# Use of Imaging Spectroscopy to Detect Plant Physiological Traits

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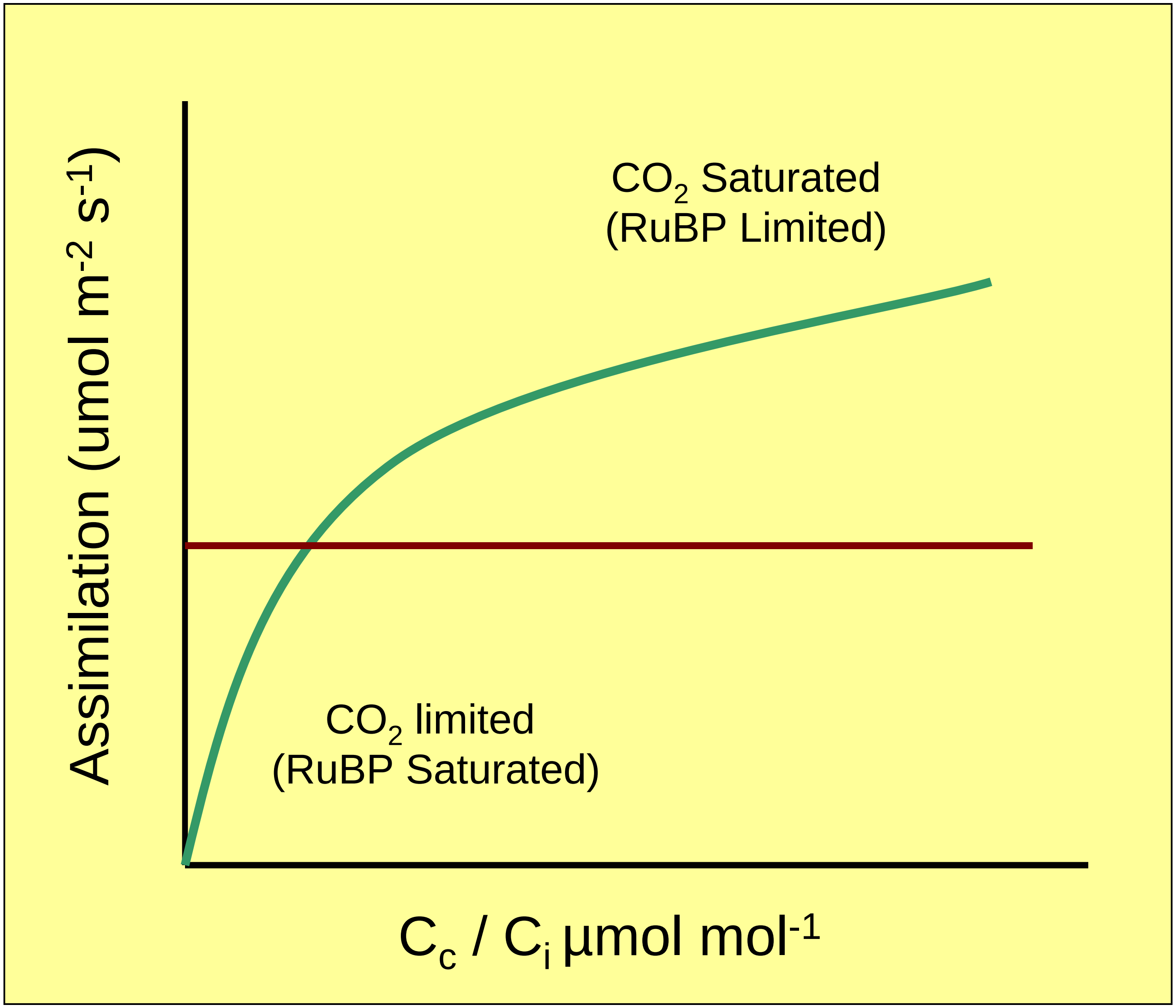
# Introduction

- Carbon fluxes governed by forest structure and foliar biochemistry
- Chief attributes for $CO_2$ fluxes are those that determine forest metabolic, photosynthetic capacities and resource-use efficiencies:
  - Specific leaf area (SLA, $m^2$ $kg^{-1}$), leaf nitrogen (N), pigments, other photosynthetic and respiratory enzymes, and electron transport systems
  - Radiation, temperature, and $CO_2$ concentration
- Key parameters for modeling ($C_3$) photosynthesis (Farquhar et al., 1980, Farquhar & von Caemmerer 1982, Sharkey, 1985)
  - $V_{(c)max}$ – Maximum rate of Rubisco-limited carboxylation (RuBisCO is the key enzyme in plants that catalyzes RuBP carboxylation for carbon fixation)
  - $J_{max}$ – Maximum rate of RuBP regeneration through electron transport (determined by chlorophyll concentration)
- Parameters sensitive to enzymatic capacity, nutrients and the environment
  - Short-term variations in leaf temperature
  - Leaf nitrogen, leaf age (deciduous vs. conifer), functional groups, climate (MAT, MAP), $CO_2$, and position within canopy (irradiance)



CO2 Saturated
(RuBP Limited)
CO2 limited
(RuBP Saturated)
Assimilation (umol m-2 s-1)
Cc / Ci µmol mol-1

# Spectroscopy & Carbon Assimilation

- Extensive literature on the use of spectral indices to monitor leaf and canopy physiology and carbon assimilation. Examples:
  - The photochemical reflectance index (PRI, Gamon et al., 1992,1997)
  - Chlorophyll index (CI, Gitelson et al. 2008)

- Imaging spectroscopy has also been used to map variables important to plant physiology and $CO_2$ uptake
  - Ollinger & Smith 2005, Wessman et al., 1989, Rahman et al., 2001

- Require methods for detecting variations in plant physiology at regional scales
  - Inconsistency between spatial (remote sensing) and temporal (e.g. leaf gas exchange, other field data, flux towers) measurements
  - **Our goals:** Detection of key leaf metabolic, biochemical and structural parameters with spectroscopy
  - Generalize models

# Methods

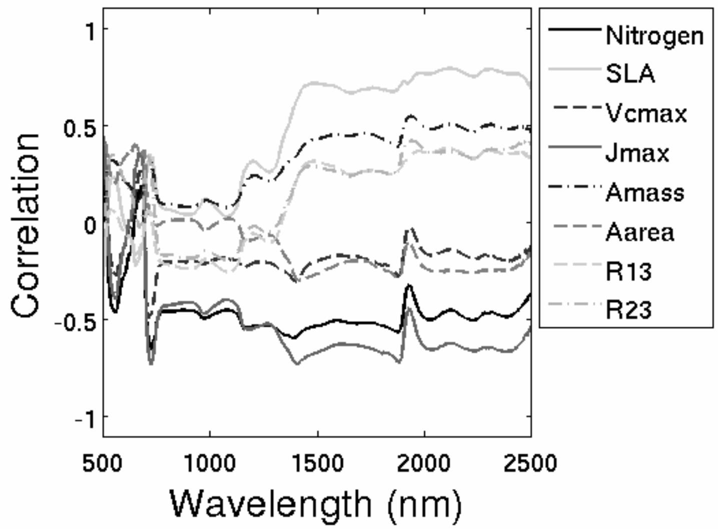
- Study was conducted on the campus of the University of Wisconsin – Madison
  - Glasshouse study in the Biotron facility
- Used six climate and light controlled glasshouses
  - Three temperature treatments of 20 / 13, 25 / 18, and 30 / 23 °C with one replicate each
  - Chosen to coincide with high / low (i.e. day / night) growing season temperatures for a concurrent field study (Dillaway and Kruger, in review)
- Two species were studied: Trembling aspen (*Populus tremuloides*), Eastern cottonwood (*P. deltoides*)

