

# **HYPERSPECTRAL IMAGERY FOR THE DETECTION OF NITROGEN STRESS IN POTATO FOR IN-SEASON MANAGEMENT**

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## **ABSTRACT**

Potato (*Solanum tuberosum*, L.) yield and quality are highly dependent on the availability of nitrogen (N) during the crop's critical growth stages. Canopy-level hyperspectral (HS) imagery has been shown to be an effective research tool for determining the best wavelengths and/or indices for the detection of N stress in a number of crops. Research findings from HS imagery can be applied to active sensors as a way to increase the effectiveness of real-time, variable rate N applications, but limited data exist for potato production. A field study was conducted in 2010 and 2011 at the Sand Plain Research Farm in Becker, MN on a Hubbard loamy sand soil to evaluate the effects of water stress, N fertilizer rate/timing, the varieties Russet Burbank (RB) and Alpine Russet (AR), and growth stage on the ability of canopy-level HS imagery (401-982 nm) to detect N stress in a potato crop. The ability of canopy-level narrowband reflectance to detect differences in potato N status was evaluated by performing linear regression between HS narrowband reflectance and leaf N concentration as a means to distinguish the optimum wavelengths to detect N stress. As the potato crop matured, the coefficient of determination ( $r^2$ ) decreased at most HS wavelengths, especially in the NIR region. The far green and near red regions from ~582-610 nm, and those at the beginning of the red-edge from ~685-695 nm were the best performing wavelengths for detecting N stress overall. Canopy reflectance was able to predict leaf N among image dates more consistently for RB than for AR.

**Keywords:** Hyperspectral imagery, nitrogen stress, potato, in-season fertilizer applications

## INTRODUCTION

Well-drained, coarse-textured soils with soil moisture conditions that are maintained to be nearly constant via irrigation are ideal for potato production (Phene and Sanders, 1976). The sandy loam and loamy sand soils used for potato production in Minnesota are typically low in organic matter and cation exchange capacity (CEC), and therefore, have a relatively low reserve of soil nutrients. The low inherent soil fertility, coupled with a large nitrogen (N) requirement for potato production results in high N fertilizer inputs (Dean, 1994). Overhead irrigation is used to meet water requirements, but unpredicted rainfall following irrigation can enhance nitrate leaching. In addition, potato plants have a relatively shallow root system and poor nutrient use efficiency (NUE), which can potentially result in further N losses (Rosen and Bierman, 2008; Zvomuya et al., 2003).

The goal of N management for potato production is to provide the crop with a sufficient quantity of available N throughout the growing season to optimize yields, while minimizing the quantity of N lost from the root zone. However, managing N is a challenge because there are usually many unknown factors involved. One strategy used by producers in an attempt to optimize crop N uptake is to match the timing and rate of fertilizer N with the needs of the crop during different growth stages (Errebhi et al., 1998). A minimum of three split N applications (planting, emergence, and post-emergence) is a recommended best management practice for irrigated potato on coarse-textured soils in Minnesota (Rosen and Bierman, 2008). If fertigation is available, additional split N applications can be made post-emergence. Increased NUE and yields have been shown to result from split applications of N fertilizer during tuber initiation and early bulking (Errebhi et al., 1998; Westermann et al., 1988).

Crop N uptake and soil N losses depend on the interaction of many complicated and sometimes unpredictable factors, including: fertilizer source, soil organic matter, soil texture/CEC, and the weather conditions. Each of these can influence crop N uptake rates or soil N transformations throughout the growing season. While fertigation is a convenient method to apply frequent split applications of N fertilizer throughout the season, diagnostic tools are needed to help guide appropriate rates and timing of N applications that best match crop N demands. A logical strategy for determining the appropriate rate and timing for post-emergence N applications is to make adjustments based on in-season plant monitoring. This approach relies on plant measurements during the growing season, and therefore, is able to account for the effect of seasonal weather conditions on crop N availability (Meisinger et al., 2008).

Hyperspectral (HS) reflectance acquired during the growing season can be used to monitor crop N status since: (1) spectral characteristics of green-leaved vegetation change as leaf chlorophyll content changes, and (2) N is closely related to chlorophylls in plant cell metabolism (Miao et al., 2009; Stroppiana et al., 2012). Reflectance of vegetation, specifically in the visible (i.e., 400-670 nm) and near-infrared (NIR; i.e., ~670-1000 nm) regions of the spectrum, are most influenced by leaf chlorophyll content (Jongschaap and Booij, 2004). The absorption of light energy by chlorophyll results in low leaf reflectance in the visible region, and the scattering of light energy by the mesophyll results in high leaf reflectance in the NIR region (Rees, 2001). As leaf chlorophyll content increases, leaf reflectance in the visible and NIR regions generally decrease and increase, respectively (Goffart et al.,

2008; Rees, 2001). In addition to the optical properties of leaves, N deficiencies affect canopy architecture and leaf area (Moran et al., 2004), which can also affect the spectral characteristics of a crop at the canopy level.

