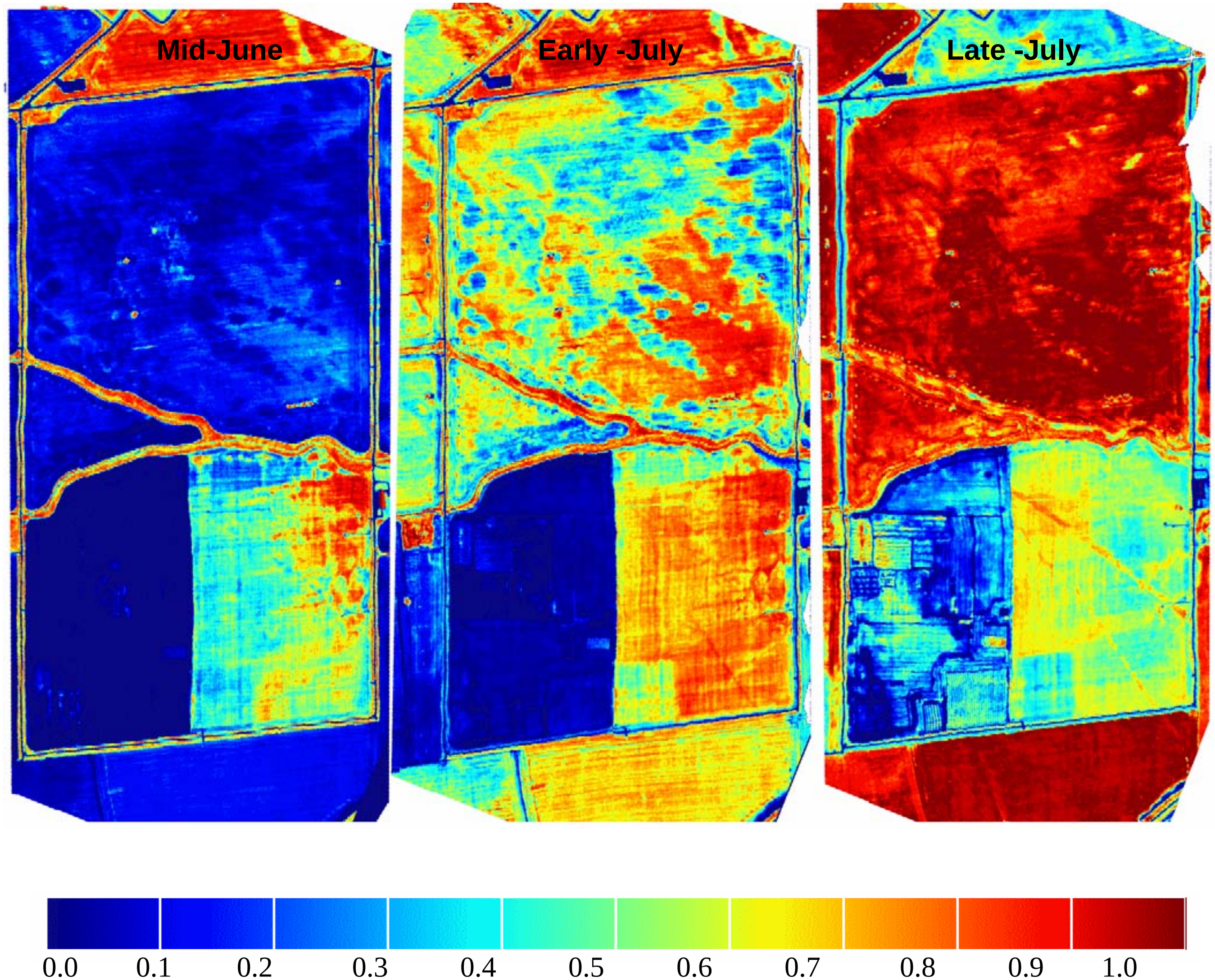
Crown+Shadow+Soil
PROSPECT-SAILH &
PROSPECT-SAILH-FLIM

