Optical Sensing of Crop N – Under Water-Limited Conditions

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In-Season N Management

• Applying fertilizer N based on information acquired during the growing season (in-season) when crop N demand is greatest.

Traditional Up-Front       In-Season
Rationale

• N use efficiency will be greatest when N is provided at the time of greatest crop N demand.
  • Increase yields and grain quality.
  • Increase dollar returns.
  • Minimize N loss to the environment.

• Growers can delay a decision on N fertilization until later in the season when weather, yield potential, and grain prices are clearer.
Contents

• Outward appearance of plant nitrogen deficiency
• Light reflectance from leaves
• Normalized Difference Vegetation Index (NDVI)
• Equipment for nutrient sensing
• “N-rich” strip
• Calibration methods for in-season crop sensing
• Limitations for use in dry environments
• Recommendations
Nitrogen-Chlorophyll Relationship

• A lack of N supplied to the plant will result in suppression of chlorophyll formation.

\[ \text{C}_{55}\text{H}_{72}\text{O}_5\text{N}_4\text{Mg} \]
Nitrogen Chlorosis

• Condition in which plant leaves produce insufficient chlorophyll.
• Typically caused when leaves do not have enough nitrogen to synthesize all of the chlorophyll they need.
• By absorbing red light, chlorophyll is responsible for the green color of plant leaves.
• Chlorotic leaves are yellow and have fewer chloroplasts where photosynthesis is carried out.
Visual Symptoms

Poor Growth

Yellowing
Electromagnetic Spectrum
Leaf Reflectance Curves

- Healthy
- Chlorotic
- Dead

Wavelength:
- Blue
- Green
- Red
- Near IR

Reflectance:
- Absolute Reflectance
Varying Leaf Color

Visible

Healthy

Chlorotic

Visible

Blue Green Red Near IR
Chlorophyll Meter

- How much red light is transmitted through the leaf where chlorophyll absorbs light.
- Calculate a relative value that is correlated with the amount of leaf chlorophyll.
Differences Between Bands of Light

- **Near Infrared (Near IR)**
- **Red**
- **Green**
- **Blue**

Visible light spectrum with arrows indicating differences.
Reflectance of Red and NIR

- Chloroplasts in the mesophyll absorb red light, while the cell structure strongly reflects near infrared (NIR) light.
Normalized Difference Vegetation Index

- NDVI
- An index of vegetation biomass derived from sensing in the red and near infrared wavelengths.

\[
\text{NDVI} = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}
\]

- Values vary between -1.0 and 1.0
- Vegetation will tend to positive values from 0.3 to 0.8
NDVI vs. Crop Biomass

- NIR reflectance is larger than red reflectance and increases with amount of green vegetation present.
- NDVI was mainly developed to detect the density of plant growth.
Plant Density

- **Biomass**: The mass of vegetation per unit area of ground.
- **Cover**: The vertical projection of vegetation covering the ground surface per unit area of ground.
- **Leaf area index**: Ratio of green plant material per unit of area of ground.
NDVI vs. Crop Nitrogen

- NDVI has been shown to be correlated to crop chlorophyll status.

- NDVI is related to chlorophyll through the direct effect of nitrogen fertility on crop growth and development.
# Crop Canopy Sensors

<table>
<thead>
<tr>
<th></th>
<th><strong>GreenSeeker</strong></th>
<th><strong>OptRx</strong></th>
<th><strong>CropSpec</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parent Co.</strong></td>
<td>Trimble</td>
<td>Ag Leader</td>
<td>Topcon</td>
</tr>
<tr>
<td><strong>Development Co.</strong></td>
<td>NTech Industries</td>
<td>Holland Scientific</td>
<td>Yara</td>
</tr>
<tr>
<td><strong>Origin</strong></td>
<td>OK/CA</td>
<td>NE</td>
<td>Germany</td>
</tr>
<tr>
<td><strong>Wavebands</strong></td>
<td>656 nm</td>
<td>Configurable 3 band 670, 730, &amp; 760 nm</td>
<td>735 nm</td>
</tr>
<tr>
<td></td>
<td>774 nm</td>
<td>670, 730, &amp; 760 nm</td>
<td>808 nm</td>
</tr>
<tr>
<td><strong>Light Source</strong></td>
<td>LED</td>
<td>LED</td>
<td>Pulsed Laser Diode</td>
</tr>
<tr>
<td><strong>Sensing Height</strong></td>
<td>2-3 ft above canopy</td>
<td>2-3 ft above canopy</td>
<td>6-13 ft above ground</td>
</tr>
<tr>
<td><strong>Pointing angle</strong></td>
<td>90°</td>
<td>90°</td>
<td>45-55°</td>
</tr>
<tr>
<td><strong>Sensing footprint</strong></td>
<td>2 ft</td>
<td>2 ft</td>
<td>6-13 ft</td>
</tr>
</tbody>
</table>
Ground-Based Sensing

• Sensors produce own light energy.
• Eliminate effects of sun angle and cloud variations.
• Can be used at night.