Research on the use of HS imagery and development of appropriate indices for the potato crop under various cultural conditions is limited. Therefore, the objective of this study was to evaluate the potential for using canopy-level HS reflectance as an indicator of potato N status in two varieties subjected to various N treatments and irrigation regimes.

## MATERIALS AND METHODS

### Study site

Field experiments were conducted over two years (2010-2011) at the University of Minnesota Sand Plain Research Farm (45°23'N, 95°53'W) near Becker, MN. The soil at this location is classified as an excessively drained Hubbard loamy sand (sandy, mixed, frigid Typic Hapludoll) comprised of 82% sand, 10% silt, and 8% clay. The available water holding capacity in the top 120 cm of soil is 10 cm. During the growing season (April – September), the 30-year average temperature and rainfall are 16.5° C and 550 mm, respectively (MRCC, 1971-2000). The previous crop in both years was non-irrigated cereal rye (*Secale cereal* L.).

### Experimental design

Each year, the experiment was set up as a randomized complete block design with a split-split plot restriction on randomization, replicated four times. The whole plot treatment was irrigation rate (unstressed and stressed). Irrigation was applied with an overhead sprinkler system. A water balance method was used to schedule irrigation rate for the unstressed treatment (Wright, 2002). The stressed plots were irrigated at a rate in which total water equaled approximately 89% and 81% of the unstressed plots in 2010 and 2011, respectively and was calculated from total water applied between emergence and vine kill. Timing was variable between years and depended on weather conditions. On average, approximately four days elapsed between irrigation applications.

The sub plot treatment included a low, medium, and high N rate (i.e., 34, 180, and 270 kg N ha<sup>-1</sup>) with variable timing of post-emergence N applications for the high rate, for a total of five N treatments [i.e., N1, N2, N3, N4, and N5 (Table 1)]. On average, about two weeks passed between split applications of post-emergence N for treatments N2, N3 and N4. Treatments N3 and N4 had the same rate and timing of N application, but a soil surfactant was used for N4 to investigate possible effects of the surfactant on soil moisture and N uptake under different irrigation regimes. Because treatments N2, N3, and N4 had split applications of post-emergence N fertilizer, actual N applied at the time of data acquisition varied. All N applications were completed by the later image date in 2010, but one post-emergence N application remained at the later image date in 2011. Treatment N5 had the same N rate as N3 and N4, but all post-emergence N was applied early. In both years, the planting and emergence N source was mono-ammonium phosphate and urea, respectively. Post-emergence N was split applied four times by hand as a 1:1 mixture of urea and

**Table 1. Nitrogen fertilizer treatments.**

Nitrogen fertilizer treatment	Timing of application						Total N
	planting	2010	2011	2010	2011	kg N ha <sup>-1</sup>	
		emergence	post-emergence				
N1 34 N (control)	34	0	0	0	0	34	
N2 180 N split	34	78	90	17 x 4	11.2 x 5	180	
N3 270 N split	34	124	124	28 x 4	22.4 x 5	270	
N4 270 N split + surf.	34	124	124	28 x 4	22.4 x 5	270	
N5 270 N early	34	124	124	112	112	270	

NH<sub>4</sub>NO<sub>3</sub> in 2010 and five times by spray boom and tractor as 28% urea and NH<sub>4</sub>NO<sub>3</sub> solution in 2011. All post-emergence N was irrigated in immediately following application.

The sub-sub plot treatment consisted of two potato varieties, Russet Burbank (RB) and Alpine Russet (AR). Russet Burbank, the most widely grown processing potato variety in the U.S. and in Minnesota, has a mid-season maturity class of 111-120 days after planting (Whitworth et al., 2011). Alpine Russet, which has a late-season maturity class of 121-130 days after planting, is a relatively new variety that is being grown in Minnesota. Compared to RB, it has similar yields, superior processing quality after long-term storage, and greater resistance to water-stress induced tuber defects (Whitworth et al., 2011).

In both years, whole “B” seed and cut “A” see were used for the RB and AR varieties, respectively. Seed was hand planted in furrows with 90 cm row spacing and approximately 30 cm spacing between seed pieces within rows. Each plot consisted of seven 13.7 m rows. Planting dates were 16 April 2010 and 29 April 2011 and plant emergence occurred on 15 May 2010 and 24 May 2011. Two days after plant emergence in each year, emergence fertilizer was applied and rows were mechanically hilled. Chemicals were applied as needed during the season for the control of pests, disease, and weeds according to standard practices in the region (Engel et al., 2012).

