

# **NITROGEN AND WATER STRESS IMPACTS HARD RED SPRING WHEAT (*TRITICUM AESTIVUM*) CANOPY REFLECTANCE**

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## **ABSTRACT**

Remote sensing is a method for implementing an in-season site-specific N recommendation program for spring wheat (*Triticum aestivum*) nitrogen (N) fertilization program. However, in fields where yields are influenced by both water and N stress, accurate N recommendations require that the N and water stress signals be separated from each other. The objective of this study was to determine the impact of water and N stress on canopy reflectance and the ability of vegetation (NDVI, GNDVI, and BNDVI), and chlorophyll (CGreen and CRedEdge) indices to separate water and N stress. A split-plot experiment containing four blocks was conducted in 2002, 2003, and 2005 at Aurora South Dakota. The treatments were two soil moisture regimes and four N rates. Canopy reflectance was measured with a handheld multispectral radiometer at Haun 2, 4-4.5, 6, and 10-10.2. Canopy reflectance was measured in 16 different bands. Remote sensing-based prediction models for yield, yield loss due to N stress, yield loss for water stress, and protein were developed. Yield loss due to N stress decreased with increasing N, while yield loss to water stress had the opposite relationship. Protein concentration generally increased with N. The remote sensing models for protein and yield loss due to N stress explained more of the variability than the yield model at Haun 4-4.5 and Haun 6. These data suggest that canopy reflectance can be used to separate N and water stress signals in hard red spring wheat.

## INTRODUCTION

In the Great Plains, wheat (*Triticum aestivum* L.) yields can be reduced by both too much and too little N and water that can vary across landscapes. Because N requirements increase with water (Thomas and Oerther, 1972; Sinclair and Horie, 1989), misdiagnosing crop water stress as N deficiency can result in over-fertilization and reduced yields in areas limited by water stress (Reese et al., 2002). Remote sensing may provide the information needed for simultaneous management of water and N stress (Shanahan et al., 2007; Raun et al., 2002).

One of the most common remote sensing-based approaches for assessing crop health is the Normalized Difference Vegetation Index (NDVI; Rouse et al., 1973). NDVI contrasts the reflectance in the chlorophyll-absorbing red wavelengths with reflectance in the near infrared (NIR) wave lengths. In North Carolina, Flowers et al. (2003) used the NDVI to direct in-season N application between tillering and stem elongation when biomass was  $> 1000 \text{ kg ha}^{-1}$ . Raun et al. (2001 and 2002) conducted similar research in eastern Oklahoma. In spite of these successes, several problems have been reported. First, NDVI may be better at predicting water than N stress (Clay et al., 2006), and second, the index value can become saturated, reducing its sensitivity (Gitelson and Merzylak, 1996; Daughtry et al., 2000). Saturation occurs because as biomass increases, canopy reflectance in the red band decreases, resulting in the difference between NIR and red approaching the value of the canopy reflectance in the NIR band. Chlorophyll indices were developed to overcome these problems (Gitelson and Merzylak, 1994a, 1994b, 1996; Penuelas et al., 1994; Gitelson et al., 2003, 2005; Clay et al., 2006).

Combinations of indices have also been used to overcome problems associated with NDVI (Daughtry et al., 2000). For example, Rodriguez et al. (2006) reported that the Normalized Difference Red Edge Index (NDRE) divided by NDVI (Barnes et al., 2000) is correlated to the foliar N content in dryland wheat. Haboudane et al. (2004) reported that the Transformed Chlorophyll in Absorption Ratio Index (TCARI) divided by the Optimized Soil Adjusted Vegetation Index (OSAVI) can be used to enhance chlorophyll sensitivity and reduce soil background noise. Eitel et al. (2007) reported that the ratio between the Modified Chlorophyll in Absorption Ratio Index (MCARI; Daughtry et al., 2000) and second Modified Triangular Vegetation Index (MTV12; Haboudane et al., 2004) can be used to predict flag leaf N concentration of dryland wheat.

The study objective was determination of the impact of water and N stress in combination and alone on canopy reflectance. The ability of vegetation (NDVI, GNDVI, and BNDVI), and chlorophyll (CGreen and CRedEdge) indices were assessed to separate water and N stresses.

