Spectral Imagery to Estimate Leaf Area Index and Above-Ground Biomass in Maize

Introduction

Spatial Variability Exists in Soil
• Maize yield and fertilizer requirement vary spatially (Machado et al., 2002), so precision agriculture techniques can be used to estimate and apply the economic optimum nitrogen (N) rate variation over space and time (Holland & Schepers, 2010).
• Knowledge of plant height is generally a strong indicator of how soil spatial variability affects crop growth and yield potential (Machado et al., 2002), especially when it is used in combination with spectral indices (Sharma et al., 2016).
• Leaf area index (LAI), defined as the green leaf area per unit horizontal soil area (Daughtry et al., 1992; Watson, 1947), and above-ground biomass are two common biophysical parameters of interest, largely because they play a key role in plant biophysical processes and influence the spectral reflectance of vegetation canopies (Baret et al., 2009).
• Accurate estimates of crop height, above-ground biomass, and LAI are critical for informing remote sensing algorithms and crop models (Baret et al., 2007; Casas et al., 2012; Fang et al., 2011), which can be used to predict crop N status across space.

Using Sensors for Estimating Biophysical Parameters – Motivation
• Measuring above-ground biomass and LAI via destructive methods is both time consuming and costly, especially as the growth stage progresses and there is more plant material to handle.
• There is strong interest in developing models for estimating these biophysical parameters using sensors, largely because it is the only practical method for characterizing them at scale.
• There are several noninvasive sensor-based methods published in recent literature to estimate plant height, LAI, and above-ground biomass (references available upon request), some of which include:
  - Optical spectral sensors
  - Hyperspectral imaging
  - Structured light/demographic cameras (e.g., Microsoft Kinect®)
  - 3D reconstruction/structure from Motion
  - Acoustic height sensors
  - Terrestrial laser scanners
• There are tradeoffs for each of these methods related to accuracy, scale, processing power, and/or implementation feasibility for estimating plant height, LAI, or above-ground biomass.
• Prediction models that use spectral data to predict plant biophysical parameters tend to over-fit and are generally constrained to local conditions, limiting their use under varying conditions (e.g., growth stages, variety/hybrid, soil color etc.).

Field and Site Treatments
• An experiment was conducted in 2017 at the Agricultural Ecology Research Farm at the Southern Research and Outreach Center near Waseca, MN.
• Four N fertilizer rates (0, 67, 135, and 202 kg N ha⁻¹) were applied to a total of eight plots to ensure differences in plant growth among treatments.

Plant Sampling
• In each treatment plot, six maize plants were chosen for sampling. Painted stakes were placed between corn rows and aligned with the North-east and South-west most plants to be sampled; every third plant in each row was sampled (Figure 2).
• Plant height and LAI (Li-COR LAI-2000; Lincoln, NE) were measured for each plant (n=6) at the V5, V8, and V10 growth stages.
• Following all other field measurements and image acquisition, plants were cut on ground-level and placed in a 100" OVEN for drying.
• After drying for several days, samples were weighed to determine above-ground biomass (dry weight basis); note that above-ground biomass at V5 was consolided by plot (n=6).

Image Acquisition
• Hyperspectral aerial images (2.1 nm spectral resolution) were captured with a gimbal-stabilized Pi4 LiDAR hyperspectral camera (Resonon, Inc.; Bozeman, MT) mounted on an unmanned hexacopter (Microdrones 600 Pro, Naranjon District, Shenzhen, China; Figure 1).
• DJI Ground Station Pro (iPad app) was used to create and execute flight plans for controlling altitude, heading, and ground speed (Table 1).
• Grey reference panels with known reflective properties were placed in the study area prior to image capture; panels were 60 cm x 60 cm and the surface was 50% BaSO4/50% grey paint by weight.

Table 1: Camera and flight specifications for each growth stage/sampling date.