### Data collection

Leaf samples were collected on 1 July and 5 August in 2010 and 7 July and 28 July in 2011. The fourth leaf from the apex of the shoot was sampled from twenty plants in the fifth row from the alley in each sub-sub plot. Tissue samples were oven-dried at 60°C and ground with a Wiley mill to pass a 2 mm screen. Total N concentration was determined with an Elementar Vario EL III combustion analyzer (Horneck and Miller, 1997).

Aerial HS imagery was acquired with an Airborne Imaging Spectrometer for Applications (AISA Eagle) visible/near-infrared HS imaging sensor (SPECIM, Spectral Imaging, Ltd., Oulu, Finland) by the Center for Advanced Land Management Information Technologies (CALMIT) from the University of Nebraska-Lincoln, USA. The AISA Eagle is a complete pushbroom system, consisting of a HS sensor head, a miniature GPS/INS sensor, and a data acquisition unit in a rugged PC

with a display unit and power supply. It has a 1,000 pixel swath width and was configured to capture imagery in 63 narrowbands (2.3 nm spectral resolution) covering a spectral range from 401 to 982 nm; band widths ranged from 8.8 - 9.6 nm. Images were captured with 1.0 m spatial resolution on 1 July [47 days after emergence (DAE)] and 6 August (83 DAE) in 2010 and on 6 July (43 DAE) and 29 July (66 DAE) in 2011. The flyover for the late growth stage was much later in 2010 than in 2011 due to equipment problems and weather-related scheduling conflicts; this resulted in apparent differences in the data that were likely due to a difference in actual crop maturity rather than a difference between years.

### **Image processing**

A post processing software package, CaliGeo, was used for radiometric correction (using NIST traceable calibrations), rectification (using a C-Migits III GPS/INS unit manufactured by Systron Donner Inertial Division, Walnut Creek, CA, USA), and geo-referencing. Geographic coordinates of plot corners were acquired with a GPS unit (0.3 m accuracy), which allowed in-house geo-referencing to minimize image distortion. ENVI software (Version 4.8, Exelis, Inc.) was used for all further image processing.

To extract plot-based pixel data for all analyses, regions of interest (ROIs) were created for every treatment plot on each image date. Pixels that were most affected by bare soil were automatically excluded from ROIs by including only pixels that were above a minimum threshold value using a narrowband Greenness index (Smith et al., 1995) image. This technique was an effective way to exclude pixels that were affected by bare soil during growth stages with full canopy cover. Since plant senescence had already occurred for the low and medium N rates on the later image date in 2010 (i.e., 83 DAE), each pixel was affected by bare soil in these treatment plots to some extent; this resulted in ROIs that included pixels that were partially affected by bare soil on this date.

### **Statistical analysis**

Data were analyzed as a randomized complete block design with four replications and a split-split restriction on randomization using the MIXED procedure of SAS with Type III ANOVA method at  $\alpha=0.05$  (SAS Institute, 2008). Pairwise comparisons of the least square means were made using the *lsmeans / pdiff* statement ( $\alpha = 0.05$ ) to determine significant differences among treatment means of the main effects and interactions in Table 2 (individual treatment means are not presented, but trends are discussed if effects were significant). Irrigation, N treatment, and variety were considered as fixed effects, while replication was considered as random.

To evaluate the effectiveness of canopy-level narrowband reflectance as an indicator of potato N status, the coefficient of determination was calculated between potato leaf N and canopy reflectance at all AISA Eagle narrowbands. The CORR procedure of SAS (SAS Institute, 2008) was performed to obtain a correlation coefficient ( $r$ ) for each image date and variety, and then  $r$  was squared to obtain the coefficient of determination ( $r^2$ ), which represents the quality of the relationship between the predictor (e.g., canopy reflectance) and the modeled values (e.g., leaf N concentration).

## RESULTS AND DISCUSSION

Results are divided into three sections based on the type of data presented. The first two sections (reflectance spectra and linear regression analysis) begin with results that were similar between varieties, followed by results that were unique to each variety. The third section (analysis of variance) is divided into sub-sections for the main effects and interactions, and is presented last because the wavelengths selected for analysis were obtained from regions in which consistent trends were observed across image dates and varieties from linear regression analysis.