## MATERIALS AND METHODS

### Experimental Design and Cultural Practices

This study was conducted on a Brandt silty clay loam (fine-silty, mixed,

superactive, frigid calcic Hapludoll) at a site located near Aurora, South Dakota (96°40'W, 44°18'N) in 2002, 2003, and 2005. Previous crops were soybean (*Glycine max*) in 2001 and 2002 and flax (*Linum usitatissimum*) in 2004. The field was no-tilled in 2002 and 2003; and chisel-plowed and disked in 2005. Composite soil samples (0-15 cm and 15-60 cm), consisting of 15 to 20 individual cores, were collected in spring prior to urea application. Samples were air dried and analyzed for NH<sub>4</sub>-N and NO<sub>3</sub>-N after extraction with 1.0 M KCl (Clay et al., 2006) (Table 1). Phosphorus and potassium fertilizers were applied in accordance with university fertilizer guidelines. Hard red spring wheat cultivar “Russ” was planted on 15 April 2002 and 2003 and the cultivar, “NorPro”, was planted on 7 April 2005 at a rate of 100 kg ha<sup>-1</sup>. Russ is an awned, medium-height variety that has early-midseason maturity whereas NorPro is an awned, short semi-dwarf wheat variety that has midseason maturity. Lodging can be a problem at high fertility level with Russ, while NorPro has good lodging resistance.

The two water treatments were rainfed (Table 1) or rainfed and supplemental irrigation and were split within plots. Irrigation was applied with a lateral-move irrigation system with drop nozzles. Randomization was achieved across the areas by plugging adjacent nozzles along different sections of the lateral-move irrigator. The four N rates were 0-, 56-, 140-, and 224-kg urea-N ha<sup>-1</sup>, applied pre-emergence. A randomized split-plot design was used with water as the main treatment and N rates randomized within each plot. Blocks were replicated four times. Individual plot size was 12.2 m wide and 24.4 m long in 2002 and 12.2 m long in 2003 and 2005.

Growing degree days (GDD, base 4.4°C, Table 1) were calculated based on the equation:

$$\text{GDD} = \frac{(\text{Temperature}_{\text{max}} + \text{Temperature}_{\text{min}})}{2} - 4.4^{\circ}\text{C} \quad (1)$$

Table 1. Water, preseason inorganic N, and growing degree days in 2002, 2003, and 2005

| Year | Water         |                           | Inorganic N  |                    | GDD           |
|------|---------------|---------------------------|--|--------------------|---------------|
|      | Rainfed<br>Cm | Rainfed and<br>Irrigation | NH <sub>4</sub> and<br>NO <sub>3</sub> -N<br>kg ha <sup>-1</sup> | NH <sub>4</sub> -N | Base<br>4.4°C |
| 2002 | 59.4          | 65.7                      | 51   | ND <sup>†</sup>    | 1416          |
| 2003 | 43.6          | 49.4                      | 70   | 26                 | 1274          |
| 2005 | 61.2          | 63.7                      | 73   | 10                 | 1458          |

<sup>†</sup> ND, not determined

### Canopy Reflectance Measurements

Canopy reflectance was measured at Haun 6 and 10-10.2 in 2002; Haun 2, 4, and 10-10.2 in 2003; and Haun 4.5 and 6.0 in 2005 (Haun, 1973). The Haun scale for wheat was used because the scale is sensitive to early leaf growth.

The Cropscan Multispectral radiometer (Cropscan Inc., Rochester,

Minnesota), factory-calibrated each season, was held 2 m above the canopy with the sensor receptor oriented parallel to the canopy surface. Based on the height of the sensor, data were collected from a 1-m diameter circle. Irradiance and canopy reflectance readings were collected simultaneously between 11:00 a.m. and 3:00 p.m. Central Standard Time. Canopy reflectance values in 5 broad bands [blue,  $485 \pm 45$  nm; green,  $560 \pm 40$  nm; red,  $660 \pm 30$  nm; NIR,  $830 \pm 70$  nm; and mid infrared (MIR),  $1650 \pm 100$  nm] and 11 narrow bands ( $510 \pm 3.65$ ,  $566 \pm 5$ ,  $610 \pm 5.15$ ,  $661 \pm 5.8$ ,  $710 \pm 6.2$ ,  $760 \pm 5.3$ ,  $810 \pm 5.7$ ,  $840 \pm 6$ ,  $870 \pm 6$  nm,  $905 \pm 5$ , and  $1050 \pm 5$  nm) were measured.