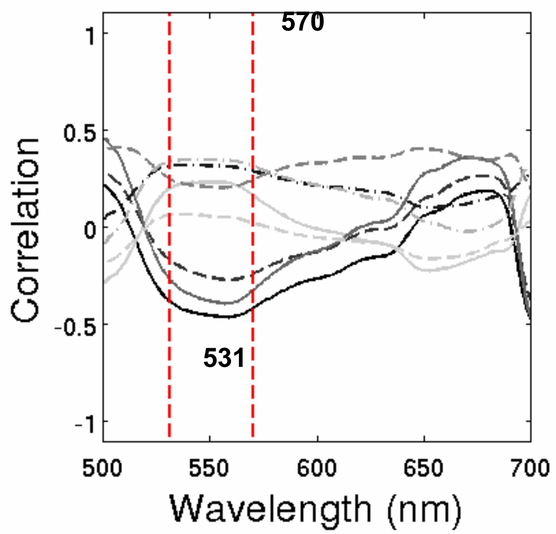
# Physiological Measurements

- Leaf gas exchange was measured on 16-20 individuals with a LI-6400XT Portable Photosynthesis System
- Assimilation measured at light saturation (1800 µmol $m^{-2}$ $s^{-1}$) at several $pCO_2$ (7.5 to 120 Pa, A-*p*CO2 curves)
- Leaf nocturnal respiration measured at 13 °C (cool) and 23 °C (warm)
  - Rates were temperature adjusted to compare across thermal treatments using a modified Arrhenius equation (Lloyd and Taylor 1994)

| **Temp (°c)** | **SLA ($m^2$ $kg^{-1}$)** | **$V_{(c)max}$ (µmol $m^{-2}$ $s^{-2}$)** | **$J_{max}$ (µmol $m^{-2}$ $s^{-2}$)** | **$A_{mass}$ (nmol $m^{-2}$ $s^{-1}$)** | **$R_{cool}$ (nmol $m^{-2}$ $s^{-1}$)** | **$R_{warm}$ (nmol $m^{-2}$ $s^{-1}$)** |
|---|---|---|---|---|---|---|
| 20 / 13 | 19.5 ± 0.7 | 69.1 ± 2.9 | 128.9 ± 6.0 | 12.4 ± 0.7 | 23.7 ± 1.4 | 39.0 ± 2.9 |
| 25 / 18 | 19.9 ± 0.6 | 94.0 ± 4.4 | 165.0 ± 8.0 | 11.5 ± 0.6 | 19.2 ± 0.9 | 32.7 ± 2.1 |
| 30 / 23 | 23.9 ± 0.9 | 131.7 ± 5.4 | 159.0 ± 7.6 | 14.0 ± 0.7 | 27.9 ± 1.4 | 37.0 ± 1.8 |

# Spectral Properties of Leaves

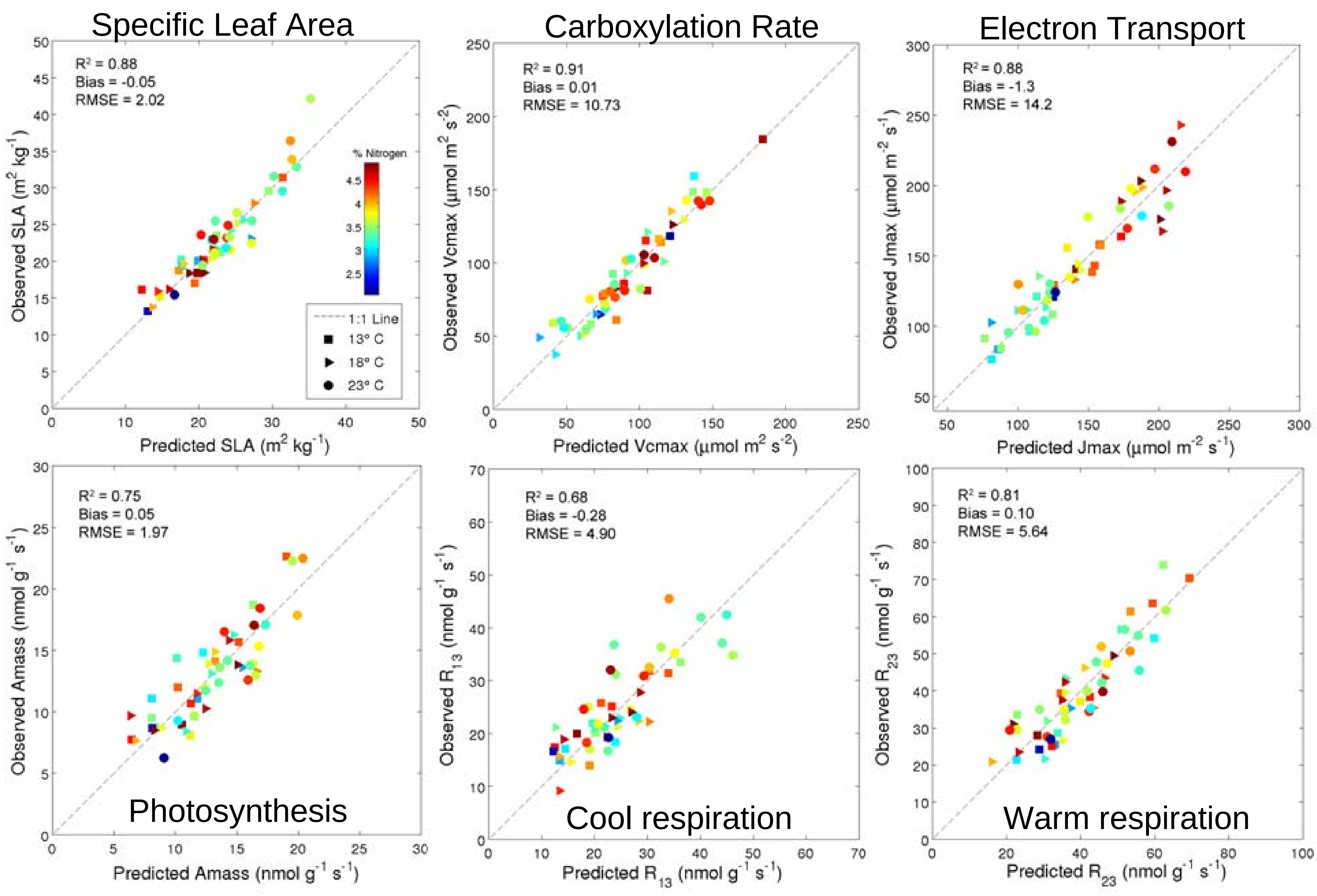



- High spectral resolution measurements acquired with an ASD FieldSpec 3 ® FR (350-2500 nm) spectroradiometer
- Measured on the same individuals as physiological measurements
  - Generally within 24 but no later than 36 hours
- Observed strong correlations between leaf spectra and leaf physiology
- Spectral regions consistent with previous studies (e.g. Asner et al., 2008)
- NIR and SWIR wavelengths had highest correlations

