Remote Sensing and Environmental Plant Physiology

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What is Remote Sensing?
Remote Sensing

• Remote sensing is defined as the art and science of obtaining information about an object without in direct physical contact with the object.

• It is a scientific technology that can be used to measure and monitor important biophysical characteristics and human activities on Earth.
Remote Sensing Includes ....

- Remote sensing often involves collection of diverse pieces of information or data for a particular site, field or a target.

- The data is combined and interpreted to provide useful information concerning the site or the target.

- Geographic Information Systems (GIS), Geographic Position Systems (GPS) and geo(spatial)-statistics are sometimes used to organize spatial data.
Scientific Principles

• Sunlight strikes the Earth’s surface and certain wavelengths are either absorbed, reflected or transmitted.

• Various materials absorb sunlight over specific wavelength intervals resulting in absorption features in reflectance spectra.

• The location and shape of these unique absorption features provide information on the chemical composition of materials.
A-Energy source or Illumination
B-Radiation and atmosphere
C-Interaction with target
D-Recording energy of target by sensor
E-Transmission, reception & processing
F-Interpretation & Analysis
G-Application
Spectral Characteristics of the Vegetation

- A healthy leaf intercepts incident radiant flux directly from the Sun or from diffuse skylight scattered on to the leaf.
- Using the energy balance equation, we can keep track of what happens to all the incident energy.
- The general equation for interaction of spectral radiant flux on and within the leaf is

\[
\text{Incident radiant flux} = \text{reflectance} + \text{transmittance} + \text{absorbance}
\]

\[
\text{Reflectance} = \text{Incident radiant flux} - (\text{Absorbance} + \text{Transmittance})
\]

Percent reflectance = (target / reference) * 100
Spectral Characteristics of the Vegetation

Energy Balance

Additive reflectance from Leaf 1 and Leaf 2
\[ R_1 + T_3 = \frac{5}{8} \Phi_i = 62.5\% \]

Reflected radiant flux, \( \Phi_r \)
\[ R_1 = \frac{1}{2} \Phi_i = 50\% \]

Transmitted radiant flux, \( \Phi_T \)
\[ T_3 = \frac{1}{2} R_2 \]
(or \( \frac{1}{8} \Phi_i = 12.5\% \))

Incident radiant flux, \( \Phi_i \)

Leaf 1

Transmitted radiant flux, \( \Phi_T \)
\[ T_1 = \frac{1}{2} \Phi_i \]

Leaf 2

\[ R_2 = \frac{1}{2} T_1 \]
(or \( \frac{1}{4} \Phi_i \))

\[ R_3 = \frac{1}{2} R_2 \]
(or \( \frac{1}{8} \Phi_i \))

\[ R_4 = \frac{1}{2} R_3 \]
(or \( \frac{1}{16} \Phi_i \))

\[ T_4 = \frac{1}{2} R_3 \]
(or \( \frac{1}{16} \Phi_i \))

\[ T_5 = \frac{1}{2} R_4 \]
(or \( \frac{1}{32} \Phi_i \))

\[ T_6 = \frac{1}{2} R_4 \]
(or \( \frac{1}{32} \Phi_i \))
Typical Reflectance, Transmittance and Absorption Characteristics of Big bluestem Leaf
Typical Leaf Spectrum and Atmospheric Water Absorption Bands

**Figure 10-1** Spectral reflectance characteristics of healthy, green vegetation for the wavelength interval 0.4 – 2.6 μm. The dominant factors controlling leaf reflectance are the various leaf pigments in the palisade mesophyll (e.g., chlorophyll a and b, and β-carotene), the scattering of near-infrared energy in the spongy mesophyll, and the amount of water in the plant. The primary chlorophyll absorption bands occur at 0.43 – 0.45 μm and 0.65 – 0.66 μm in the visible region. The primary water absorption bands occur at 0.97, 1.19, 1.45, 1.94, and 2.7 μm.
Typical reflectance spectrum of cotton leaf

- Reflectance vs. Wavelength (nm)
- Internal tissue strongly reflective, biomass content
- Moisture content of vegetation, contrast between vegetation types
- Chlorophyll
- Phenolics

- COTTON
Peep through Spectrally
Cotton Leaves and Spectral Images

589

700

760

800
What causes the reflectance to change?

Absorption Spectra of Chlorophyll a, b
Beta Carotene, and other pigments
Reflectance and leaf structure
What can we measure?

- Cellulose, Pigments (chlorophyll, carotenoids), lignin, nonstructural carbohydrates, protein, oil etc.
- Greenness per surface area
- Canopy coverage
What can Remote Sensing Contribute?

- Topography for site-specific management
- Soil properties for site-specific management
- Plant properties to estimate insect populations for site-specific management
- Site-specific identification of water stress?
- Sites with late-season nutrient deficiency
- Site-specific identification and management of weeds.
What can Remote Sensing Contribute?

- Site-specific history for field
- Stand establishment
- Early detection of disease
- Presence of buried structures, tracks
- Phenology or Developmental stages (e.g., bloom)
Remote Sensing

Multi-spectral

or

Hyperspectral
What is Multispectral Imaging?

• Collection of reflected, emitted, or backscattered energy from an object or area of interest in multiple bands (less than 10) or regions of the electromagnetic spectrum.

• Multispectral imaging allows the analyst to perform reflectance spectroscopy on few spatial elements of the image scene.
What is Hyperspectral Imaging?

- Collection of reflected, emitted, or backscattered energy from an object or area of interest in multiple bands (from 10 to hundreds) or regions of the electromagnetic spectrum with each channel covering a narrow and contiguous portion of the light spectrum.