Zarco-Tejada et al., Brugges 2004

Precision Agriculture: AAFC Ottawa Study site –2002: Crop Fraction Estimate

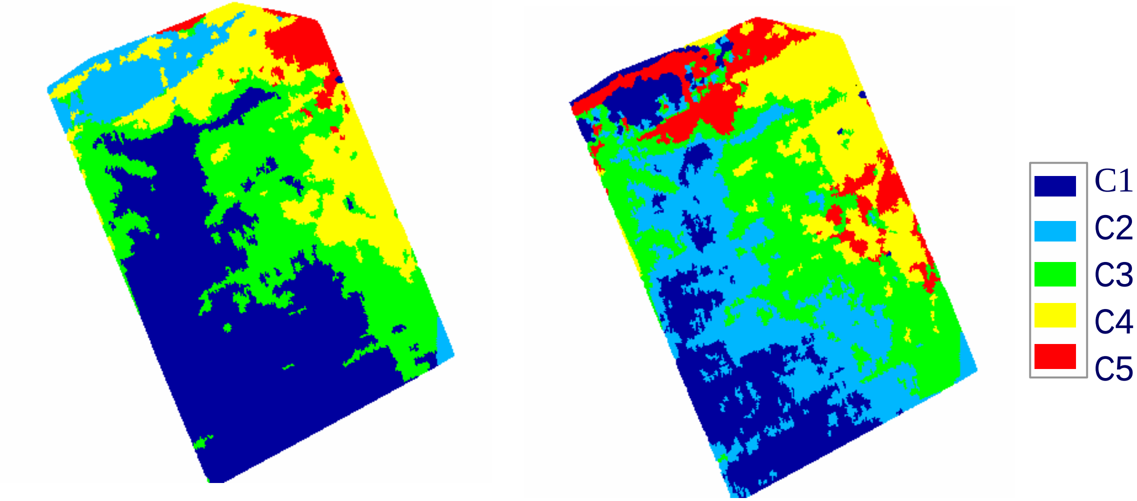
Maps of Crop Fraction Estimated:
- (i) Using Linear Spectral Unmixing
- (ii) Using VIs: TSAVI, OSAVI, MTVI2

found comparable in performance, but with advantages & disadvantages in implementation

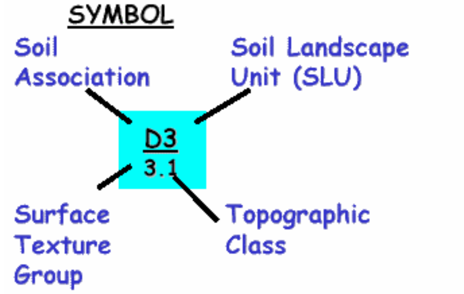


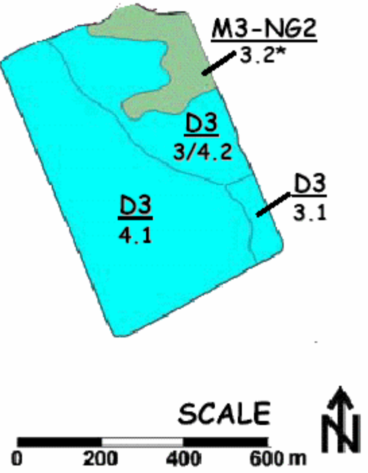
J. Liu et al CJRS (2004)

Soil Spectra: Bare Soils Unsupervised Classification: - Management Zones



Soil Brightness and Colour Soil Principal Components





LEGEND

SLU	Soil Series (Slope)
D3	Brandon series (0-2%)
M3	Montain & Allendale series (1-3%)
NG2	North Gower series (0-2%)

J. Liu et al CJRS (2004)

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1. Earth Observations and Analysis Approaches - A perspective
2. Analysis Approach Selected: Rationale and Challenges
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4. Variable Retrievals: Forestry & Agriculture 1st Steps
5. Towards Products: Forestry & Agriculture, Next Steps
6. Satellite HIS Issues
7. Conclusions

Products in Foresty & Agriculture: Model-Based Approach

Products for Agriculture & Forestry (eg)

- cover map – inventory, speciation, land cover
- stress (condition) map – water stress, nitrogen stress, etc
- productivity/ yield prediction/potential map
- carbon map

Applicability of Model-based approach?