# PLS Methods

- Used partial least-squares (PLS) regression techniques (Wolter et al., 2008)
- PLS optimizes the covariance between variables
  - Develops component factors which capture the variance and are highly correlated with the response variable(s)
  - Overcomes restrictive assumptions in OLS and avoids collinearity (in lower order factors)
- Iterative wavelength selection
  - Examining GA-PLS and iPLS methods in Matlab
  - Selects wavelengths with highest loadings for final models
  - Optimizes modeling and helps assess whether selected wavelengths make sense physiologically


Specific Leaf Area
R² = 0.88
Bias = -0.05
RMSE = 2.02
Observed SLA (m² kg⁻¹)
Predicted SLA (m² kg⁻¹)
% Nitrogen
1:1 Line
13° C
18° C
23° C
Carboxylation Rate
R² = 0.91
Bias = 0.01
RMSE = 10.73
Observed Vcmax (μmol m² s⁻²)
Predicted Vcmax (μmol m² s⁻²)
Electron Transport
R² = 0.88
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RMSE = 14.2
Observed Jmax (μmol m⁻² s⁻¹)
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Photosynthesis
R² = 0.75
Bias = 0.05
RMSE = 1.97
Observed Amass (nmol g⁻¹ s⁻¹)
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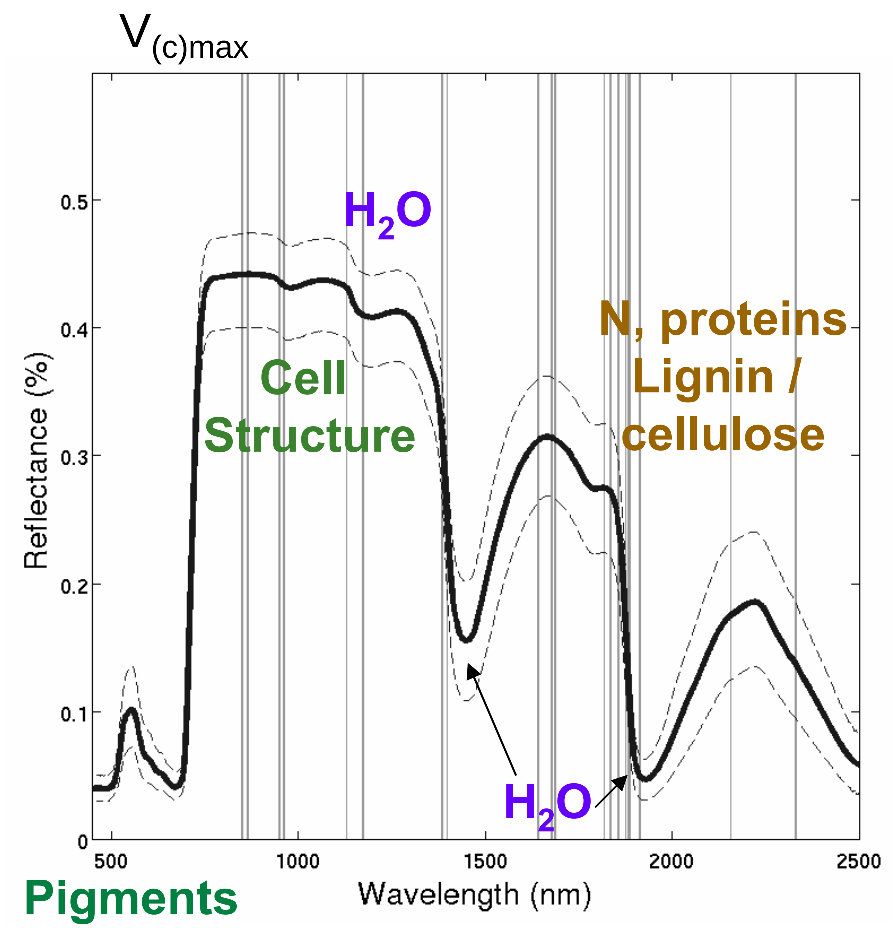
Cool respiration
R² = 0.68
Bias = -0.28
RMSE = 4.90
Observed R13 (nmol g⁻¹ s⁻¹)
Predicted R13 (nmol g⁻¹ s⁻¹)
Warm respiration
R² = 0.81
Bias = 0.10
RMSE = 5.64
Observed R23 (nmol g⁻¹ s⁻¹)
Predicted R23 (nmol g⁻¹ s⁻¹)