N. Kitchen, USDA-ARS
N Rich Strip

- Reflectance from a non-N limiting strip standardizes the reflectance from the rest of the field.

N. Kitchen USDA-ARS
Historic Perspective
N-Rich Plot Concept

• N-rich treatment was initially used to normalize data from plot studies and allow leaf N concentration comparisons across time, fields, & cultivars (1988).

• Extended to chlorophyll meters (1990)

J. Schepers, USDA-ARS

<95% means “needs more N”
Historic Perspective

• Adapted to field situations to accommodate crop canopy sensors (2000)

• Extended to postage stamp arrangement with multiple N rates (2002)

• Ramped calibration strip with multiple N rates introduced (2005)
Variable Rate System

Pre-processed base map and application algorithm
- Yield
- Management zone
- Soil type
- Elevation
- Soil color / OM
- Electrical conductivity
- Soil testing

Real-time crop data

DGPS Receiver

Raven or Rawson Variable-Rate Compatible Controller

Up to 8 sensors with a minimum of 2 sensors

Courtesy: Newell Kitchen
Ntech GreenSeeker

• Top-dress N rates are based on estimated grain yield and likely response to additional N fertilizer.
Nitrogen Algorithm

• Predict potential yield (in-season estimate of yield)
  • \( \text{YP}_0 \sim \text{NDVI} / \text{GDD} \) from planting to sensing

• Determine response index
  • \( \text{RI} = \frac{\text{NDVI} \text{ (N Rich)}}{\text{NDVI} \text{ (rest of field)}} \)

• Determine potential yield with added N:
  • \( \text{YP}_N = \text{YP}_0 \times \text{RI} \)
  • N Recommendation = \( \frac{\text{YP}_N - \text{YP}_0}{\text{expected efficiency}} \)

Diagram:
- Planting Date
- Sensing Date
- Corn V6
- \( \text{YP}_N \)
- \( \text{YP}_0 \)
- \( \text{RI} \)
OptRx Crop Sensor

- Operates with a “red edge” band that is more sensitive to variation in chlorophyll than the “red” band.
Virtual Reference Strip

• Eliminate need for N rich strip.
  • May be hard to locate
  • Need to move each year
  • Difficult to understand the algorithm and sensor calibration procedure

• Identify healthy plants while driving down and back across a field. Somewhere there is enough N to produce full yield.
  • Turn-key approach
  • Algorithm is simple and easy to adapt to local conditions.
General Nitrogen Algorithms

N Rate = \(317\sqrt{0.97 - SI}\)  
N Rate = \((220 \times SI) - 170\)
TopCon CropSpec

• Producer identifies poor part of the field and assigns the desired N rate.
• Producer identifies a good part of the field and assigns the desired N rate.
• Sensor readings are taken from each area.
• Readings in the rest of the field are linearly related with N rate.
Factors Affecting Crop Reflectance

- Sun angle and lighting
- Crop variation
  - Growth stage
  - Cultivar
  - Wheat class
  - Chlorophyll content
  - Biomass, cover, LAI

Variation in Soil Color or Background Reflectance
Problem in Dryland Crops

NDVI is less well correlated with plant chlorophyll and N under semiarid conditions.
... because water affects leaf area and plant size too. NDVI is best correlated to biomass and yield when N is limiting.
Limitations of NDVI

• NDVI is related to plant nitrogen through the indirect effect of N fertility on crop biomass.

• This concept works well in environments where water is plentiful!

• What about dryland wheat grown in the inland PNW?
# Combined Spectral Indices

<table>
<thead>
<tr>
<th>Index</th>
<th>Mathematical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Difference Vegetation Index</td>
<td>$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$</td>
</tr>
<tr>
<td>Normalized Difference Red Edge Index</td>
<td>$NDRE = \frac{(RE - Red)}{(RE + Red)}$</td>
</tr>
<tr>
<td>Combined Index</td>
<td>$\frac{NDRE}{NDVI}$</td>
</tr>
<tr>
<td>Modified Triangular Vegetation Index</td>
<td>$MTVI = 1.5 \left[ 1.2(NIR-Green) - 2.5(\text{Red-Green}) \right] / \left[ (2NIR+1) 2 - (6NIR-5\text{Red}^{1/2}) - 0.5 \right]^{1/2}$</td>
</tr>
<tr>
<td>Modified Chlorophyll Absorption in Reflection Index</td>
<td>$MCARI = \left[ ((\text{RE-Red}) - 0.2) \ (\text{RE-Green}) \right] (\text{RE}/\text{Red})$</td>
</tr>
<tr>
<td>Combined Index</td>
<td>$\frac{MCARI}{MTVI}$</td>
</tr>
</tbody>
</table>
Isolating the Chlorophyll Signal

\[
\frac{\text{Chlorophyll Index (NDRE)}}{\text{Structural Index (NDVI)}}
\]

\[
\frac{(\text{Chl} \times \text{LAI})}{\text{LAI}}
\]

Chl
Field Measurements

Dr. Jan Eitel, Assistant Professor, UI
Soil Variability Issue

• Different spectral index values despite abundant N availability in each strip.