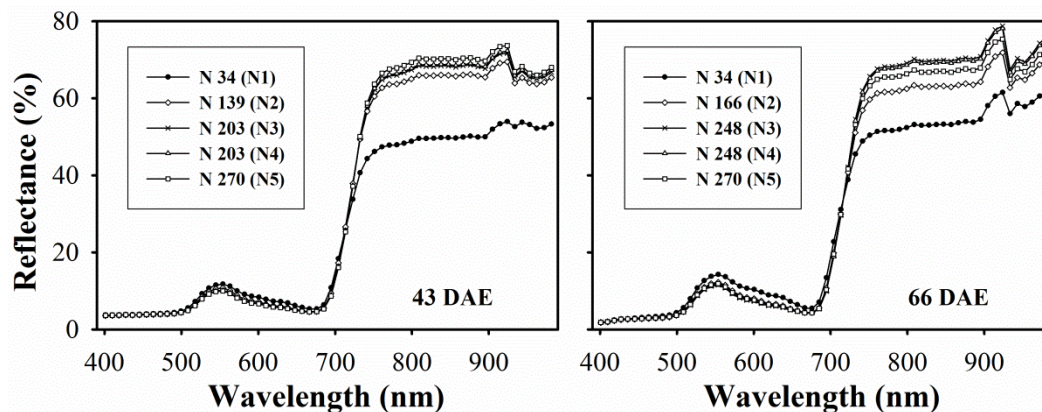
Canopy-level HS reflectance in the 400-980 nm range was obtained from the potato crop growing under five N treatments (Table 1, Fig. 1). Reflectance data were averaged across irrigation treatments to simplify the results in this study. This approach can be justified because the main effect of irrigation and its interactions were not statistically significant in most cases for leaf N and HS reflectance across image dates (Table 2). Furthermore, differences in  $r^2$  were very small across and between irrigation, even in the limited cases where there was a significant effect of irrigation on leaf N or HS reflectance.

Due to above average rainfall in early- to mid-summer in both 2010 and 2011, there was little difference in total water (rainfall + irrigation) until ~55 DAE in both years.

### Reflectance spectra

Reflectance spectra are presented for only 2011 image dates since similar trends were observed between years at most wavelengths (Figs. 1 and 2). Reflectance in the red and NIR regions (i.e., 600-980 nm) showed similar trends between varieties, but varied among N application rates and between image dates (Figs. 1 and 2).

On 43 DAE, reflectance was lowest for the higher N rates in the red region, and reflectance was highest for the higher N rates in the NIR region (Figs. 1 and 2). On 66 DAE, a different trend was observed, but only between the treatments with the high rates in which the timing of post-emergence N varied. N3 and N4 (Table 1) had



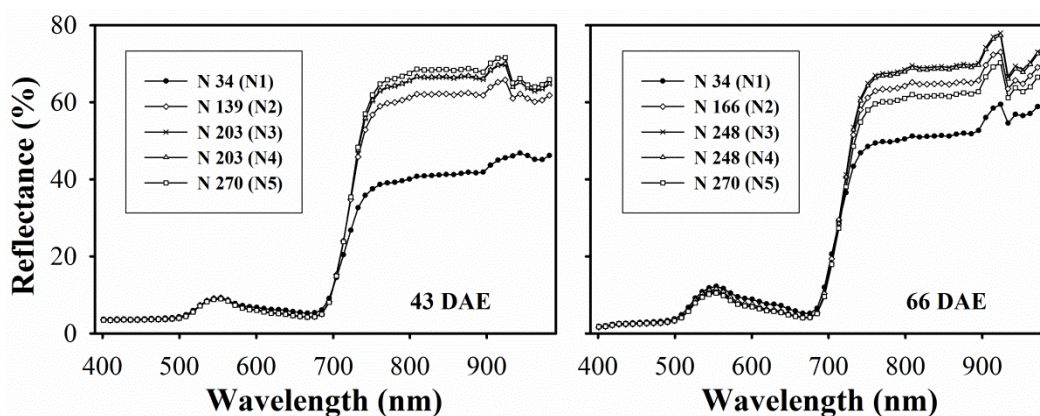
**Fig. 1. Reflectance spectra of Russet Burbank potato canopy under five nitrogen treatments at 43 (left) and 66 (right) days after emergence (DAE) in Becker, MN (2011). Treatments are labeled according to actual nitrogen applied at the time of image acquisition in kg N ha<sup>-1</sup> (refer to Table 1).**

lower reflectance in the red region and higher reflectance in the NIR region than N5, even though treatments N3 and N4 had not yet received all post-emergence N applications by 66 DAE (i.e., total N applied at this time was higher for N5 than for N3 or N4; Figs. 1 and 2). This suggests that there is less N uptake on 66 DAE if all post-emergence N is applied early than if it is split applied; the lower N uptake for N5 is likely due to losses of N fertilizer from the system, probably via leaching.