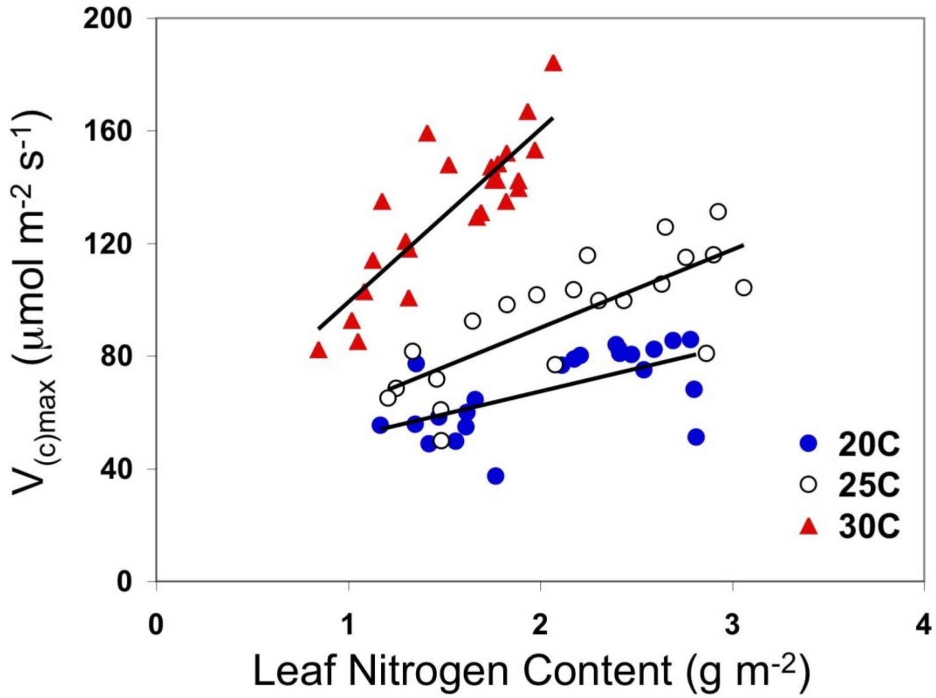
# Results Continued

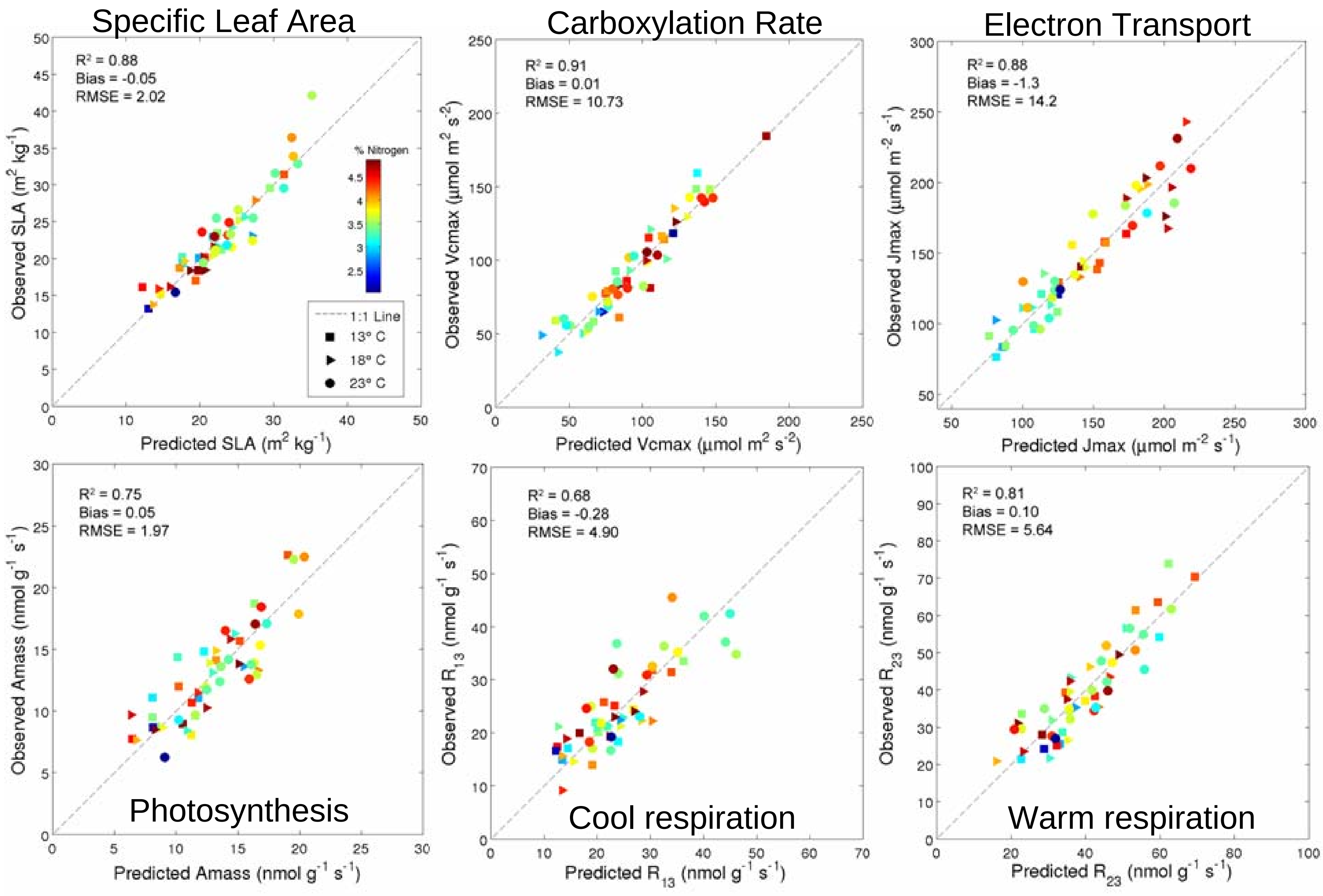



- GA-PLS dynamically selected wavelength regions
- This approach generally yields robust models, **AND**
- Wavelength regions are related to leaf structural variation, water content, nitrogen, proteins, etc

# Leaf Nitrogen

- $N_{area}$ an was effective predictor of $V_{(c)max}$ by treatment
- Leaf N performed poorly across data from all temperatures when pooled
- Therefore, relationships are not merely a reflection of the close link with leaf nitrogen





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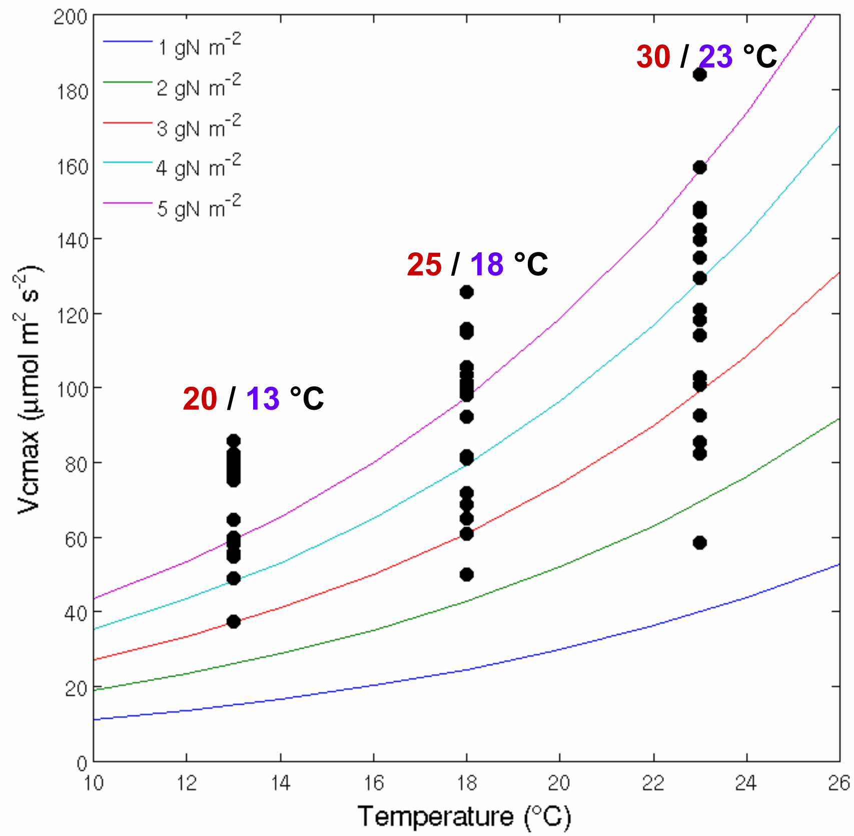
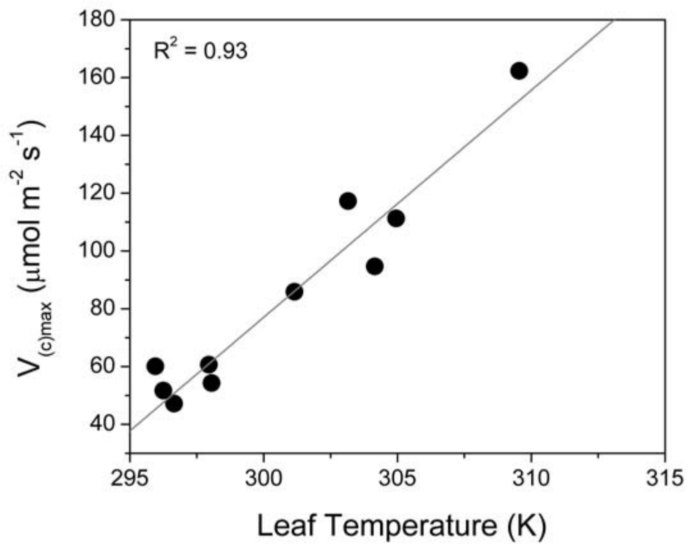
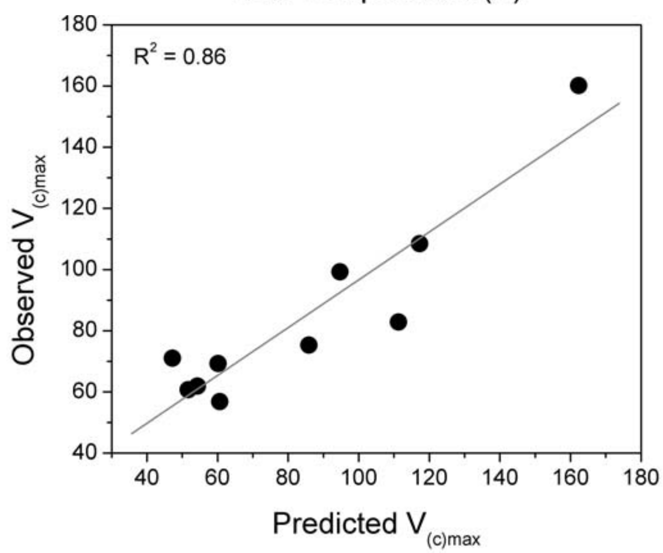
# Temperature response