### **Spectral Indices Calculations**

The percentage canopy reflectance was calculated from readings taken by the radiometer using the equation:

$$\% \text{ Canopy Reflectance} = \frac{\text{Down sensor reading}}{\text{Up sensor reading}} \times 100 \quad (2)$$

Canopy reflectance values among years were compared by growth stage.

In addition to canopy reflectance, seven different spectral indices were calculated (Table 2) using various combinations of values from different bands. Normalized difference vegetation indices,  $\text{NDVI}_w$  and  $\text{NDVI}_n$ , were calculated using either the wide (w) or narrow (n) red and NIR canopy reflectance, respectively. Green normalized difference vegetation indices,  $\text{GNDVI}_w$  and  $\text{GNDVI}_n$ , were developed using the wide (w) or narrow (n) green band and NIR canopy reflectance, respectively. The narrowband indices ( $\text{NDVI}_n$  or  $\text{GNDVI}_n$ ) are based on canopy reflectance in similar regions of the electromagnetic spectrum as commercially available two-sensor systems that measure canopy reflectance values from a light emitting diode source. The wide bands of blue and NIR were used to create a blue normalized vegetation index,  $\text{BNDVI}_w$ . The  $\text{BNDVI}_w$  index was selected due to overlap in the green area of the electromagnetic spectrum and due to previous successes by Yang et al. (2004) and Hancock and Dougherty (2007) to estimate biomass in cotton and alfalfa, respectively.  $\text{CGreen}$  and  $\text{CRedEdge}$  were calculated by dividing the narrow NIR by either the narrow green or narrow red reflectance bands, respectively, and subtracting 1. These indices were selected due to reported increased sensitivity to plant chlorophyll (Gitelson et al., 2005).

### **Yield and Grain Measurements**

Wheat was harvested with a Massey Ferguson model MF8 combine (AGCO, Bloomington, Minnesota) at physiological maturity in late July (2002 and 2005) or early August (2003). Yield was determined at 13.5% moisture. Grain protein (12% moisture) was determined using a Foss Tecator Infratec™ 1241 Grain Analyzer (Eden Prairie, Minnesota). Grain samples were dried at 60° C to constant weight, ground to flour, and analyzed on a Europa Ratio Mass

Spectrometer (Europa Scientific Ltd., United Kingdom) for total N, carbon (C),  $^{13}\text{C}$ , and  $^{15}\text{N}$ . The  $^{13}\text{C}$  natural abundance approach was used to calculate yield loss to N stress (YLNS) and yield loss to water stress (YLWS) (Clay et al., 2001, 2005, and 2006).

Table 2. Spectral indices computed from the actual Cropscan bands and formulas to derive the index are provided in the column titled “Cropscan Bands Used to Calculate Indices”

| Description                                  | Index              | Cropscan Bands Used to Calculate Indices | Reference                                      |
|--|--------------------|--|--|
| Normalized Difference Vegetation Index       | NDVI <sub>w</sub>  | $(830 - 660) / (830 + 660)$              | Rouse et al., 1973                             |
|  | NDVI <sub>n</sub>  | $(760 - 661) / (760 + 661)$              |  |
| Green Normalized Difference Vegetation Index | GNDVI <sub>w</sub> | $(830 - 560) / (830 + 560)$              | Gitelson et al., 1996                          |
|  | GNDVI <sub>n</sub> | $(870 - 566) / (870 + 566)$              |  |
| Blue Normalized Difference Vegetation Index  | BNDVI <sub>w</sub> | $(830 - 485) / (830 + 485)$              | Hancock and Dougherty, 2007; Yang et al., 2004 |
| CGreen                                       | CGreen             | $(810 / 566) - 1$                        | Gitelson et al., 2005                          |
| CRedEdge                                     | CRedEdge           | $(810 / 710) - 1$                        |  |

### Calculations to Determine Yield Loss Due to Water or N Stress

Yield loss due to N (YLNS) and water stress (YLWS) was determined using carbon isotopic discrimination. The grain gives a season-long integrated look at these stresses in the plant environment as N and water stress have differential impacts on the relative amounts of  $^{13}\text{C}$  and  $^{12}\text{C}$  fixed during photosynthesis. Complete explanation for calculation of YLNS and YLWS based on grain  $^{13}\text{C}$  maybe found in Reese, 2009.