<table>
<thead>
<tr>
<th>Growth Stage</th>
<th>Date</th>
<th>Camera Frame Rate</th>
<th>Flight Altitude (m)</th>
<th>Ground Speed (m/s)</th>
<th>Ground Sampling Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V5</td>
<td>15 June 2017</td>
<td>99</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>V8</td>
<td>26 June 2017</td>
<td>91</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>V10</td>
<td>01 July 2017</td>
<td>109</td>
<td>9.0</td>
<td>8.3</td>
<td></td>
</tr>
</tbody>
</table>

Image Processing
• Radiometric correction was performed via SpectrononPro software (Resonon, Inc.; Bozeman, MT) using the calibration file provided by Resonon for the specific camera and lens that were used.
• Pixels representing the grey reference panels were used to convert spectral radiance to surface reflectance across all images.
• Imagery was visually inspected to determine the plants that were chosen for sampling. ENVI software version 5.2 (Harris Geospatial Solutions, Inc.) was used to create bounding squares around each sampled plant (see V5 column of Figure 2).
• Bounding squares for the image data were 9 x 9 pixels in size (550 cm²) for the V5 and V8 growth stages, and 3 x 3 pixels in size (620 cm²) for the V10 growth stage.
• Only spectral data extracted from the area of each sampled plant’s bounding square were used for analysis.
• The Improved Modified Chlorophyll Absorption Ratio Index (MCARI2; Equation 1) was applied to each pixel: MCARI2 incorporates a soil adjustment factor while preserving sensitivity to LAI and resistance to chlorophyll influences and has been shown to be a good predictor of green LAI (Haboudane et al., 2004).

Equation 1: MCARI2 spectral vegetation index.

\[ \text{MCARI2} = \frac{1.525 \times (\text{P590} - \text{P685}) - 1.3 \times (\text{P685} - \text{P706})}{(\text{P685} - \text{P706})^2} = 0.5 \]

Results

Plant Sample Measurements
• Variability among plant samples within sampling date was substantially greater as growth stage progressed from V5 to V8 to V10, especially for above-ground biomass and LAI (Figure 3).
• Plant height and above-ground biomass were most closely related of all biophysical parameters (\( R^2 = 0.87 \)), as plant height increased, above-ground biomass increased exponentially.
• The kernel density estimates (i.e., probability) for plant height and MCARI2 are similar, but those for above-ground biomass and LAI are skewed and not similar at V8 and V10.

Figure 3: Scatterplot matrix illustrating relationships among plant height, above-ground biomass, leaf area index (LAI), and Improved Modified Chlorophyll Absorption Ratio Index (MCARI2). Plots on the diagonal are kernel density estimates illustrating relative probability of occurrence for respective variable. Colors represent samples collected at different growth stages (i.e., V5, V8, and V10). *Note: MCARI2 is the only variable indirectly measured (via spectral data).

Evaluating the Relationship between MCARI2 and the Plant Biophysical Parameters
• The mean RMSE values from the cross-validation were less than the full dataset (Figure 4), indicating that the reported prediction models do not over-fit the measured data.
• The approaches described herein for predicting plant biophysical parameters is a viable option for reliably informing remote sensing algorithms and crop models, but variability in these models may require further evaluation as the growth stage.
• Error between measured and predicted values increased as growth stage progressed, especially for biomass and LAI. The predicted model performed better at V5 and underestimated at V10.
• Conclusions
  - The MCARI2 spectral index extracted from high resolution, narrowband aerial imagery produced satisfactory results for estimating plant height, above-ground biomass, and LAI.
  - The measured/predicted plant height best-fit line had a closer relationship to the perfect 1:1 line than either above-ground biomass or LAI, which suggests that estimating plant height via MCARI2 is more accurate than estimating either above-ground biomass or LAI.
  - It is unclear how well above-ground biomass can be predicted at the V5 growth stage from this experiment due to a small number of samples.
  - Error between measured and predicted values increased as growth stage progressed, especially for biomass and LAI. The predicted models described herein did not over-fit the measured data (determined via cross-validation), but it is clear that predictions were generally overestimated at V5 and underestimated at V10.
  - The approaches described herein for predicting plant biophysical parameters is a viable option for reliably informing remote sensing algorithms and crop models, but variability in these models may require further evaluation as the growth stage.
• Future Directions
  - The full hyperspectral dataset (240 bands from ~400 – ~900 nm) will be used to model these same biophysical parameters to determine if models can be improved.
  - We plan to use these approaches in a future experiment to calibrate remote sensing algorithms and crop systems models for estimating optimum rates of fertilizer during the crop season.
• Works Cited
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Objectives

1. Investigate the relationships among maize height, LAI, above-ground biomass, and spectral reflectance during early and late growth stages (V5 - V10).
2. Determine the reliability of spectral imagery to predict height, LAI, and biomass.