- Temperature is also an important source of variation
  - Photosynthetic and respiration rates vary with climate and N status
- For example, instantaneous $V_{(c)max}$ generally increased with temperature
  - Capacity is strongly linked with leaf N
- Spectroscopy is most valuable if it can detect changes in rate and capacity through time
  - Predict instantaneous & time integrated photosynthesis



# Temperature Response cont.




- We tested whether methods could detect changes in physiology for individual leaves
  - Measured 5 leaves in July during the morning (low temp) and afternoon (high temp) hours
- Spectroscopy appears to detect changes in leaf physiology
  - Sensitive to the acclimation of photosynthetic rate to temperature & biochemistry
- Thus overpass time, surface conditions, and the timing of ground calibration are all important considerations for the HyspIRI mission

# Conclusions

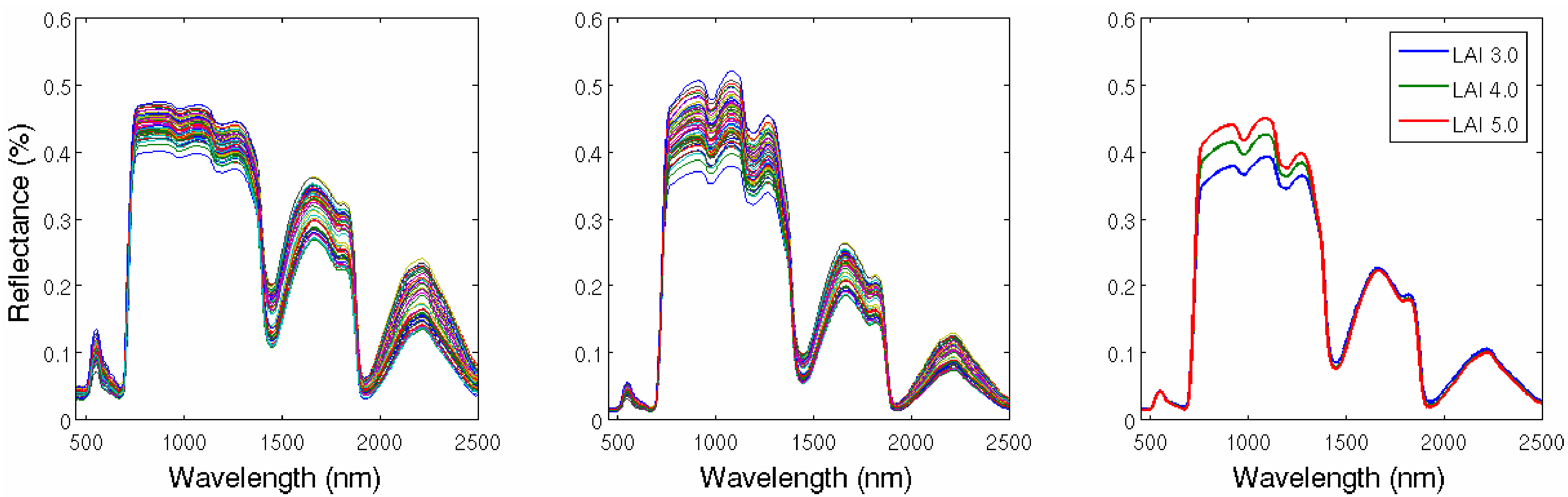
- Further evidence that leaf-level spectral properties are closely related to leaf physiology
- PLS methods provide a robust means to interpret spectroscopic modeling results, specifically:
  - Builds upon the use of physiological indices to predict physiological parameters
  - Key regions of the spectrum are selected (e.g. N, water)
- Leaf spectra appear sensitive to leaf metabolic acclimation to temperature
  - Spectroscopy may enable the prediction of instantaneous and time integrated rates of $CO_2$ assimilation and respiration at broad spatial scales

# Next steps in research

- Further examination of leaf-level response to temperature and biochemistry
  - Additional data are needed to rigorously test the ability to detect photosynthetic acclimation to temperature
- Extend research into natural settings
- Expand methods to other species
  - For example, evaluate and compare broadleaf and conifer species
- Scaling results to the canopy for landscape-scale analysis
  - Application to AVIRIS and HyspIRI imaging spectroscopy data
  - Detailed monitoring of forest health and productivity

