Computers and Electronics in Agriculture 148 (2018) 121–131

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Integrating aerial images for in-season nitrogen management in a corn field

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ARTICLE INFO

Keywords:
Remote sensing
Plant pigment ratio
Corn yield
Nitrogen fertilization
Timing

ABSTRACT

Methods of determining in-season corn (*Zea mays* L.) nitrogen (N) requirements and yield estimates are needed for designing a resource-efficient corn production system that is both profitable and environmentally sustainable. The objectives of this study were to examine: (1) the role of spectral signatures of corn plants obtained by aerial images in examining the yield variability across various N treatments, (2) whether the images could be used to guide in-season N management decisions, and to predict in-season corn yield and corn yield loss, and (3) the influence of spatial resolution of imagery on the accuracy of corn yield prediction models. Twenty-four treatments evaluated were the combinations of eight fertilization times (at-planting (A), pre-planting (P)∗A, P∗A∗mid-season (M), P∗A∗late-season (L), PAML, AM, AL, and AML) and three at-planting N rates (11, 45, and 78 kg N ha^{-1}). Visual and thermal images were collected from manned aircraft and geo-corrected for the analyses. Vegetation indices and ratios were derived from three waveband combinations of visual images, and they were examined in relation to yield. Two linear regression models - model 1 (based solely on imagery) and model 2 (based on imagery and information about elevation and N fertilizer application rate), were tested on their performances (in terms of coefficient of determination (R^2) and root mean square error (RMSE)) for in-season corn yield prediction at four spatial resolutions (0.35, 0.5, 1, and 2 m px^{-1}). Among individual wavebands, and vegetation indices and ratio, plant pigment ratio (PPR) at early growth stages were highly correlated to corn yield, particularly in the field that received limited N application. The correlation improved as the corn growth stage progressed, but weakened towards the end of the growing season. There were significant differences in PPR values between the treatments receiving the least and the most N application, and it was the amount of N applied at planting that created the most significant differences. The models for 0.35 to 1 m px^{-1} spatial resolutions did not show significant improvements in R^2 over the lowest ground resolutions (2 m px^{-1}) (differences in $R^2 \leq 0.05$). The model 2 showed higher R^2 (up to 0.64 at tasseling stage) and lower RMSE than model 1. These results indicate that the models developed integrating spectral and spatial information from aerial imagery with the information about elevation and N application rate help improve in-season corn yield estimates under different N management practices.

1. Introduction

Nitrogen (N) fertilizer management in corn (*Zea mays* L.) production is under scrutiny because of the mounting environmental problems resulting from high N concentration in both water (Donner and Kucharik, 2008; Zhang et al., 2015; Zillén et al., 2008) and air (Aneja et al., 2009). This in combination with recent increases in worldwide N fertilizer prices (Huang, 2009) have stimulated the need to create a highly resource-efficient corn production system that is both profitable and environmentally sustainable (Spiertz, 2010). Site-specific N fertilizer management practices, which match N application rates and timing with variable crop needs, have potential to address these issues by providing maximum N to plants when they need the most. This improves crop N use efficiency and leaves minimum residual nitrate in the soil for runoff (Williams et al., 2010). Diagnosing in-season N stress in corn production, however, is challenging due to the dynamic nature of N transformation in the soil and unpredictable weather patterns that make N losses highly variable (Kyveryga et al., 2012).

Crop color is the most reliable indicator for determining in-season crop N requirements (Scharf and Lory, 2009) for site-specific N fertilizer management. Crops respond to N through changes in chlorophyll concentration in leaves, plant biomass, and leaf area index, that in turn alter crop reflectance in the visible and near-infrared (NIR) wavelengths (Lebourgeois et al., 2012). The sensitivity of green wavelength to N

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https://doi.org/10.1016/j.compag.2018.03.008
Received 28 March 2017; Received in revised form 4 March 2018; Accepted 6 March 2018

levels is higher than for other wavelengths (Gitelson et al., 2003). Compared to N-sufficient crops, N-deficient crops reflect more light in the visible wavelengths and less in the NIR. This difference corresponds mainly to the shortage of chlorophyll and other light-absorbing pigments under N stress conditions. Due to the ability to provide rapid, nondestructive, and spatially exhaustive measurements in the form of spectral responses (Magri et al., 2005; Panda et al., 2010), remotely sensed imagery have been considered as one of the various tools and strategies useful for evaluating the performance of various N fertilizer recommendation systems and management practices on crop production. Prior studies (Blackmer and Schepers, 1996; Sripada et al., 2005) used aerial images to relate corn N status with the reflectance in the visible wavebands, and demonstrated that the changes in corn N status could be determined by assessing the changes in visible wavebands. They identified N stressed areas within fields by comparing their color with that from areas where sufficient N fertilizer was applied, and suggested that these relative within-field color differences could indicate a crop's response to available soil N. Using aerial photographs, Scharf and Lory (2002) developed an algorithm for side-dress N application to corn. This algorithm considers the difference in green light intensity between an unfertilized corn relative to well-fertilized corn, and recommends higher N application rate when the difference in color increases. Vegetation indices (VI) and ratios, developed based on combinations of various wavebands, have also been linked with chlorophyll content, and thus, with the N status of crops (Lebourgeois et al., 2012). Additionally, studies (Geipel et al., 2014; Hatfield and Prueger, 2010; Shanahan et al., 2001) have used VIs from high resolution aerial images to estimate in-field variability in crop yield and suggested that this approach offers a potentially attractive alternative to use of a combine yield monitor.