- Hyperspectral imaging allows the analyst to perform reflectance spectroscopy on each spatial element of the image scene.
Multispectral / Hyperspectral Comparison
Hyperspectral Imaging - Rationale

Principal objective is to identify and map specific vegetation, rock, and soil types.

- Many disciplines require *quantitative* results.
- Multispectral imaging systems under sample the spectrum.
- Identification of vegetation types, rock and soil types requires *high-resolution* spectra.
Hyperspectral Remote Sensing is one part of an Inevitable Progression in Technology

1972
- Landsat 1, 2, 3: 4 bands @ 80 m
- Landsat 4, 5: 7 bands @ 30 m
- SPOT: 4 bands @ 20 m, Pan @ 10 m
- GER: 63 bands @ 10 m
- AVIRIS: 224 bands @ 20 m

1990
- HYDICE: 210 bands @ 1-3 m

1998
- PROBE-1: 128 bands @ 3 m

Greater Spectral and Spatial Resolution
Global Remote Sensing Market

- Space-based Sensors (raw data)
- Aerial-based Sensors (raw data)
- Value-added reseller (processed data)
Remote Sensing Includes ....

- Satellite imagery
- Aerial photography
- Radar and Lidar
- Tractor-mounted sensors
- Hand-held instruments or sensors
Sensors

- Ground-based
  - GER
  - ASD FieldSpec

- Aerial
  - PHOTOGRAPHY
  - RADAR, LIDAR
  - CASI
  - MEIS II
  - ITD RDACS

- Space/Satellite
GER Radiometer - Typical Spectra

Figure 2-17  Typical spectral reflectance curves for urban-suburban phenomena in the region 0.4 – 0.9 μm (Jensen, 1989).
ASD FieldSpec Radiometer - Typical Spectra

Well-watered and well-fertilized

Reflectance vs. Wavelength (mm)

CORN
SORGHUM
SOYBEAN
COTTON
Remote Sensing

Examples:

- **High-resolution black-and-white or color photography.**

- **Radar (Radio Detection And Ranging, active microwave)** and **LIDAR** (laser radar).
  
  Lidar is an acronym which stands for **Light Detection And Ranging**.

- **Sonar** (Transmission of sound waves through water column and then recording the energy backscattered from the bottom or from objects within the water column.)
High-Resolution Black-and-White Photography

- Identification of landscape features
High-Resolution Color Photography

- Identification of landscape features
Remote Sensing – Radar and LIDAR

- Topography
- Tree height
- Canopy water content
- Vegetation type
- Biomass by component
- Canopy structure
Remote Sensing - LIDAR


Light Detection and Ranging (LIDAR) is a remote sensing system used to collect topographic data. This technology is being used by the National Oceanic and Atmospheric Administration (NOAA) and NASA scientists to document topographic changes along shorelines. These data are collected with aircraft-mounted lasers capable of recording elevation measurements at a rate of 2,000 to 5,000 pulses per second and have a vertical precision of 15 centimeters (6 inches). After a baseline data set has been created, follow-up flights can be used to detect shoreline changes.
Remote Sensing – Images to Information

Overview of how digital remotely sensed data are turned into useful information. The data recorded by the detectors are often converted from an analog electrical signal to a digital value and calibrated. Ground preprocessing removes geometric and radiometric distortions. This may involve the use of ephemeris and/or ancillary data such as map x,y coordinates, a digital elevation model, etc. The data are then ready for visual or digital analysis to extract biophysical or land-use/land-cover information.
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Remote Sensing – Agriculture
In the beginning …

Large area Inventories

Regional Crop Mapping
Remote Sensing – Agriculture
Today, We do Several Things

• Pest Management (Insects and weeds)
• Irrigation Scheduling
• Crop Growth Monitoring
• Nutrient Management
• Stress Detection
• Invasive Species Detection
• Natural Resource Management and Applications
Mean grain yield measured for 22 fields in October 1995 = **9.36 t/ha**
Mean of corresponding satellite derived yield = **9.18 t/ha**

Analyses of deviations: RMS-error=1.38t/ha
\[ R^2 = 0.50 \]
Estimating Grain Yield of Maize

The graph shows the yield of corn grains per hectare over time, based on different prediction methods and harvest periods:

- **Yield Prediction based on satellite data 6 weeks before harvest:** 9.16
- **Conventionally predicted yield in September:** 8.2
- **Conventionally predicted yield in October:** 8.1
- **Sample harvest 23 fields, 2 weeks before harvest:** 9.38
- **Complete harvest 7 fields, during harvest:** 9.67
Estimating Crop Yield in Hungary

Crop maps for the 6 counties in Hungary derived from multitemporal high-resolution satellite data (Landsat TM and IRS-1C LISS III.) from the early May-August period of 1997.
Estimating Crop Yield in Hungary

Winter wheat yield forecast for the 6 counties in Hungary using our developed Landsat/IRS + NOAA AVHRR model.
Winter wheat yields per county and Hungary

Winter barley yields per county and Hungary

Maize yields per county and Hungary

Sunflower yields per county and Hungary

COSH
Central Statistical Office, Hungary

FOMI RSC
FOMI Remote sensing Center
Vegetation Index Greenness Map
Period 42 October 5 - October 18, 2001

Greenness Value
- .01 - .05
- .06 - .10
- .11 - .15
- .16 - .25
- .26 - .33
- .34 - .40
- .41 - .47
- .48 - .52
- .53 - .59
- .60 - .66
- .67 - .99
- Water

KARS
The GreenReport®
Remote Sensing and Biodiversity
Typical Spectra - Species Differences
Well-watered and well-fertilized

Wavelength, nm

Reflectance

Corn
Sorghum
Cotton
Soybean

Wavelength, nm
Remote Sensing and Weed Species

Reflectance

Wavelength (nm)

Total Chlorophyll (µg cm⁻²)

Weed species

Ipomea | Cocklebur | Prickly Sida | Sesbania | Sicklepod
Interpretation and Analysis – Data Types

1. Image space: Display of data in relation to one another in a geometric or geographic sense, and provides a way to associate each pixel with a location on the ground.