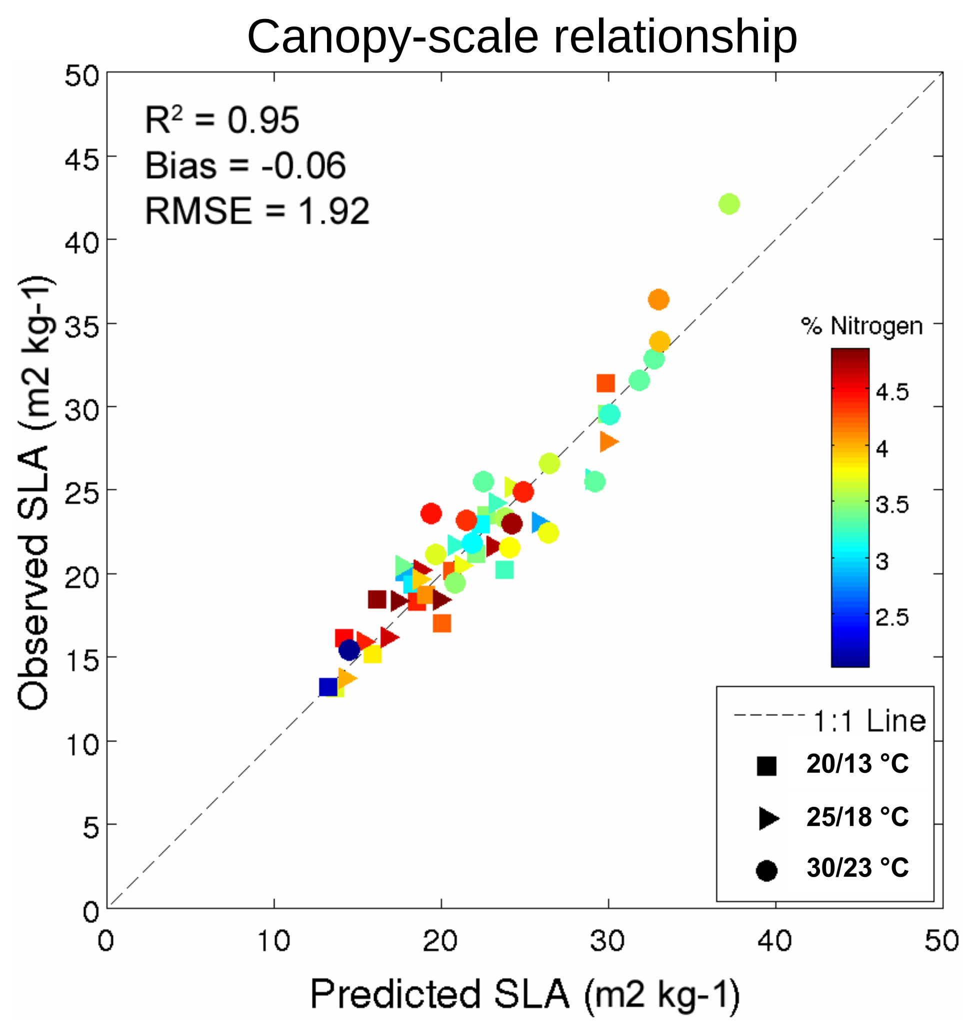
# Scaling to the canopy

- Radiative transfer models (e.g. SAIL2)
- Use modeled spectra to build new PLS models
  - Test the same iterative PLS methods for wavelength selection
- Apply relationships to imagery
  - Examine spatial and temporal patterns
  - Parameterize broad-scale carbon models
    - Example: Medlyn et al., 2005; Kattge et al., 2009

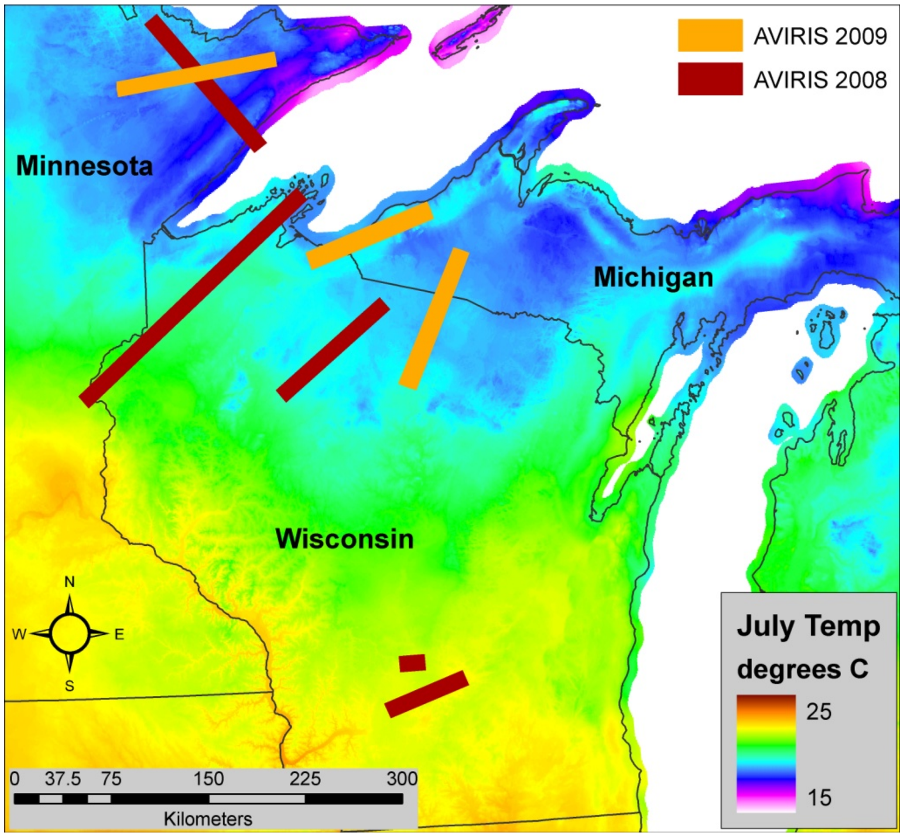


# Scaling to the canopy cont.

- Preliminary research shows promise for scaling relationships
- More research needed to test upscaling procedures
  - Explore multi-layer methods (e.g. sun vs shade leaves)
  - Scaling leaf vs. canopy values (typical leaf vs. whole canopy value)
- Maps will be useful for landscape analyses and modeling of forest productivity