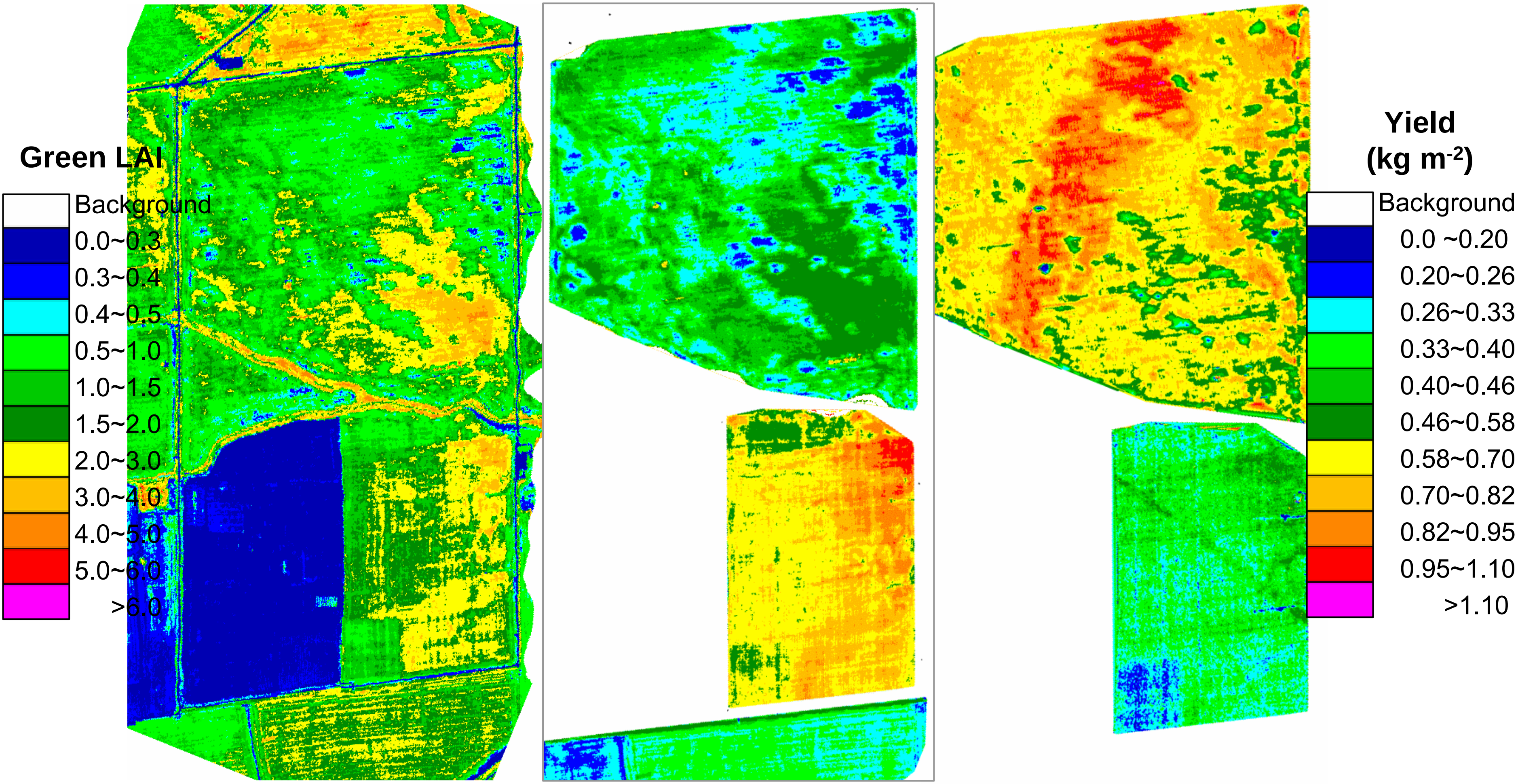
Variables can in many cases be directly retrieved, with sufficient accuracy and flexibility.

Products not directly retrievable – require new approaches & developments to exploit model-based advantages

--- some examples

Precision Agriculture Products: AAFC Ottawa: Related but NOT the same

IGARSS 2006 & 27th CSRS



IFC -2: LAI

IFC -2: Dry Shoot Biomass

Ground Measured Yield

J. Liu et al IGARSS (2004) + Pattey

Derived Leaf Pigment Content, as a surrogate for Land Cover?