2. Spectral space: High degree of spectral detail or response to the type of material on the ground (grass, trees, soil, water etc.).

3. Feature space: Provides pattern recognition.
Interpretation and Analysis – Interpretation

Analog

1. Tone
2. Shape
3. Size
4. Pattern
5. Texture
6. Shadow
7. Association

Digital

1. Preprocessing
2. Image Enhancement
3. Image Transformation
4. Image Classification and Analysis
Interpretation and Analysis – Analysis

Single Bands (*Any given band*)
Simple Ratios (*Band1*/ Band2)
Indices (*Band1*-Band2)/(Band1+Band2)
Fourier transformation
Wavelet decomposition

**Statistical Packages**
- SAS
- GENSTAT
- MATLAB

**Software Tools**
- Arc View
- Arc Info
- IDRISI
- ENVI
- IMAGINE

**Principle Component Analysis**
**Supervised Classification**
**Unsupervised Classification**
Hyperspectral Technology Applications

• **Agriculture and Forestry**
  – vegetation type identification, assessment of vegetative stress, crop yield, resource monitoring

• **Geology**
  – mapping of minerals and rock types for mineral and hydrocarbon exploration

• **Environmental**
  – detection of spills, baseline studies, land use planning

• **Marine and inland waters**
  – mapping of shoreline materials, bathymetry, water quality

• **Civil**
  – Transportation corridors, city planning
Agriculture Applications

1. Crop type classification
2. Crop condition assessment
3. Crop yield estimation
4. Mapping of soil characteristics
5. Mapping of soil management practices
6. Compliance monitoring (farming practices)
Forestry Applications

1) Reconnaissance mapping:
   • forest cover type discrimination
   • agroforestry mapping
2) Commercial forestry:
   • clear cut mapping / regeneration assessment
   • burn delineation
   • infrastructure mapping / operations support
   • forest inventory
   • biomass estimation
   • species inventory
3) Environmental monitoring
   • deforestation (rainforest, mangrove colonies)
   • species inventory
   • watershed protection (riparian strips)
   • coastal protection (mangrove forests)
   • forest health and vigor
Geological Applications

1. Surface deposit / bedrock mapping
2. Lithological mapping
3. Structural mapping
4. Sand and gravel (aggregate) exploration/ exploitation
5. Mineral exploration
6. Hydrocarbon exploration
7. Environmental geology
8. Geobotany
9. Baseline infrastructure
10. Sedimentation mapping and monitoring
11. Event mapping and monitoring
12. Geo-hazard mapping
13. Planetary mapping
Hydrology Applications

1. wetlands mapping and monitoring,
2. soil moisture estimation,
3. snow pack monitoring / delineation of extent,
4. measuring snow thickness,
5. determining snow-water equivalent,
6. river and lake ice monitoring,
7. flood mapping and monitoring,
8. glacier dynamics monitoring (surges, ablation)
9. river /delta change detection
10. drainage basin mapping and watershed modeling
11. irrigation canal leakage detection
12. irrigation scheduling
Sea Ice Applications

1. ice concentration
2. ice type / age /motion
3. iceberg detection and tracking
4. surface topography
5. tactical identification of leads: navigation: safe shipping routes/rescue
6. ice condition (state of decay)
7. historical ice and iceberg conditions and dynamics for planning purposes
8. wildlife habitat
9. pollution monitoring
10. meteorological / global change research
Land Use Applications

1. natural resource management
2. wildlife habitat protection
3. baseline mapping for GIS input
4. urban expansion / encroachment
5. routing and logistics planning for seismic / exploration / resource extraction activities
6. damage delineation (tornadoes, flooding, volcanic, seismic, fire)
7. legal boundaries for tax and property evaluation
8. target detection - identification of landing strips, roads, clearings, bridges, land/water interface
Mapping Applications

1. planimetry
2. digital elevation models (DEM's)
3. baseline thematic mapping / topographic mapping
Ocean and Coastal Monitoring Applications

• Ocean pattern identification:
  • currents, regional circulation patterns, shears
  • frontal zones, internal waves, gravity waves, eddies, upwelling zones, shallow water bathymetry

• Storm forecasting
  • wind and wave retrieval

• Fish stock and marine mammal assessment
  • water temperature monitoring
  • water quality
  • ocean productivity, phytoplankton concentration and drift
  • aquaculture inventory and monitoring

• Oil spill
  • mapping and predicting oil-spill extent and drift
  • strategic support for oil spill emergency response decisions
  • identification of natural oil seepage areas for exploration

• Shipping
  • navigation routing
  • traffic density studies
  • operational fisheries surveillance
  • near-shore bathymetry mapping

• Intertidal zone
  • tidal and storm effects
  • delineation of the land/water interface
  • mapping shoreline features / beach dynamics
  • coastal vegetation mapping
  • human activity / impact
Visit Remote sensing tutorial sites

http://rst.gsfc.nasa.gov/
http://www.vtt.fi/aut/rs/virtual/
http://www.remotesensing.org/
http://www.research.umbc.edu/~tbenja1/
http://dynamo.ecn.purdue.edu/~biehl/MultiSpec
http://www.cla.sc.edu/GEOG/rslab/images.html
http://www.cla.sc.edu/geog/rslab/rsccnew/fmod1.html
Early Sensitive Indication of Particular Stresses

Intensity of stress

Mild

Severe

Development of Stress
Remote Sensing environmental limitation of crop growth, development and yield