Reflectance in the visible spectrum (i.e., 400-680 nm) peaked in the middle of the green region [i.e., 554 nm (Fig. 1)] in both varieties on both image dates. The trend for reflectance among N application rates in the green region (i.e., 500-600 nm) varied by variety, primarily on 43 DAE. In RB, the reflectance was the lowest for the high N rates on both image dates (Fig. 1). This finding is consistent with previous reports of canopy reflectance in RB potato (Wang and Rosen, 2004), as well as with what is typical spectral behavior of vegetation in general (Goffart et al., 2008; Rees, 2001). Conversely, in AR, there was less difference in reflectance between N rates, and reflectance was lowest for the low N rate and highest for the medium N rate (Fig. 2). A similar trend was observed in potatoes grown in India for the K. Chandramukhi variety at 45 days after planting (Jain et al., 2007), although data from that study at a later growth stage was similar to the trends observed in RB in this study. Discussion was not provided by the authors regarding this difference, but in both cases, it is likely due to an external factor. Visual observations on this date suggest that it could be due to either the effects of bare soil or the effects of crop flowering (bare soil was present in N1 treatment plots, and flowering was most prevalent in N1 treatment plots, but only for AR). This trend was not observed in the 2010 data on 47 DAE, but there was less difference in reflectance between N rates for AR than for RB – AR was flowering for the N1 treatment on this date, but there was little bare soil.

### Prediction of leaf nitrogen concentration from HS imagery

The  $r^2$  representing the relationship between potato leaf N concentration and canopy reflectance varied as a function of HS wavelength (Figs. 3 and 4). For both varieties,  $r^2$  decreased at most wavelengths as the crop matured and was especially



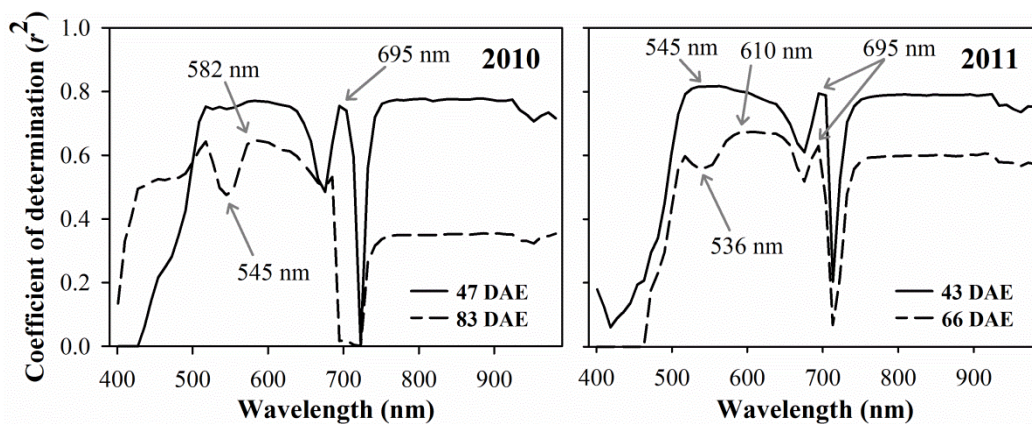
**Fig. 2. Reflectance spectra of Alpine Russet potato canopy under five nitrogen treatments at 43 (left) and 66 (right) days after emergence (DAE) in Becker, MN (2011). Treatments are labeled according to actual nitrogen applied at the time of image acquisition in kg N ha<sup>-1</sup> (refer to Table 1).**

true in the NIR region. Also, a dip in  $r^2$  was observed in the green region for both varieties. For RB, the dips occurred only in the later image dates, and for AR, the dips occurred in both image dates in 2011 only. A connection between the two varieties regarding the occurrence of these dips cannot be explained from the data in this study since the dips only occurred in one year for AR. With the exception of the NIR region, the trends of  $r^2$  as a function of HS wavelength (e.g., the spectral location of peaks and dips) differed between varieties.

### Prediction trends in Russet Burbank

In general, canopy reflectance was better correlated to RB potato leaf N on the earlier image dates (i.e., 47 and 43 DAE for 2010 and 2011, respectively) than on the later image dates in each year (i.e., 83 and 66 DAE for 2010 and 2011, respectively; Fig. 3). On the earlier image dates,  $r^2$  was consistent as a function of wavelength between years, and the highest  $r^2$  occurred in the green and red regions from ~518-638 nm, at the beginning of the red-edge from ~695-704 nm, and throughout most of the NIR region from ~751-924 nm (Fig. 3). In these regions,  $r^2$  ranged from 0.74-0.78 in 2010 and from 0.76-0.82 in 2011. On the later image dates,  $r^2$  was noticeably different as a function of wavelength between years. This is likely due to the 17 day difference in image acquisition relative to crop emergence on the later image date between years (i.e., imagery was captured 83 DAE in 2010 and 66 DAE in 2011). Because of this, data on the later image date cannot be directly compared between years.