### Statistical Analysis

Yield parameters were analyzed using PROC GLM of SAS ver. 9.1 (SAS Institute, Cary, NC) for main treatment effects of year, N, water, and interactions. Values from F tests were used to calculate *P* values. Pearson correlation coefficients (*r*) were computed using PROC CORR of SAS to determine strength of relationships between each of the seven spectral index and yield parameters. The SAS procedure MAXR was used to develop predictive equations for each yield parameter using the spectral indices as regression estimators. The MAXR method selects regression models that provide the highest degree of correlation with the least number of variables and is an improvement over the STEPWISE method in that many more models are evaluated.

## RESULTS AND DISCUSSION

### Wheat Yield and Quality

Grain yields were highest in 2003 and lowest in 2002, whereas protein was lowest in 2003 and highest in 2002 (Table 3). The inverse relationship between yield and protein has been reported by others (Clay et al., 2001; Kim et al., 2008; Norword, 1995). The high yields in 2003 were attributed to consistently lower seasonal temperatures, as observed by 11% fewer GDD, as contrasted with lower yields in 2002 and 2005, when seasonal GDD was higher (Table 1).

Protein contents were much more sensitive to N in 2003 than 2005 (Figure 1). The small response to N in 2005 was attributed to chisel plowing the field prior to planting that most likely stimulated N mineralization rates. These results were not attributed to high inorganic N levels at the beginning of the season (Table 1).

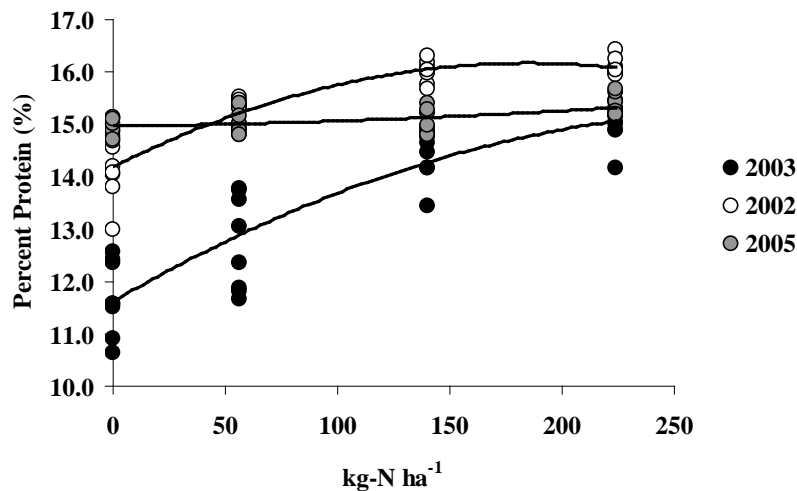


Figure 1. Hard red spring wheat protein response function to increasing N rates in 2002, 2003, and 2005

As expected, YLNS was greater than YLWS under conditions of relatively infrequent water stress that are typical of eastern South Dakota. In all three years, YLNS decreased as N rate increased. For example, the highest N rate alleviated 78% of the calculated YLNS of the 0N rate in 2002, 48% in 2003, and 16% in 2005. The YLWS increased as N rate increased in 2002 and 2003 and did not vary with N in 2005 (Table 3). In the 0N treatment, YLWS was reduced by 34% in the irrigated compared with the rainfed treatment. In corn, Kim et al. (2008) reported that water alleviated some N stress due to higher soil mineralization rates under irrigation and the subsequent replacement of fertilizer N ( $\delta^{15}\text{N}$  value = -1 to 0) with soil-derived N ( $\delta^{15}\text{N}$  value >1) (Bateman and Kelly, 2007). Calculated values for YLNS were not influenced by water. However, water affected  $\delta^{15}\text{N}$  values. The  $\delta^{15}\text{N}$  values were greatest in the 0N for all years and decreased from 1.23 in 0N to -0.825 in the highest N treatments, indicating more soil-derived N in the 0N

treatment. Irrigation increased  $\delta^{15}\text{N}$  value from -0.167‰ to 0.046 ‰. The higher value suggests that more soil N was used under irrigated conditions.