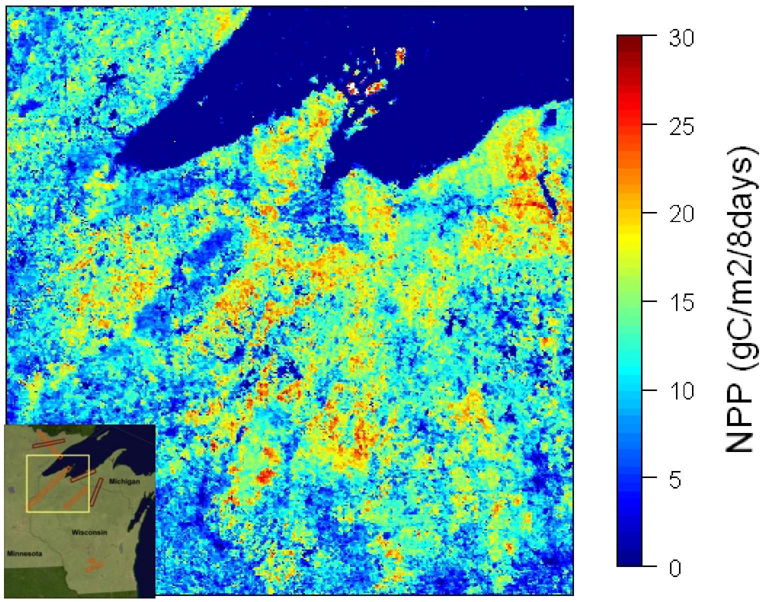
# Application to HyspIRI

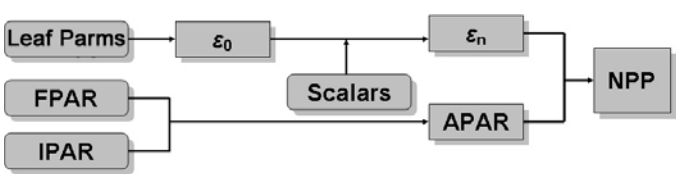



Data from PRISM database (http://www.prism.oregonstate.edu)

- Spatially explicit estimates of leaf and canopy photosynthetic properties (using NIR & SWIR channels)
- Surface temperature (TIR) to predict water use and test the sensitivity to climate
  - Foliar respiration and assimilation rates
  - Combined spatial patterns of vegetation response to temperature and $CO_2$
- Significant for climate change research

# Concurrent Research




- Watershed science
  - N inputs to forested streams
  - Disturbance and forest nutrient balance
- Forest functional traits
  - Key traits that mediate responses to disturbance
- Regional carbon fluxes
  - Impacts of disturbance on NPP
- Atmospheric deposition
  - Forest health and productivity
- Utilizing imaging spectroscopy

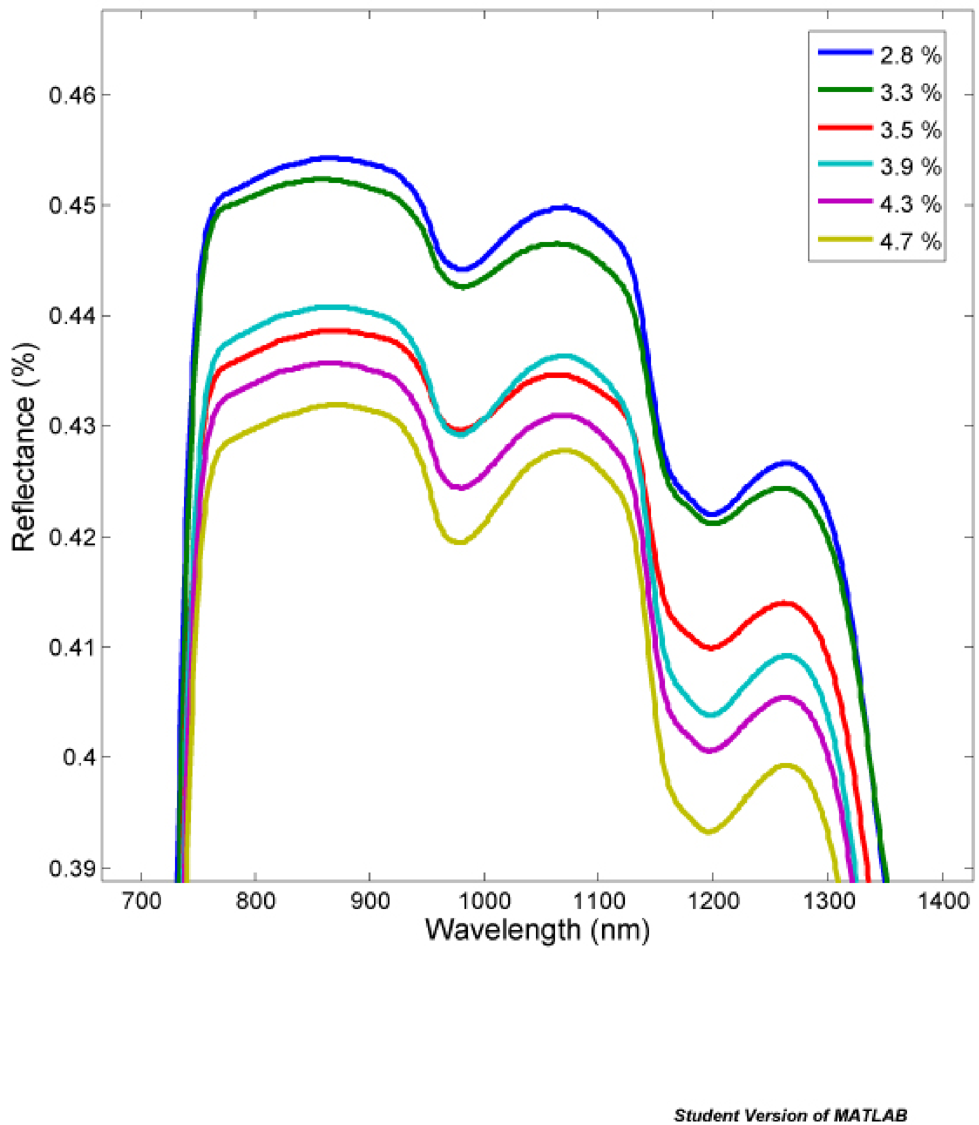

Thank you!