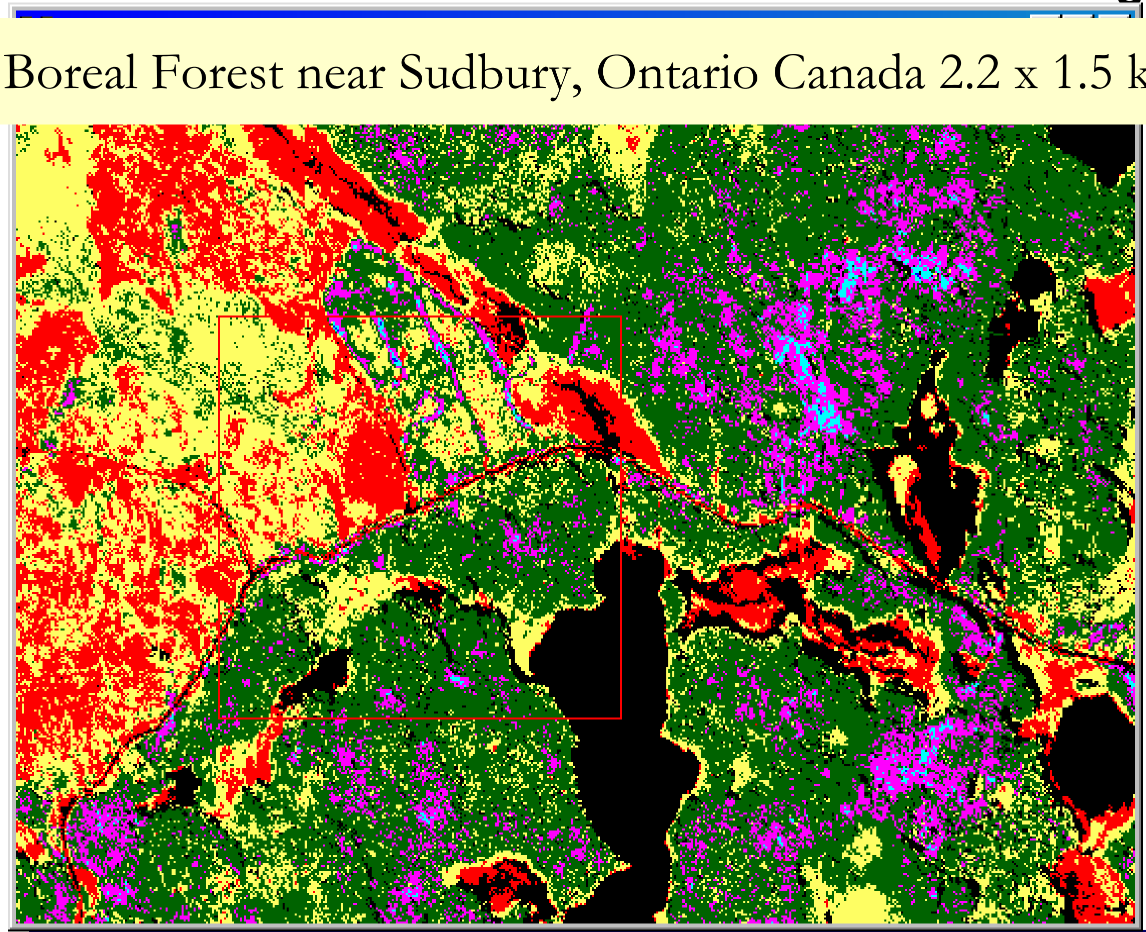
🟥 < 15 ug/cm^2

🟨 15 - 30 ug/cm^2

🟩 30 - 45 ug/cm^2

🟪 45 - 60 ug/cm^2

🟦 > 60 ug/cm^2



Boreal Forest near Sudbury, Ontario Canada 2.2 x 1.5 km

Land Cover Issues:

Patterns of estimated leaf pigment content over boreal forests (north Ontario) are indicative of land cover patterns

Moorthy et 2003

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Some Satellite HIS Issues

Issues

- required spatial resolution for specific applications
- challenges to the model-based approach for variable retrieval

Crops with varying Fcover: Upscaling based on combined indices for C_{ab} estimation with PROSPECT+ SAILH

Methodology: Haboudane *et al.*, 2002)

⇒ **CARI** → minimize effects of non-photosynthetic materials

⇒ **MCARI** → depth of chlorophyll absorption at 670 nm relative to the reflectance at 550 nm and 700 nm
still sensitive to non-photosynthetic element effects

$$\mathrm{MCARI} = [(R_{700} - R_{670}) - 0.2 \cdot (R_{700} - R_{550})] \cdot \left(\frac{R_{700}}{R_{670}}\right)$$