Table 3. The influence water regime, N rate, and year on wheat yield, protein content, yield from N stress (YLNS), yield loss from water stress (YLWS), and grain  $\delta^{15}\text{N}$

| Water Regime          | N Rate                | Year   | Grain Yield         | Protein      | YLNS                | YLWS          | $\delta^{15}\text{N}$ |
|-----------------------|-----------------------|--|---------------------|--------------|---------------------|---------------|-----------------------|
|                       | kg-N ha <sup>-1</sup> |  | kg ha <sup>-1</sup> | %            | kg ha <sup>-1</sup> |               | ‰                     |
| Rainfed               | 0                     | 2002   | 2964                | 14.1         | 980                 | 385           | 1.07                  |
|                       | 56                    |  | 3564                | 15.4         | 446                 | 319           | 0.36                  |
|                       | 140                   |  | 3087                | 16.2         | 555                 | 687           | -1.25                 |
|                       | 224                   |  | 3615                | 16.3         | 217                 | 497           | -1.61                 |
| Irrigated             | 0                     |  | 3161                | 14.5         | 932                 | 236           | 1.26                  |
|                       | 56                    |  | 3128                | 15.4         | 676                 | 525           | 0.39                  |
|                       | 140                   |  | 3274                | 16.1         | 390                 | 665           | -1.06                 |
|                       | 224                   |  | 3644                | 16.1         | 206                 | 479           | -1.14                 |
| Rainfed               | 0                     | 2003   | 3585                | 10.8         | 1506                | 297           | 1.11                  |
|                       | 56                    |  | 3963                | 12.2         | 1239                | 186           | -0.09                 |
|                       | 140                   |  | 4030                | 13.8         | 857                 | 501           | -1.43                 |
|                       | 224                   |  | 4130                | 15.0         | 701                 | 558           | -0.76                 |
| Irrigated             | 0                     |  | 3819                | 11.9         | 1419                | 149           | 1.66                  |
|                       | 56                    |  | 3740                | 12.7         | 1350                | 298           | 0.43                  |
|                       | 140                   |  | 3809                | 14.4         | 1053                | 527           | -1.08                 |
|                       | 224                   |  | 4127                | 14.6         | 819                 | 442           | -1.22                 |
| Rainfed               | 0                     | 2005   | 3422                | 14.8         | 1909                | 167           | 1.07                  |
|                       | 56                    |  | 3529                | 14.8         | 1751                | 217           | -0.15                 |
|                       | 140                   |  | 3538                | 14.9         | 1689                | 269           | -0.11                 |
|                       | 224                   |  | 3673                | 15.0         | 1605                | 219           | -0.22                 |
| Irrigated             | 0                     |  | 3424                | 14.6         | 1896                | 177           | 1.23                  |
|                       | 56                    |  | 3524                | 14.7         | 1767                | 206           | 0.17                  |
|                       | 140                   |  | 3606                | 14.6         | 1702                | 189           | -0.08                 |
|                       | 224                   |  | 3752                | 15.0         | 1607                | 138           | 0.01                  |
| Interaction or Factor | DF <sup>†</sup>       | <i>P</i> Value and LSD () at <i>P</i> = 0.50 |                     |              |                     |               |                       |
| Water x N Rate X Year | 6                     | 0.051  | 0.183               | 0.020        | 0.235               | 0.468         |                       |
| Water x N Rate        | 3                     | 0.004 (139)                                  | 0.056               | 0.043 (82)   | 0.009 (86)          | 0.854         |                       |
| Year x N Rate         | 6                     | 0.126  | <0.001 (0.4)        | <0.001 (100) | <0.001 (105)        | <0.001 (0.50) |                       |
| Year x Water          | 2                     | 0.781  | 0.006 (0.2)         | 0.262        | 0.849               | 0.957         |                       |
| Water                 | 1                     | 0.883  | 0.100               | 0.200        | 0.519               | 0.280         |                       |
| N Rate                | 3                     | <0.001 (98)                                  | <0.001 (0.2)        | <0.001 (58)  | <0.001 (61)         | <0.001 (0.29) |                       |
| Year                  | 2                     | <0.001 (87)                                  | <0.001 (0.4)        | <0.001 (47)  | <0.001 (56)         | 0.015 (0.30)  |                       |