# Extra slides

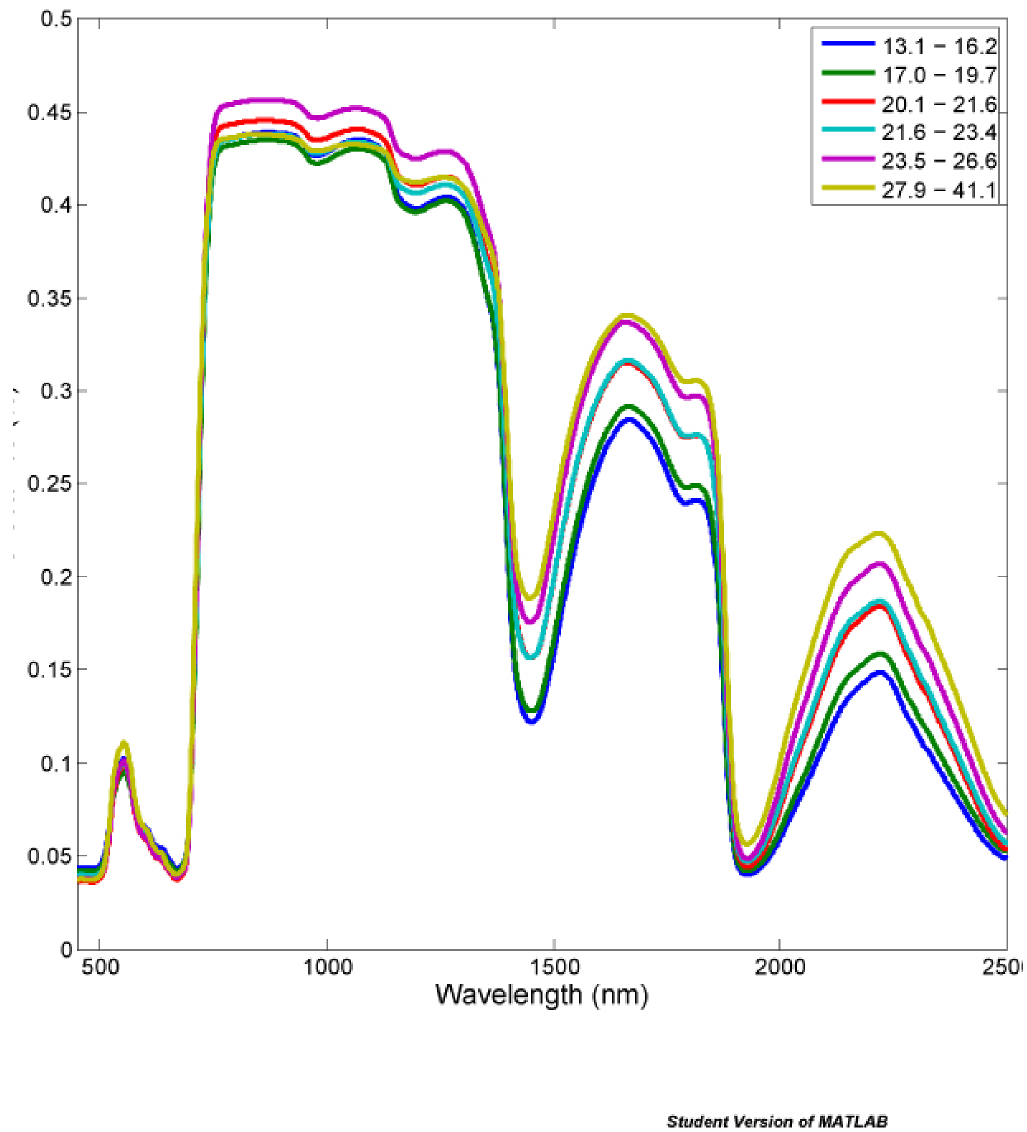
# Outline

- Introduction
  - Key parameters for predicting photosynthesis
  - Spectroscopy and carbon assimilation
- Data collection methods
  - Biotron
  - Leaf physiological and spectral measurements
- Statistical methods
  - PLS methods and selection techniques
- Results
  - Leaf N and temperature response of parameters
- Conclusions
- Next steps in research
  - Scaling
  - Concurrent research

# Leaf albedo and N

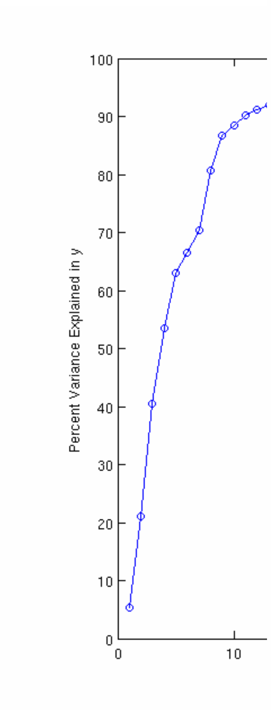


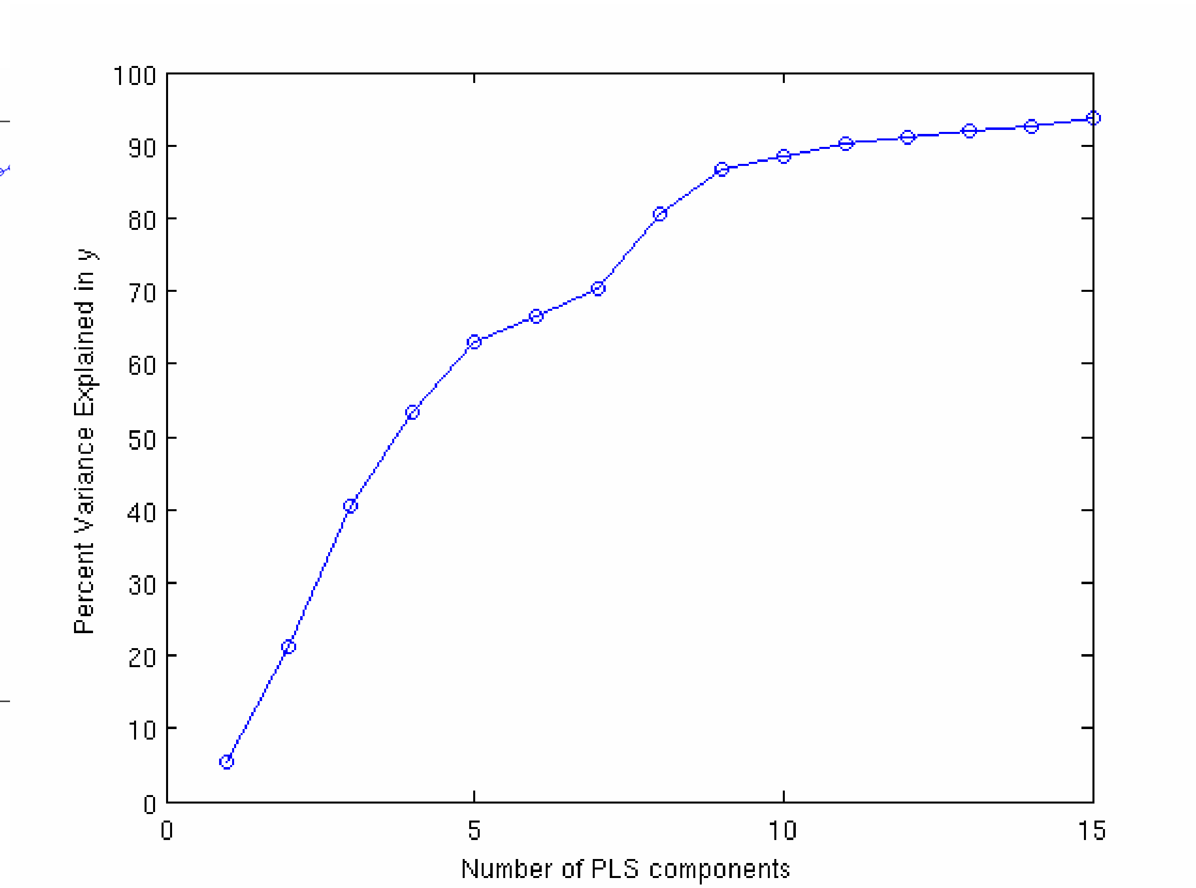
# SLA



0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
500
1000
1500
2000
250
Wavelength (nm)
13.1 – 16.2
17.0 – 19.7
20.1 – 21.6
21.6 – 23.4
23.5 – 26.6
27.9 – 41.1
Student Version of MATLAB

# Vcmax vs PLS components



# PRI & leaf physiology