With recent advancements in variable rate technologies (VRT), use of aerial images in agriculture has grown substantially. However, to date, very few studies have been conducted to examine the temporal differences in spectral properties of corn plants as an opportunity for in-season N management or the influence of spatial resolution of remote sensing images on the accuracy of in-season corn yield prediction models. The objectives of this study were to determine (1) the role of spectral signatures of corn plants obtained by high resolution aerial images in assessing yield variability in various N treatments, (2) whether the images could be used to guide in-season N management decisions and predict corn yield and yield loss, and (3) the influence of spatial resolution on the accuracy of in-season corn yield prediction models.

2. Materials and Methods

2.1. Experimental setup

A field-scale experiment was conducted in 2015 at the Molly Caren Farm near London (39.962°N, 83.4367°W), Ohio to examine the effect of both timing and N application rates on the spectral properties of the corn canopy and corn yield. The site has primarily been in a corn-soybean rotation, where wheat is planted each 5th year. In 2014, the field was planted in wheat. For this study, field operations included conservation tillage and different N application times and rates. Table 1 summarizes the N application times, methods, fertilizer types, and rates used for this study.

Table 2
Summary of N application treatments.

Treatment	N application breakdown by timing (kg/ha)	Total N (kg/ha)	Nitrogen application timing
A10	11	11	At-planting
A40	45	45	
A70	78	78	
PA10	179+ 11	190	Pre-planting and at-planting
PA40	179 + 45	224	
PA70	179 + 78	257	
PAM10	179 + 11 + 45	235	Pre-planting, at-planting, and mid-season
PAM40	179 + 45 + 45	269	
PAM70	179 + 78 + 45	302	
PAL10	179 + 11 + 50	240	Pre-planting, at-planting, and late-season
PAL40	179 + 45 + 50	274	
PAL70	179 + 78 + 50	307	
PAML10	179 + 11 + 45 + 50	284	Pre-planting, at-planting, mid-season, and late-season
PAML40	179 + 45 + 45 + 50	318	
PAML70	179 + 78 + 45 + 50	351	
AM10	11 + 45	56	At-planting and mid-season
AM40	45 + 45	90	
AM70	78 + 45	123	
AL10	11 + 50	61	At-planting and late-season
AL40	45 + 50	94	
AL70	78 + 50	128	
AML10	11 + 45 + 50	106	At-planting, mid-season, and late-season
AML40	45 + 45 + 50	140	
AML70	78 + 45 + 50	173	

A - at-planting, P - pre-plant, M - mid-season, L - late-season; N application at different times of the growing season is indicated by "+" symbol.

Before planting, anhydrous ammonia was applied at 20.32 cm depth. Nitrogen serve (2.34 kg/ha) was added during pre-planting to inhibit potential N loss through nitrification of applied N. To minimize potential border effect during fertilization, both pre-plant and side dress N applications were banded in between 76 cm corn rows. Late-season N was applied by dribble banding on the surface between corn rows using drop hoses. All treatments were planted to the same hybrid (LG2620) using a row spacing of 0.76 m with a planted population of 81,510 seeds/ha (33,000 seeds/acre).

A total of 24 N treatments were evaluated using the combinations of eight application times and three planter N rates as summarized in Table 2. Except for the treatment receiving N application only at-planting, all other treatments received two or more N applications (Table 2). For example, *PA10* treatment received 179 kg N ha^{-1} prior to planting (P) and 11 kg N ha^{-1} at-planting (A); *AM70* treatment received 78 kg N ha^{-1} at-planting and 45 kg N ha^{-1} for side-dressing (termed as mid-season (M)); *PAML* treatment received four N applications: pre-planting, at-planting, mid-season, and late-season (L).

The study was conducted on a 9.67 ha field, and treatments were established using a block design, with individual blocks ranging from

Table 1
Summary of N application time and method, fertilizer type and rate, and equipment.

Time	Method	Fertilizer type	Rate (kg ha^{-1})	Equipment
Pre-planting (April 13)	20.32 cm depth with banding	Anhydrous Ammonia	179	15 shank applicator
At-planting (May 9)	5.1 cm beside and 5.1 cm below the seeds	Liquid (18-18-0)	0, 34, or 67	Case IH Magnum 240 with a 16-row Case IH 1255 planter
	In-furrow	Pop-up (10-34-0)	11	
Mid-season (June 11)	Side-dressing	UAN 28%	45	Magnum 240 with a 16-row Case IH 2800
Late-season (July 7)	Between row surface dribbled	UAN 28%	50	27.4 m John Deere 4730 sprayer

Three planter applied N rates: A10 = A (11 + 0), A45 = A (11 + 34), A70 = A (11 + 67). "A" represents treatment receiving N included in starter fertilizers at planting (kg/ha), "11" represents N rate (kg/ha) applied in-furrow with the seed, and "0", "34" and "67" represent N rate (kg/ha) applied 5.1 cm beside and 5.1 cm below the seed.