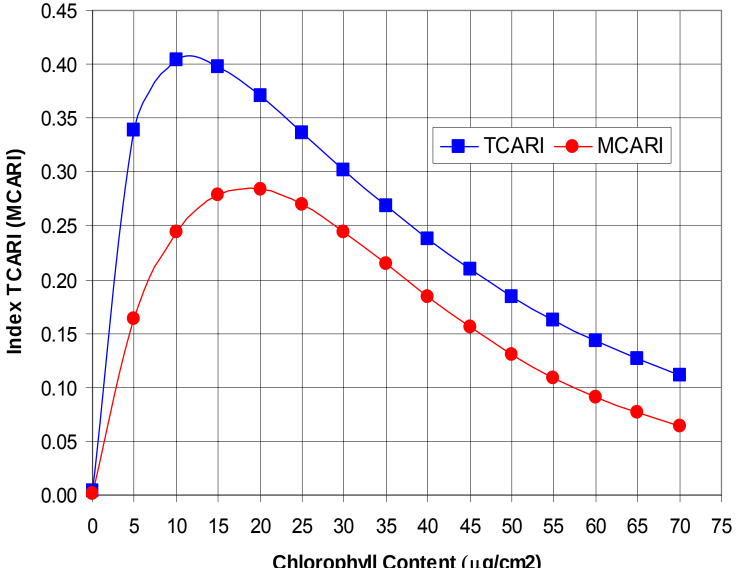
⇒ **TCARI** → improving its sensitivity at low chlorophyll values

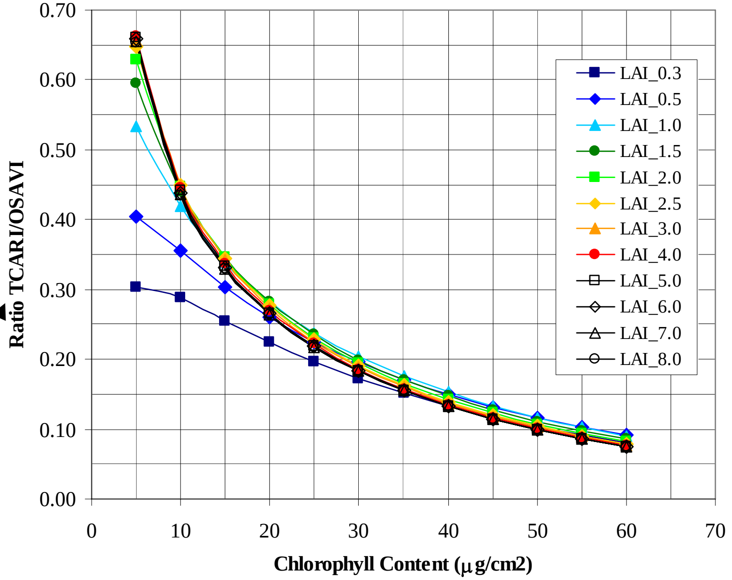
$$\mathrm{TCARI} = 3 \cdot \left[(R_{700} - R_{670}) - 0.2 \cdot (R_{700} - R_{550}) \cdot \left(\frac{R_{700}}{R_{670}}\right)\right]$$

⇒ Influence by soil reflectance for low values of LAI
→ **OSAVI** minimizes soil effects with MCARI

$$\mathrm{OSAVI} = (1 + 0.16) \cdot \left[\frac{R_{800} - R_{670}}{R_{800} + R_{670} + 0.16}\right]$$