- Atmospheric Carbon Dioxide
- Solar Radiation
- Temperature
- Water (indirect)
- Wind
- Nutrients (N, P, K)
- Ozone, UV-B etc.,
- Growth Regulators
Remote Sensing – Atmospheric Carbon Dioxide

Reflectance

Wavelength (nm)

360 ppm CO₂
720 ppm CO₂
Remote Sensing environmental limitation of crop growth, development and yield

- Atmospheric Carbon Dioxide
- Solar Radiation
- Temperature
- Water (indirect)
- Wind
- Nutrients (N, P, K)
- Ozone, UV-B etc.,
- Growth Regulators
Crop Growth and Development - Environment
Response to Temperature

4-week old cotton seedlings
Environment Factors

Temperature:

➢ Strongly Affects:
  -- Phenology
  -- Vegetative growth, LAI, LAD
  -- Fruit Growth and Retention
  -- Respiration
  -- Water-loss and Water-Use

➢ Moderately Affects:
  -- Photosynthesis on a canopy basis
Remote Sensing and Environment
Thermal Imagery

http://wwwghcc.msfc.nasa.gov/irgrp/lst_goes_UHEI.html

Urban signatures in GOES night-time thermal image
Remote Sensing and Environment
Thermal Imagery

Thermal image of a cotton canopy that was part of a water and nitrogen study in Arizona. Blues and greens represent lower temperatures than yellow and orange. The image was acquired with a thermal scanner on board a helicopter. Most of the blue rectangles (plots) in the image correspond to high water treatments.
Relationships between NDVI and plant height, the number of nodes, LAI or biomass

\[ Y = 0.944(1-e^{-0.030x}) \]
\[ R^2 = 0.99 \]

\[ Y = 1.48(1-e^{-0.057x}) \]
\[ R^2 = 0.97 \]

\[ Y = 0.669X^{0.296} \]
\[ R^2 = 0.97 \]

\[ Y = 0.231X^{0.215} \]
\[ R^2 = 0.94 \]
Remote Sensing environmental limitation of crop growth, development and yield

- Atmospheric Carbon Dioxide
- Solar Radiation
- Temperature
- Water (indirect)
- Wind
- Nutrients (N, P, K)
- Ozone, UV-B etc.,
- Growth Regulators
Water plays essential roles in plants as a:

- Constituent
- Solvent
- Reactant in various chemical processes
- Maintenance of turgidity

The physiological importance of water is reflected in its ecological importance.

The distribution plants over the earth’s surface is controlled by the availability of the water (amount and seasonal distribution of precipitation) where ever temperature permits growth.
Figure 10

Relative Precipitation Changes (%/°C)

Mean of 15 Models

Dec-Jan-Feb

Mar-Apr-May

Jun-Jul-Aug

Sep-Oct-Nov

-4 -2 0 2 4 6 8
Environment Factors

Water Deficits:

- **Strongly affects:**
  - Vegetative growth, LAI, LAD
  - Fruit Growth and Retention
  - Water-loss and Water-Use
  - Photosynthesis

- **Moderately affects certain phenological events:**
  - Phenology (leaf development)
Fig. 5. Sensitivity and sequence in water stress I: the processes involved in dry matter production.
Role of water in cotton

Water deficit

- Cell expansion
- Mesophyll Resistance
- Stomatal Resistance
- Cell division & differentiation

Sensitivity to water deficit

Leaf GR
Stem GR
Root GR
Rate of Photosynthesis
Rate of Transpiration
Rate of squaring
Node production
Boll GR

LAI
Vegetative yield
Seasonal transpiration
Economic yield
Canopy photosynthesis
Sequence of events

bolls
shedding
Reflectance response of a single Magnolia leaf (*Magnolia grandiflora*) to decreased relative water content. As moisture content decreased, reflectance increased throughout the 0.4 – 2.5 μm region. However, the greatest increase occurred in the middle-infrared region from 1.3 – 2.5 μm (after Carter, 1991).
Progressive changes in percent reflectance for a Sycamore leaf at varying oven dry weight moisture contents. The dominant factors controlling leaf reflectance and the location of six of the Landsat Thematic Mapper bands are superimposed.
Plant water status

Plant water status is usually defined by measuring leaf water content.

As it is the seat for the major plant events like photosynthesis, transpiration, respiration.

Irrigation is provided to crop plants to maintain the plant water status so as not to limit growth and development processes.
Indices to Define Water Status

Relative Leaf Water Content  = \frac{(FW-DW)}{(TW-DW)}

Relative Water Content  = \frac{(FW-DW)}{FW}

Relative Drought Index  = \frac{WSD_{\text{act}}}{WSD_{\text{crit}}}

Leaf Water Content  = FW-DW

Equivalent Water Thickness  = \frac{(FW-DW)}{A} (g \text{ cm}^{-2}) \text{ or cm}

Fuel Moisture Content  = \frac{(FW-DW)}{FW} \text{ or DW}

Leaf water potential (\psi_W)  = \psi_s + \psi_p + \psi_g
Leaf water potential – indicator of plant health

Leaf water potential (LWP) is measured as negative pressure in bars or MPa. The LWP depends on:
- soil moisture (in the root zone)
- resistance to move from root surface to water conducting vessels
- resistance to flow through xylem
- resistance from xylem to leaf cells
- resistance to water loss from stomates depending on degree of opening

Leaf water potential is measured using:
- Psychrometer
- Cryoscopic osmometer
- Pressure probe
- Pressure chamber
Remote Sensing – Water Stress

Figure 13. Schematic representation of the Scholander pressure chamber that allows measurement of negative hydrostatic pressures in the xylem. A cut shoot or twig is sealed around the stem and placed upside down in the chamber and the chamber is hermetically sealed. Positive pressure is exerted on the shoot or twig, using a gas cylinder. When the exerted positive hydrostatic pressure equals the negative water potential (negative osmotic potential and negative pressure) in the xylem, the xylem fluid will appear at the cut surface. After determination of the osmotic potential of the xylem fluid, the negative hydrostatic pressure is calculated.
Identifying the hyperspectral reflectance index