There are, however, notable trends that can be observed by examining  $r^2$  as a function of wavelength based only on DAE (i.e., examining the shape of the  $r^2$  curves). As the potato crop matured,  $r^2$  generally decreased for nearly every wavelength (Fig. 3). This trend is especially apparent throughout the entire NIR region, as well as in the red region from ~610-638 nm. The same trend also occurred with the peak at the beginning of the red-edge region from ~685-695 nm; this peak diminished as DAE increased (Fig. 3). On the later image dates (i.e., 66 and 83 DAE), maximum  $r^2$  values were higher in the visible region than in the NIR region;



**Fig. 3. Coefficient of determination ( $r^2$ ) for the relationship between leaf nitrogen concentration and canopy reflectance at all AISA Eagle wavelengths (401-982 nm) for Russet Burbank potato. Data are grouped by days after emergence (DAE) for 2010 (left) and 2011 (right).**



the highest  $r^2$  values for 66 and 83 DAE occurred at 610 and 582 nm, respectively.

A dip in  $r^2$  in the green region occurred from ~518-572 nm on the later image date in each year. This dip is more pronounced at 83 DAE than 66 DAE, suggesting that the ability to detect N stress using this wavelength region decreases as growth stage progresses. On all image dates, the lowest  $r^2$  occurred in the red edge around 713 nm, although this varied slightly depending on the growth stage (Fig. 3). The 563 nm band at 43 DAE had the highest  $r^2$  (0.82) of all wavelengths for RB.

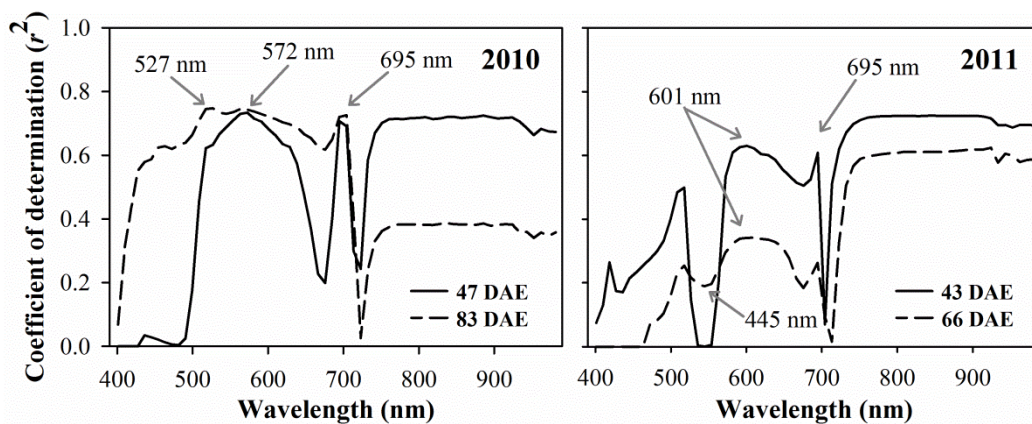
These results suggest that the differences in reflectance for RB potato with differing degrees of N stress become less apparent during the later growth stages. The optimal date to obtain HS measurements over a RB potato canopy to detect N stress cannot be precisely determined based solely on this data; however, earlier dates appear to be better correlated with leaf N concentration.

### Prediction trends in Alpine Russet

The peaks in  $r^2$  were relatively consistent as a function of wavelength for AR on the earlier image dates between years. Peaks occurred in the green and red regions from ~572-610 nm, in the beginning of the red-edge from ~695-704 nm, and throughout most of the NIR region from ~751-924 nm (Fig. 4). Throughout most of the NIR region from ~751-924 nm,  $r^2$  ranged from 0.70-0.72 in both years (Fig. 4).

In the green region, a dip occurred in  $r^2$  from ~536-554 nm for both image dates in 2011; however, the dip was much less pronounced on 66 DAE (Fig. 4). The formation of these dips was not consistent with either of the image dates in 2010, and is likely a result of the unexpected similarity in reflectance among N treatments in the green region (Fig. 2). These dips may have formed because of an external factor that was only present in 2011, but currently there is no definitive explanation for their occurrence. If these dips are present in other AR data, it could potentially cause poor performance for narrowband indices that use those wavelengths to detect N stress.

The relationship between leaf N concentration and canopy reflectance decreased as the crop matured (Fig. 4). This trend is especially apparent throughout the entire



**Fig. 4. Coefficient of determination ( $r^2$ ) for the relationship between leaf nitrogen concentration and canopy reflectance at all AISA Eagle wavelengths (401-982 nm) for Alpine Russet potato. Data are grouped by days after emergence (DAE) for 2010 (left) and 2011 (right).**

NIR region, but is also evident in the visible and beginning of the red-edge regions from ~400-704 nm (with the exception of the 83 DAE image date). The  $r^2$  values on 83 DAE in the blue and red regions were remarkably higher than for any of the other image dates. The 527 nm band on this date had the highest  $r^2$  (0.74) of all wavelengths for AR (Fig. 4). This could have occurred because of a combination of the cooler night-time temperatures in 2010 and the late season maturity class of AR, which likely resulted in better overall growing conditions during the late growth stages in 2010 for AR; however, this does not explain the low  $r^2$  in the NIR region.