Area used as reference When making variable-Rate N applications

Courtesy: Jim Schepers, ARS-Lincoln
Soil Background Color

Relatively little is known how combined indices are affected by variations in soil background reflectance.
## Percent Variance Explained

<table>
<thead>
<tr>
<th>SI</th>
<th>Chl</th>
<th>LAI</th>
<th>Soil</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI</td>
<td>0.0</td>
<td>47.9</td>
<td>16.1</td>
<td>28.6</td>
</tr>
<tr>
<td>OSAVI</td>
<td>0.0</td>
<td>50.4</td>
<td>5.5</td>
<td>35.8</td>
</tr>
<tr>
<td>MTVI2</td>
<td>0.2</td>
<td>47.6</td>
<td>0.8</td>
<td>41.4</td>
</tr>
<tr>
<td>NDRE</td>
<td>3.6</td>
<td>56.7</td>
<td>10.9</td>
<td>25.6</td>
</tr>
<tr>
<td>MCARI</td>
<td>14.1</td>
<td>15.4</td>
<td>1.1</td>
<td>46.2</td>
</tr>
<tr>
<td>TCARI</td>
<td>14.7</td>
<td>3.2</td>
<td>11.8</td>
<td>57.0</td>
</tr>
<tr>
<td>NDRE/NDVI</td>
<td>62.1</td>
<td>13.1</td>
<td>4.7</td>
<td>18.0</td>
</tr>
<tr>
<td>TCARI/OSAVI</td>
<td>14.0</td>
<td>11.5</td>
<td>43.1</td>
<td>26.0</td>
</tr>
<tr>
<td>MCARI/OSAVI</td>
<td>32.8</td>
<td>1.9</td>
<td>2.8</td>
<td>41.2</td>
</tr>
<tr>
<td>MCARI/MTVI2</td>
<td>59.3</td>
<td>2.2</td>
<td>4.0</td>
<td>23.8</td>
</tr>
</tbody>
</table>

What Could One Expect?

SWW – 13 May 2011
Wheat N Uptake

early season: increase yield

late season: increase protein

M. Flowers, L. Lutcher, M. Corp, and B. Brown. 2007. OSU Extension
Early Season?

• Sensing Issues:
  • Too little biomass and cover.
  • Variation in crop growth may be absent, or confused with non-N related factors.
  • Variation in crop color may be absent, or be temporary.
  • Field conditions in spring may be too wet for wheeled applicators.
Early Season?

• Fertilizer Issues:
  • Uptake efficiency depends upon rainfall to move the N into the root zone.

  • Broadcast applications of granular fertilizer may become stranded at the surface in dry soil and promote weeds.

  • Liquid application/injection into the soil minimizes stranding and losses of N due to volatilization.
OptRx NDVI – 26 May 2011

![Graph showing the relationship between NDVI and Applied N (lb/ac) for Control Plots. The graph plots NDVI on the y-axis and Applied N (lb/ac) on the x-axis. The data points suggest a positive correlation between the two variables.]
Crop Response

Soft White Winter Wheat – Spoke Wheel Injection

Grain Yield (bu/ac) vs. In-Season Applied N (lb/ac)
Crop Response

Increasing N Sufficiency

Yield Response (bu/ac) vs. Sufficiency Index

- Control Plot
- 50 lb Rate
- 100 lb Rate
Late Season?

• Rainfall is not required for foliar applications of liquid fertilizer.