- Simple correlation analysis between leaf physiological parameters and spectral reflectance

- Linear regression analysis to determine the relation between leaf water potential and reflectance ratios

\[
LWPR = \frac{X_{ij}}{X_{ij}} \quad \text{where } i \text{ and } j \text{ indicate the reflectance values in a given spectrum and at a given leaf water potential}
\]

\[
LWPI = \frac{(X_{ij} - X_{ij})}{(X_{ij} + X_{ij})}
\]
Co-ordination of measurements

10:00:00  10:02:00  10:02:15  10:02:30

Photosynthesis  Hyperspectral reflectance  Fresh weight  Leaf water potential
Diurnal trends of leaf water potential and transpiration rate in cotton
Leaf water potential

\[ y = -0.0036x + 0.7141 \quad R^2 = 0.9877 \]

\[ y = -0.003x + 0.1888 \quad R^2 = 0.9818 \]

\[ y = -0.0017x - 0.0614 \quad R^2 = 0.9976 \]
Leaf water potential vs. Photosynthesis

\[ P_n = 39.29 - 0.097 \times LWP^{0.7732} \]

\[ R^2 = 0.78 \]

\[ P < 0.001 \]
Hyperspectral reflectance spectra of 90 leaves

Reflectance vs. Wavelength (nm)
Hyperspectral reflectance ratio vs. Leaf water potential

\[ y = 0.005x + 0.9954 \]

\[ R^2 = 0.6636 \]
Prediction of weekly measured data leaf water potential

\[ y = 0.9091x - 0.1827 \]

\[ R^2 = 0.6263 \]
Photosynthesis prediction using LWP and hyperspectral ratio

\[ y = 0.9272x + 2.0227 \]

\[ R^2 = 0.6444 \]

\[ r = 0.80 \]
Indices reported in literature – Vegetative indices

<table>
<thead>
<tr>
<th>Reflectance Ratio</th>
<th>WS Treatments</th>
<th>Time of day</th>
</tr>
</thead>
<tbody>
<tr>
<td>R750/R650</td>
<td>-0.718</td>
<td></td>
</tr>
<tr>
<td>R935/R661</td>
<td>-0.736</td>
<td></td>
</tr>
<tr>
<td>R695/R760</td>
<td>0.609</td>
<td></td>
</tr>
<tr>
<td>R605/R760</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>(R750-R650)/(R750+R650)</td>
<td>-0.713</td>
<td></td>
</tr>
<tr>
<td>(R935-R661)/(R935+R661)</td>
<td>-0.728</td>
<td></td>
</tr>
<tr>
<td>(R850-R680)/(R850+R680)</td>
<td>-0.727</td>
<td></td>
</tr>
<tr>
<td>(R900-R680)/(R900+R680)</td>
<td>-0.728</td>
<td></td>
</tr>
<tr>
<td>(R790-R670)/(R790+R670)</td>
<td>-0.739</td>
<td></td>
</tr>
<tr>
<td>(R531-R570)/(R531+R570)</td>
<td>0.835</td>
<td></td>
</tr>
<tr>
<td>(R550-R530)/(R550+R530)</td>
<td>0.449</td>
<td></td>
</tr>
<tr>
<td>R900/R970</td>
<td>-0.75</td>
<td></td>
</tr>
</tbody>
</table>
Indices reported in literature – Water indices

<table>
<thead>
<tr>
<th>Reflectance Ratio</th>
<th>WS Treatments</th>
<th>Time of day</th>
</tr>
</thead>
<tbody>
<tr>
<td>R750/R550</td>
<td></td>
<td>0.901</td>
</tr>
<tr>
<td>R695/R420</td>
<td></td>
<td>-0.904</td>
</tr>
<tr>
<td>R710/R760</td>
<td></td>
<td>-0.906</td>
</tr>
<tr>
<td>R970/R900</td>
<td></td>
<td>-0.74</td>
</tr>
<tr>
<td>(R415-R435)/(R415+R435)</td>
<td></td>
<td>0.857</td>
</tr>
<tr>
<td>(R790-R720)/(R790-R720)</td>
<td></td>
<td>0.848</td>
</tr>
<tr>
<td>R1450/R900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R970/R902</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R790/R760</td>
<td>0.942</td>
<td>0.7</td>
</tr>
<tr>
<td>1689/1657</td>
<td>0.901</td>
<td>-0.928</td>
</tr>
</tbody>
</table>
Remote Sensing environmental limitation of crop growth, development and yield

- Atmospheric Carbon Dioxide
- Solar Radiation
- Temperature
- Water (indirect)
- Wind
- Nutrients (N, P, K)
- Ozone, UV-B etc.,
- Growth Regulators
Cotton and Nitrogen
Physiology and Spectral Properties
Photosynthesis - Variability Among Species
Response to Leaf Nitrogen

Leaf Nitrogen, g m⁻²

Photosynthesis, mg CO₂ m⁻² s⁻¹

Maize
Sorghum
Cotton
Sunflower
Rice
Soybean

Leaf Nitrogen, g m⁻²
Cotton Nitrogen - Physiology and Spectral Properties

- Reflectance
  - Wavelength, nm
  - Control
  - Nitrogen deficit

Reflectance

Wavelength, nm
Cotton Leaf N Concentration vs. $R_{517}/R_{413}$
(Field N and Pix Studies)

$n = 120$ (5 times $\times$ 4 N treatments $\times$ 3 reps $\times$ 2 studies)