### **Analysis of variance for selected spectra and leaf nitrogen concentration**

Analysis of variance for main effects (irrigation, N treatment, and variety) and their interactions was performed for canopy reflectance at four narrowband wavelengths (536, 601, 695, and 799 nm) and for leaf N (Table 2). These wavelengths were selected because these were the regions where differences in peaks and dips were evident for the relationship between leaf N concentration and reflectance between varieties and/or among image dates. The 536 nm band was near the reflectance peak in the visible region and was also near the central location of the dips that were observed on the later image dates for RB and in 2010 for AR. The 601 and 695nm bands were the locations of two of the  $r^2$  peaks on all image dates and both varieties. The 799 nm band was selected to represent the NIR wavelengths since  $r^2$  was consistent throughout most of the NIR region. Because the three-way interaction for all wavelengths and leaf N concentration on all image dates was not significant, only main effects and two-way interactions are discussed.

### **Main effects**

The main effect of N was highly significant for all selected variables, and the main effect of variety was significant for most of the selected variables. The 695 nm band on the later image date in 2010 was the only selected variable that did not have a significant variety effect (Table 2). The main effect of irrigation was only significant for 536, 601, and 799 nm on the earlier image date in 2010. The differences in statistical significance for these wavelengths on the earlier image dates between years may be due to differences in water stress because of rainfall the day prior to image acquisition in 2011.

Among the interactions for the selected variables, N by variety was the most significant, followed by irrigation by variety (Table 2). The irrigation by N interaction was statistically significant for only leaf N on the later image date in 2010.

### **Nitrogen by variety**

The two-way interaction between N and variety for leaf N was only significant on the earlier image date in 2010. On this date, leaf N was greatest for N3, N4, and N5 in each variety; leaf N in RB was greater than AR for all N treatments except N1, in which case it was statistically similar in both varieties. Similar to leaf N on the earlier image date in 2010, reflectance at 536, 601, and 695 nm on the earlier image dates in each year was greater for RB than for AR; however, reflectance was greater for N2

**Table 2. P-values of canopy reflectance for the analysis of variance of four narrowband wavelengths and leaf N on the four image dates.**

Selected variables		Main effects			Interactions			
		nitrogen	variety	irrigation	N x var	irr x var	irr x N	
201 0	47 DAE	536 nm	** <sup>1</sup>	**	*	**	*	NS
		601 nm	**	**	*	**	*	NS
		695 nm	**	**	*	**	*	NS
		799 nm	**	**	NS	NS	NS	NS
		leaf N	**	**	NS	**	NS	NS
	83 DAE	536 nm	**	NS	NS	*	NS	NS
		601 nm	**	**	NS	NS	NS	NS
		695 nm	**	NS	NS	NS	NS	NS
		799 nm	**	**	NS	*	*	NS
		leaf N	**	**	NS	NS	NS	*
201 1	43 DAE	536 nm	**	**	NS	**	NS	NS
		601 nm	**	**	NS	**	*	NS
		695 nm	**	**	NS	**	*	NS
		799 nm	**	**	NS	**	NS	NS
		leaf N	**	*	NS	NS	NS	NS
	66 DAE	536 nm	**	**	NS	**	NS	NS
		601 nm	**	**	NS	**	NS	NS
		695 nm	**	**	NS	**	NS	NS
		799 nm	**	*	NS	*	NS	NS
		leaf N	**	**	NS	NS	NS	NS

<sup>1</sup>\*\* , \* , and NS denote responses that were significant at  $\alpha = 0.01$ , significant at  $\alpha = 0.05$ , and not significant at  $\alpha = 0.05$ , respectively.

than for N3, N4, and N5 in RB, but not in AR. More simply, reflectance at these wavelengths was much more static across N rates in AR than in RB. When there was

a significant interaction between N and variety at these wavelengths on the later image date in 2011, reflectance for N3 and N4 tended to be similar in both varieties, but reflectance at N1, N2, and N5 were greater in RB than in AR. Since high reflectance at these wavelengths suggests an N stress, there is strong evidence of N stress for N1 and N2 in both varieties. Based on reflectance for N5 on the later image dates, the 601 and 695 nm bands show evidence for being able to detect the early stages of an N stress in RB only – reflectance at these wavelengths for N5 is greater in RB than in AR, even though reflectance for N5 is statistically similar to N3 and N4 in each variety.