• Potential for increasing grain protein concentration of hard wheat, but difficult to predict.
Precipitation from April 1 to date

<table>
<thead>
<tr>
<th>City</th>
<th>Inches</th>
<th>Percent of normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut Bank</td>
<td>4.15</td>
<td>70%</td>
</tr>
<tr>
<td>Shelby</td>
<td>3.39</td>
<td>66%</td>
</tr>
<tr>
<td>Chester</td>
<td>4.74</td>
<td>87%</td>
</tr>
<tr>
<td>Havre</td>
<td>6.81</td>
<td>140%</td>
</tr>
<tr>
<td>Harlem</td>
<td>7.97</td>
<td>149%</td>
</tr>
<tr>
<td>Malta</td>
<td>8.26</td>
<td>129%</td>
</tr>
<tr>
<td>Glasgow</td>
<td>8.60</td>
<td>165%</td>
</tr>
<tr>
<td>Sidney</td>
<td>8.83</td>
<td>134%</td>
</tr>
<tr>
<td>Plentywood</td>
<td>8.81</td>
<td>143%</td>
</tr>
<tr>
<td>Great Falls</td>
<td>6.18</td>
<td>91%</td>
</tr>
<tr>
<td>Conrad</td>
<td>5.20</td>
<td>91%</td>
</tr>
<tr>
<td>Helena</td>
<td>4.69</td>
<td>94%</td>
</tr>
<tr>
<td>Stanford</td>
<td>6.38</td>
<td>95%</td>
</tr>
<tr>
<td>Lewistown</td>
<td>10.83</td>
<td>131%</td>
</tr>
<tr>
<td>Harlowntown</td>
<td>7.04</td>
<td>105%</td>
</tr>
<tr>
<td>Jordan</td>
<td>4.90</td>
<td>75%</td>
</tr>
<tr>
<td>Glendive</td>
<td>6.30</td>
<td>93%</td>
</tr>
</tbody>
</table>

Source: USDA
*July 11 (latest figures available)
Visual Symptoms

• Lighter green color.
• 30 lb N/ac at planting.
• Above normal rainfall.
Foliar Application
## Returns

<table>
<thead>
<tr>
<th>N Rate (lb/a)</th>
<th>SPAD Meter</th>
<th>Flag leaf N (%)</th>
<th>Grain Yield (bu/a)</th>
<th>Grain Protein (%)</th>
<th>Gross Return ($/a)</th>
<th>Cost ($/a)</th>
<th>Net return ($/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>45 ± 4</td>
<td>2.9 ± 0.4</td>
<td>42 ± 11</td>
<td>12.9 ± 0.6</td>
<td>148</td>
<td>0</td>
<td>148</td>
</tr>
<tr>
<td>23</td>
<td>47 ± 3</td>
<td>3.2 ± 0.4</td>
<td>43 ± 10</td>
<td>13.8 ± 0.7</td>
<td>165</td>
<td>11</td>
<td>154</td>
</tr>
<tr>
<td>46</td>
<td>48 ± 3</td>
<td>3.5 ± 0.4</td>
<td>45 ± 12</td>
<td>14.4 ± 0.7</td>
<td>174</td>
<td>16</td>
<td>159</td>
</tr>
</tbody>
</table>

- Application 6$/ac
- Nitrogen $0.21/lb
Late-Season N Topdressing
(20 lb N/ac as fluid urea applied 5d after flowering)

Data courtesy of R. Koenig, WSU
Recommendations

• Be aware of fertilizer issues related to dryness in the inland PNW.

• Be aware of the strengths and weaknesses of available sensors and systems for translating sensor measurements to N rates.
  • Research is needed in the PNW.
  • A combined spectral index will work better than a single index for sensing chlorophyll in lower rainfall areas.
  • Consider a system in which you can choose the best spectral index for your environment.
The Future

• N prices and environmental pressures will continue to push tighter N management.


• Canopy sensing technology will continue to improve.
Terrestrial Laser Scanning

Field of View

Active ground optical sensor
Laser
Questions? Comments?

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541/278-4391
Need for Additional N

• Crop yield potential exceeds N supply.
  • Increase in growing season rainfall
  • N fertility was insufficient after planting

![Graph showing yield potential vs. applied N]

Yield Potential

Applied N
Application

• N-rich area to normalize readings
• CCCI = NDRE/NDVI

<95% means “needs more N”

J. Schepers, USDA-ARS
Spectrophotometer

- A “spectrophotometer” is an instrument that detects light in different wavelengths, or wavebands.
- The human eye is a rudimentary spectrophotometer.

<table>
<thead>
<tr>
<th></th>
<th>Human Eye</th>
<th>CropScan 470</th>
<th>GreenSeeker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range</td>
<td>350-700 nm</td>
<td>600-1100 nm</td>
<td>630-850 nm</td>
</tr>
<tr>
<td>Detectors (pixels)</td>
<td>6-7 million</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Wavelength detectors</td>
<td>3 (RGB)</td>
<td>3 (R, RE, NIR)</td>
<td>2 (R/NIR)</td>
</tr>
<tr>
<td>Wavelength resolution</td>
<td>80 nm</td>
<td>0.5 nm</td>
<td>10 nm</td>
</tr>
</tbody>
</table>
Optical Crop Sensor

- Reference crop to normalize readings
- Multiple measurements to characterize a field

\[ NDVI = \text{Sufficiency Index} \]

\(<95\%\) means “needs more N”