- **2001**
  - N study
  - MC study
  - $Y = -0.0176X + 1.9947$
  - $r^2 = 0.78$, $n = 120$

- **2001**
  - $Y = -0.0205X + 2.2225$
  - $r^2 = 0.65$, $n = 156$

- **2002**
  - $Y = -0.2784X + 2.0559$
  - $r^2 = 0.69$, $n = 120$

- **2002**
  - $Y = -0.3303X + 2.3375$
  - $r^2 = 0.73$, $n = 156$

Leaf N (g kg$^{-1}$) vs. $R_{517}/R_{413}$
Cotton Leaf Chlorophyll vs. Reflectance Ratios
(Field N and Pix Studies)

\[
\begin{align*}
R_{551}/R_{915} & \\
0.4 & 0.3 & 0.2 & 0.1 \\
0.2 & 0.3 & 0.4 & 0.5 \\
\end{align*}
\]

\[
Y = -0.0043X + 0.4549 \quad r^2 = 0.67
\]

\[
Y = -0.0077X + 0.7667 \quad r^2 = 0.76
\]

\[
2001 \\
2002
\]

\[
R_{708}/R_{915} & \\
0.4 & 0.3 & 0.2 & 0.1 \\
0.2 & 0.3 & 0.4 & 0.5 \\
\end{align*}
\]

\[
Y = -0.00029X + 0.4821 \quad r^2 = 0.83
\]

\[
Y = -0.00045X + 0.7552 \quad r^2 = 0.88
\]

\[
2001 \\
2002
\]
Corn Nitrogen Experiment
Physiology and Spectral Properties
Correlation Coefficient (r) between Leaf Pigments, Leaf N Content, Phenolics, or Specific Leaf Weight (SLW) and Leaf Hyperspectral Reflectance.

Dotted lines represent significant levels at $P = 0.05$, $n = 36$.)
Relationship between Leaf N Content and Leaf Net Photosynthesis (Leaf N Was Expressed on Both a Dry Weight % and a Leaf Area Basis).
Linear Regression of Leaf Pigment Concentrations with a Specific Reflectance Ratio

- **Chl. a**
  - Reflectance Ratio: $R_{756/R758}$
  - Linear Regression: $y = -9 \times 10^{-5}x + 0.9999$
  - $R^2 = 0.6128$

- **Chl. b**
  - Reflectance Ratio: $R_{764/R765}$
  - Linear Regression: $y = -8 \times 10^{-5}x + 1.0001$
  - $R^2 = 0.639$

- **Total Chl.**
  - Reflectance Ratio: $R_{756/R759}$
  - Linear Regression: $y = -0.0001x + 1.0001$
  - $R^2 = 0.5978$

- **Carotenoids**
  - Reflectance Ratio: $R_{756/R759}$
  - Linear Regression: $y = -0.0007x + 1.0003$
  - $R^2 = 0.5347$

Leaf Pigment Concentration (µg cm$^{-2}$)
Linear Regression of Leaf N Content with a Specific Reflectance Ratio

\[ Y = 0.0369X + 0.8949 \]
\[ R^2 = 0.750 \]

\[ Y = -0.2168X + 0.7437 \]
\[ R^2 = 0.510 \]
Sorghum Nitrogen Experiment
Physiology and Spectral Properties
Sorghum Leaf Chlorophyll or N vs. Reflectance Ratio (Pot Study)

(A) $Y = 0.0003X + 1.0124$  
$r^2 = 0.662$

(B) $Y = 0.0047X + 0.1591$  
$r^2 = 0.676$
Corn Leaf Chlorophyll or N vs. Reflectance Ratio (SPAR Study)

Y = -0.00086X + 0.845, \( r^2 = 0.59 \)

Y = -0.0017X + 1.016, \( r^2 = 0.687 \)
# Nitrogen, Physiology and Spectral Properties – Various Crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>N sensitive bands (nm)</th>
<th>Algorithm†</th>
<th>N</th>
<th>r²</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>555, 715</td>
<td>Chl = [(R_{712}/R_{1088}) - 0.845] ÷ (-0.00086)</td>
<td>36</td>
<td>0.59</td>
<td>Zhao et al., 2003a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N = [(R_{575}/R_{526}) - 1.016] ÷ (-0.0017)</td>
<td>36</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td>555, 710</td>
<td>Chl = [(R_{708}/R_{915}) - 0.722] ÷ (-0.00040)</td>
<td>156</td>
<td>0.76</td>
<td>Zhao et al., 2004b</td>
</tr>
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<td></td>
<td></td>
<td>N = [(R_{517}/R_{413}) - 1.9947] ÷ (-0.0176)</td>
<td>120</td>
<td>0.78</td>
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<tr>
<td>Sorghum</td>
<td>555, 715</td>
<td>Chl = [(R_{1075}/R_{735}) - 1.012] ÷ (0.00030)</td>
<td>21</td>
<td>0.66</td>
<td>Zhao et al., 2004c</td>
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<tr>
<td></td>
<td></td>
<td>N = [(R_{405}/R_{715}) - 0.159] ÷ (0.0047)</td>
<td>21</td>
<td>0.68</td>
<td></td>
</tr>
</tbody>
</table>

† Chl = chlorophyll (mg m⁻²); N = leaf nitrogen (g kg⁻¹); R = reflectance and subscript values are the wavelengths (nm).
Nutrient Deficiency – Potassium
Environment Factors

Fertilizers Deficits - Potassium:

- **Strongly Affects:**
  -- Leaf growth, LAI, LAD
  -- Fruit Retention

- **Moderately Affects:**
  -- Photosynthesis
  -- Stem growth
Environment - Nutrients