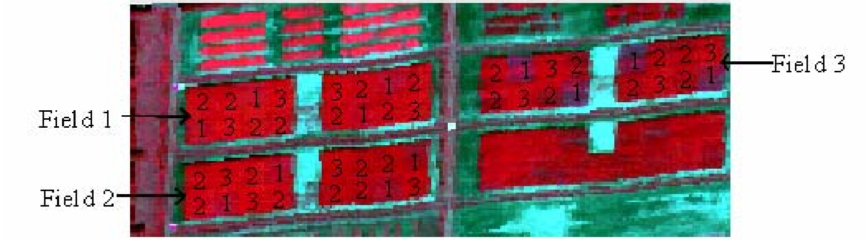
TCARI/OSAVI



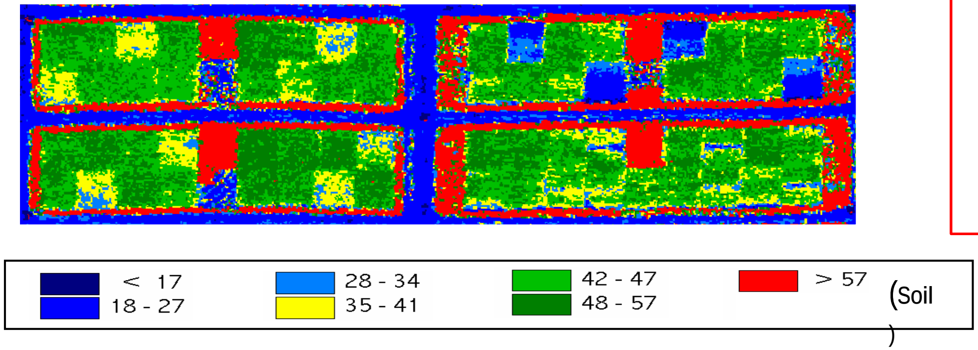


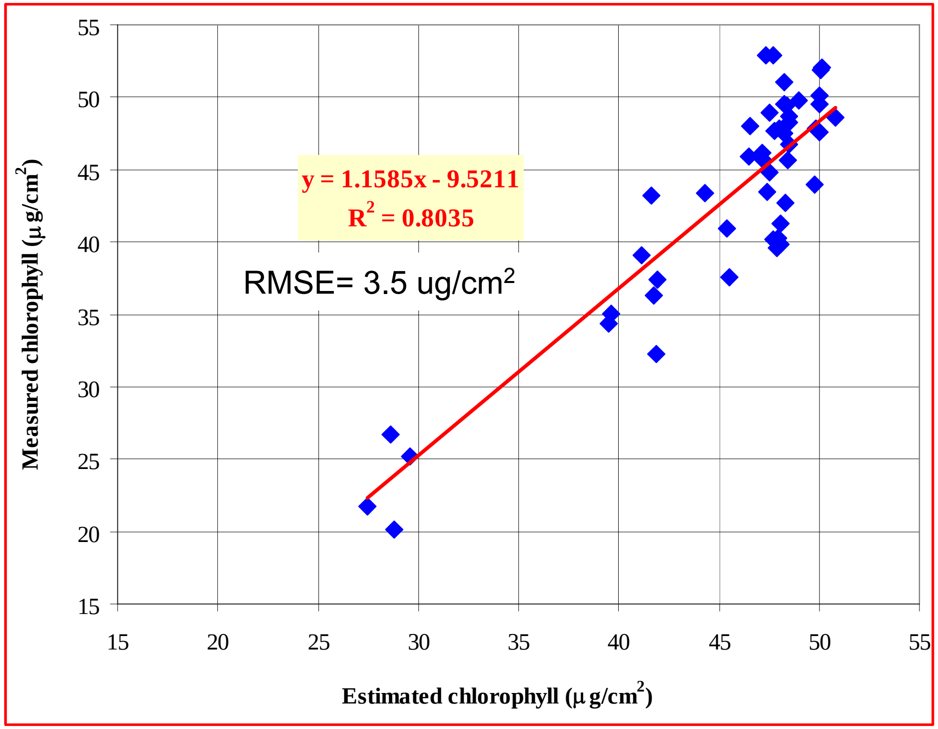
Precision Agriculture: - Leaf Chl Estimation Evaluation

Cornfield at L'Acadie Experimental farm, Agriculture and Agri-Food Canada



Field 1: 52 kg/ha	Treatment 1: no fertilization
Field 2: 51 kg/ha	Treatment 2: intermediate
Field 3: 37 kg/ha	Treatment 3: over-fertilization





Paradigm: Up-scaling of TCARI/OSAVI leaf pigment algorithm derived from PROSPECT-SAILH simulations

Application: Spatial heterogeneity mapping for N application in precision farming

Haboudane et al RSE (2002)

Conclusions on further VI algorithm development

Status and Recommendations for new VI algorithms for biophysical variables for crops

- New VI Algorithms for the remote estimation of fraction of Absorbed Photosynthetically Active Radiation, Vegetation Fraction, Green LAI and Green Leaf Biomass were developed and <u>successfully</u> applied in maize and soybean crops

- Validation using <u>independent</u> datasets proved the suitability of the algorithms to monitor crop development along the growing season, as well as inter-annual variability

- As these algorithms can be viewed as empirical models, future work should focus on comparing leaf-canopy model simulations of the the VI algorithm performances in order to infer theoretical limits or provide improvements in formulation