The N by variety interaction was significant for reflectance at 799 nm on each image date in 2011, as well as on the later image date in 2010. On the earlier image date in 2011, reflectance for N1 was lower than the other N treatments to a greater extent in AR than in RB. This is the opposite of what was observed at 536, 601, and 695 nm on the earlier image date in 2011 – at the 536, 601, and 695 nm bands, reflectance decreased with increasing N rate and tended to be more static in AR than in RB; however, at the 799 nm band, reflectance increased with increasing N rate and tended to be more static in RB. On the later image date in 2011 at the 799 nm band, reflectance was similar between varieties for all N treatments except N5, in which reflectance in AR was lower than in RB. It is also notable that reflectance for N5 in RB was similar to N3 and N4, but reflectance for N5 in AR was lower than for N3 and N4, suggesting an N stress for N5 in AR; this provides contradicting evidence towards the trends observed with reflectance at 601 nm and 695 nm for this image date.

On the later image date in 2010 at 799 nm, reflectance was similar among N3, N4, and N5 in RB, but reflectance was greater for N4 than either N3 or N5 in AR. This suggests that the added soil surfactant either increased N uptake or prolonged growth in RB compared to the other N treatments. It is also notable that reflectance on the later image date in 2010 at 799 nm is greater in AR than in RB; this is different on all other image dates at 799 nm, and provides evidence that AR continues to grow at the dates when RB is beginning to senesce. Although reflectance is greater in AR on 83 DAE, leaf N is greater in RB, which suggests that there is (1) a difference in reflectance at 799 nm due to physiological differences in leaf composition between the varieties on this date, or (2) a background soil effect on reflectance in RB that decreases reflectance at 799 nm, even though leaf N is still relatively high.

### **Irrigation by variety**

The two-way interaction between irrigation and variety was only significant at a few wavelengths for any particular image date, and they were not consistent over image dates (Table 2). Significant differences were likely due to either (1) rainfall that had occurred prior to the earlier image date in 2011, which resulted in a lack of any apparent water stress, or (2) differences in the amount of bare soil present with each variety on the later image date in 2010.

### **Irrigation by nitrogen**

The two-way interaction between irrigation and N was significant for only leaf N on the later image date in 2010 (Table 2). Leaf N on this date was similar for N2, N3,

and N4 in the unstressed irrigation, but was lower for N2 than for either N3 or N4. In addition, the added soil surfactant was also the reason for this significant response – leaf N was statistically similar for N3 and N4 in the unstressed irrigation, but was higher for N3 than for N4 in the stressed irrigation. The general lack of interaction between irrigation and N is confirmed both by spectral reflectance and leaf N data.

## CONCLUSIONS

Using leaf N samples to determine in-season crop N status is a slow, destructive process that is not spatially representative. The use of canopy-level HS imagery to estimate crop N status is much faster and non-destructive, and can also account for spatial variability. However, the ability of HS narrowbands to accurately detect N stress depended on potato variety, growth stage, and sometimes, on the wavelengths used for prediction.

Both varieties clearly demonstrated that as the potato crop matured, the relationship between leaf N and wavelength decreased for most wavelengths, especially throughout the entire NIR region. Regardless of variety, the best performing wavelengths for detecting N stress across all image dates were those at the end of the green and beginning of the red regions from ~582-610 nm and those at the beginning of the red-edge from ~685-695 nm. However, the relationship between canopy reflectance and leaf N showed a more consistent trend among image dates for RB than for AR (on a relative scale). Consistent trends among image dates are more likely to lead to more accurate prediction of N stress, regardless of growth stage.

Reflectance in the NIR region could be used to predict N stress for both varieties, but only in the early growth stages since the ability of NIR wavelengths to predict crop N stress decreases as growth stage progresses. However, reflectance at 799 nm on 83 DAE was able to detect subtle differences in leaf N that reflectance at 536, 601, and 695 nm were not able to, but only for AR. HS data may not be absolutely necessary in the NIR region since  $r^2$  was consistent across most of the NIR region, suggesting that NIR broadband reflectance obtained from a multispectral sensor would likely be as effective in predicting N stress as an NIR narrowband obtained from a HS sensor.

The presence or absence of an N stress regarding the timing of N application for a particular variety on a particular date, sometimes depended on which wavelengths were used. For example, on the later image date in 2010, reflectance at 601 and 695 nm suggested an N stress in RB when post-emergence N was applied early; however, reflectance at 799 nm on the same date suggested an N stress in AR when post-emergence N was applied early (based on the N by variety interactions).

Measurements of leaf N concentration and canopy-level HS reflectance should be obtained at more frequent intervals throughout the growing season to further understand (1) the behavior of the dips in  $r^2$  in the green region and (2) the effects of timing of split applications of post-emergence N on reflectance.

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