Potassium - Cotton Growth and Development

Environmental Productivity Indices

Leaf Potassium, %

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

Environmental Productivity Indices for Growth and Development

Leaf Growth

Stem Elongation

Photosynthesis

Leaf Initiation Rates
Cotton Potassium Experiment
Physiology and Spectral Properties
Remote Sensing environmental limitation of crop growth, development and yield

- Atmospheric Carbon Dioxide
- Solar Radiation
- Temperature
- Water (indirect)
- Wind
- Nutrients (N, P, K)
- Ozone, UV-B etc.,
- Growth Regulators
Atmospheric CO₂ and UV Radiation
Physiology and Spectral Properties
UV-B Radiation Effect on Cotton Leaf Anatomy

(A)  
(B)  
(C)  

100 µm

P  
M  
IC

ADE

ABE

8

16

Ultraviolet-B radiation treatments (kJ m⁻² d⁻¹)
UV-B Radiation – Phenology

EPI Factors for various Developmental Processes

Node addition
\[ y = -0.0003x^2 + 0.0014x + 0.9997 \quad R^2 = 0.4619 \]

Leaf area expansion
\[ y = -0.0015x^2 + 0.0102x + 0.9914 \quad R^2 = 0.8136 \]

Stem elongation
\[ y = -0.0023x^2 + 0.0105x + 0.9926 \quad R^2 = 0.9331 \]
Environment Factors

Ultraviolet-B Radiation:

- **Strongly Affects:**
  -- *Photosynthesis*
  -- *Stem growth*

- **Moderately Affects:**
  -- *Leaf growth*
  -- *Leaf aging*

- **No Effects:**
  -- *Phenology*
Hyperspectral Reflectances of Cotton Leaves Exposed to Different UV-B and CO₂ Treatments

Reflectance

Wavelength (nm)

360 ppm

720 ppm

0 kJ
8 kJ
16 kJ
Breakdown of spectral reflectances of cotton leaves into specific waveband regions with known properties exposed to different UV-B and CO₂ treatments.

- Chlorophyll reflectance
- Internal tissue reflectance
- Leaf water reflectance
Deviation of Spectral Reflectances of Cotton Leaves Exposed to Different UV-B Treatments from Control at Squaring and Flowering Stages
Remote Sensing environmental limitation of crop growth, development and yield

- Atmospheric Carbon Dioxide
- Solar Radiation
- Temperature
- Water (indirect)
- Wind
- Nutrients (N, P, K)
- Ozone, UV-B etc.,
- Growth Regulators
Remote Sensing and Plant Growth Regulators
Environment Factors

Growth Regulators - Mepiquat Chloride (PIX):

- **Moderately Affects:**
  - *Leaf, stem and branch growth and LAI*

- **Slightly Affects:**
  - *Photosynthesis*
Mepiquat Chloride (PIX) - Growth

EPI Factors

Mepiquat Chloride, mg g\(^{-1}\) dry weight

Leaf growth
Photosynthesis
Stem growth

PIX and EPI Indices

Mepiquat Chloride, mg g\(^{-1}\) dry weight
Mepiquat Chloride (PIX) and Cotton Growth and Remote Sensing
Mepiquat Chloride (PIX) and Cotton Growth and Remote Sensing

• As expected, application of MC decreased plant growth, increased leaf chlorophyll concentration, and decreased leaf reflectance.

• Reflectance values at 420, 545, 810, and 935 nm separated MC-treated plants from untreated plants under favorable growth conditions, but we were unable to distinguish the different application rates of MC.

• Forward stepwise regression and discriminant analysis suggested that changes in leaf reflectance from MC application were due to increased chlorophyll and nitrogen concentrations.
Remote Sensing environmental limitation of crop growth, development and yield

- Atmospheric Carbon Dioxide
- Solar Radiation
- Temperature
- Water (indirect)
- Wind
- Nutrients (N, P, K)
- Ozone, UV-B etc.,
- Growth Regulators
Remote Sensing – Atmospheric Carbon Dioxide

360 ppm CO₂
720 ppm CO₂
Remote Sensing and Environment

Thermal Imagery

Thermal image of a cotton canopy that was part of a water and nitrogen study in Arizona. Blues and greens represent lower temperatures than yellow and orange. The image was acquired with a thermal scanner on board a helicopter. Most of the blue rectangles (plots) in the image correspond to high water treatments.
Hyperspectral reflectance ratio vs. Leaf water potential

\[ y = 0.005x + 0.9954 \]

\[ R^2 = 0.6636 \]
Nitrogen, Physiology and Spectral Properties – Various Crops

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† Chl = chlorophyll (mg m⁻²); N = leaf nitrogen (g kg⁻¹); R = reflectance and subscript values are the wavelengths (nm).
Cotton Potassium Experiment
Physiology and Spectral Properties

![Graph showing reflectance percentage against wavelength for different potassium levels (Sufficient K, Medium K, Low K)]
Hyperspectral Reflectances of Cotton Leaves Exposed to Different UV-B and CO$_2$ Treatments
Remote Sensing and Insect Infestation

Genotype Study North Farm, MSU

Can we identify insect pest damage?
Genotype Study – Nematode Damage – MSU North Farm
NDVI

Jul 08, 2002
Aug 10, 2002
Aug 21, 2002
Environmental Factors, Crop Growth and Remote Sensing
Field Study

- **Treatments**
  - N study treatments (0, 50, 100, and 150 lbs/A)
  - PIX study treatment (0, 8, 16, and 32 oz./A)
  - Irrigation study (Irrigated, Non-irrigated)
  - Genotype study (38 genotypes)

- **Measurements**
  - Leaf and canopy hyperspectral reflectance (weekly)
  - Growth analysis (Plant height, nodes, LAI, biomass) (5 times)
  - Pigments and phenolics (weekly)
  - Yield and yield components
  - Photosynthesis
  - Leaf mineral nutrient contents
Location and Field Map for 2001 Field Study
(North Farm, MSU)

The image was taken on July 17 (First Flower Stage)
Questions We Try to Answer

• Which index or ratio is the best to estimate cotton growth and yield?

• Which growth stage is the best date to use the index in estimating cotton yield?

• Which function can be used to estimate crop physiology, growth and yield?
## Correlation Coefficient (R) of Seedcotton Yield with Several Published Indices

<table>
<thead>
<tr>
<th>Indices</th>
<th>6/25</th>
<th>7/3</th>
<th>7/10</th>
<th>7/24</th>
<th>7/31</th>
<th>8/15</th>
<th>8/22</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIR/R (R750/R650)</td>
<td>0.524</td>
<td>0.354</td>
<td>0.421</td>
<td>0.589</td>
<td>0.391</td>
<td>0.202</td>
<td>0.009</td>
</tr>
<tr>
<td>(R750/R550)</td>
<td>0.647</td>
<td>0.482</td>
<td>0.403</td>
<td>0.199</td>
<td>0.295</td>
<td>0.433</td>
<td>0.219</td>
</tr>
<tr>
<td>(R935/R661)</td>
<td>0.523</td>
<td>0.364</td>
<td>0.480</td>
<td>0.673</td>
<td>0.523</td>
<td>0.040</td>
<td>0.150</td>
</tr>
<tr>
<td>NDVI (R750 R650)</td>
<td>0.501</td>
<td>0.394</td>
<td>0.653</td>
<td><strong>0.723</strong></td>
<td>0.372</td>
<td>0.234</td>
<td>0.047</td>
</tr>
<tr>
<td>(R935 R661)</td>
<td>0.497</td>
<td>0.401</td>
<td><strong>0.815</strong></td>
<td><strong>0.752</strong></td>
<td>0.508</td>
<td>0.080</td>
<td>0.189</td>
</tr>
<tr>
<td>(R850 R680)</td>
<td>0.475</td>
<td>0.389</td>
<td><strong>0.763</strong></td>
<td><strong>0.747</strong></td>
<td>0.434</td>
<td>0.183</td>
<td>0.152</td>
</tr>
<tr>
<td>(R900 R680)</td>
<td>0.477</td>
<td>0.390</td>
<td><strong>0.774</strong></td>
<td><strong>0.760</strong></td>
<td>0.466</td>
<td>0.142</td>
<td>0.180</td>
</tr>
<tr>
<td>(R790 R670)</td>
<td>0.476</td>
<td>0.391</td>
<td>0.676</td>
<td><strong>0.768</strong></td>
<td>0.416</td>
<td>0.173</td>
<td>0.131</td>
</tr>
<tr>
<td>Sample size (n)</td>
<td>12</td>
<td>24</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Planting date: 5/14; Squaring date: 6/24; First flower: 7/17
Relationship between NDVI at One Week Prior to First Flower and Seedcotton Yield in 2001

\[ Y = 3.27 \times 10^{-5}X + 0.763 \]

\[ R^2 = 0.665 \]
Relationship between NIR and Plant Height or the Number of Mainstem Nodes (n = 96)

\[ Y = 0.331X + 1.197 \]
\[ R^2 = 0.67 \]

\[ Y = 2.379 \ln(X) - 4.006 \]
\[ R^2 = 0.63 \]
Relationship between NIR or NDVI and Biomass (n = 96)

Biomass (g m⁻², from 5-time harvest data)
Relationship between NIR or NDVI and Leaf Area Index (n = 150)

\[
Y = -39.9 + 54.9(1 - 0.22^X) \\
R^2 = 0.68
\]

\[
Y = -50.0 + 71.0(1 - 0.23^X) \\
R^2 = 0.70
\]

\[
Y = -5.65 + 12.27(1 - 0.21^X) \\
R^2 = 0.56
\]

\[
Y = -0.359 + 1.25(1 - 0.156^X) \\
R^2 = 0.62
\]
Relationship between NIR or NDVI and Leaf Area Index (n = 96)

Leaf Area Index (from 5-time harvest data)
Changes in Plant height, the number of mainstem nodes, leaf area index, and above ground biomass during cotton growth under field conditions in 2001.
Changes in NDVI of different treatments during field cotton growth

Days after Emergence

NDVI

Days after Emergence
Relationships between NDVI and plant height, the number of nodes, LAI or biomass

\[ Y = 0.944(1-e^{-0.030x}) \]
\[ R^2 = 0.99 \]

\[ Y = 1.48(1-e^{-0.057x}) \]
\[ R^2 = 0.97 \]

\[ Y = 0.669X^{0.296} \]
\[ R^2 = 0.97 \]

\[ Y = 0.231X^{0.215} \]
\[ R^2 = 0.94 \]
Relationships between NDVI and plant height, the number of nodes, LAI or biomass

- Plant Height (cm)
  - Y = 4.24 - 171X + 266X^2
  - R^2 = 0.99
  - Y = e^{7.25X}
  - R^2 = 0.95

- Mainstem Nodes (No. plant^-1)
  - Y = 6.12 - 1.29X + 2.94X^2
  - R^2 = 0.99

- Biomass (g m^-2)
  - Y = 2.35 - 1.22X + 1.54X^2
  - R^2 = 0.99

- Leaf Area index (LAI)
  - Y = e^{7.25X}
  - R^2 = 0.95
What’s Next?

Remote Sensing (RS):

Provide spatial variable data for crop health and yield, and soil conditions, and some predictive capabilities.

Crop Simulation Models and Decision Support Systems (CSM-DSS):

Provide predictive capabilities and verification of RS features.

RS and CSM-DSS:

Deliver site-specific input management or optimization.