<sup>†</sup> DF, degrees of freedom

Table 4. Correlation coefficient (r) values between yield, protein, yield loss due to N stress (YLNS), yield loss due to water stress (YLWS),  $\delta^{15}\text{N}$ , and 7 indices at hard red spring wheat growth stages Haun 2, Haun 4-4.5, Haun 6, and Haun 10-10.2. Data were aggregated (n = 64) for Haun 4-4.5, Haun 6, and Haun 10-10.2 between dates presented. Correlation coefficient values for Haun 2 are for 2003 only (n = 32). Values of ( $\pm$ ) 0.250 and ( $\pm$ ) 0.325 represent significance at  $P = 0.05$  and 0.01, respectively.

| Factor  | Vegetation Indices |                   |                    |                    |                    | Chlorophyll Indices |           |
|---|--------------------|-------------------|--------------------|--------------------|--------------------|---------------------|-----------|
|   | NDVI <sub>w</sub>  | NDVI <sub>n</sub> | GNDVI <sub>w</sub> | GNDVI <sub>n</sub> | BNDVI <sub>w</sub> | C-Green             | C-RedEdge |
| <b>Haun 2 (05/20/03)</b>                      |                    |                   |                    |                    |                    |                     |           |
| Yield   | 0.07               | 0.08              | -0.01              | 0.12               | 0.02               | 0.12                | 0.15      |
| Protein                                       | 0.14               | 0.11              | 0.21               | 0.28               | 0.15               | 0.21                | 0.30      |
| YLNS  | -0.26              | -0.23             | -0.27              | -0.40              | -0.25              | -0.31               | -0.39     |
| YLWS  | 0.32               | 0.26              | 0.44               | -0.48              | -0.37              | -0.33               | -0.42     |
| $\delta^{15}\text{N}$                         | -0.39              | -0.36             | -0.38              | -0.41              | -0.35              | -0.43               | -0.45     |
| <b>Haun 4-4.5 (06/04/03 &amp; 05/29/05)</b>   |                    |                   |                    |                    |                    |                     |           |
| Yield   | -0.48              | -0.47             | -0.46              | -0.48              | -0.47              | -0.54               | -0.54     |
| Protein                                       | 0.73               | 0.72              | 0.73               | 0.72               | 0.73               | 0.69                | 0.69      |
| YLNS  | 0.65               | 0.65              | 0.64               | 0.66               | 0.64               | 0.72                | 0.72      |
| YLWS  | -0.41              | -0.42             | -0.41              | -0.43              | -0.41              | -0.46               | -0.46     |
| $\delta^{15}\text{N}$                         | 0.03               | 0.03              | -0.01              | -0.03              | -0.02              | 0.09                | 0.10      |
| <b>Haun 6 (06/14/02 &amp; 06/06/05)</b>       |                    |                   |                    |                    |                    |                     |           |
| Yield   | 0.59               | 0.59              | 0.56               | 0.57               | 0.58               | 0.58                | 0.56      |
| Protein <sup>†</sup>                          | 0.83               | 0.84              | 0.86               | 0.86               | 0.82               | 0.86                | 0.85      |
| YLNS  | 0.52               | 0.53              | 0.58               | 0.64               | 0.57               | 0.57                | 0.74      |
| YLWS  | -0.32              | -0.32             | -0.34              | -0.39              | -0.34              | -0.34               | -0.49     |
| $\delta^{15}\text{N}$                         | -0.23              | -0.22             | -0.2               | -0.15              | -0.2               | -0.23               | -0.06     |
| <b>Haun 10-10.2 (06/24/02 &amp; 06/29/03)</b> |                    |                   |                    |                    |                    |                     |           |
| Yield   | 0.35               | 0.22              | 0.43               | 0.29               | 0.54               | 0.38                | 0.37      |
| Protein                                       | 0.28               | 0.37              | 0.19               | 0.39               | -0.13              | 0.32                | 0.30      |
| YLNS  | -0.18              | -0.26             | -0.08              | -0.26              | 0.22               | -0.21               | -0.18     |
| YLWS  | 0.32               | 0.39              | 0.27               | 0.38               | 0.10               | 0.35                | 0.36      |
| $\delta^{15}\text{N}$                         | -0.55              | -0.54             | -0.51              | -0.57              | -0.35              | -0.57               | -0.56     |

<sup>†</sup> At Haun 6, correlation between protein and indices represent data from 2002 only. Protein was unresponsive to N in 2005.

### Canopy Reflectance: Indices

Stronger relationships among canopy reflectance indices values and end of the season measurements were observed at Haun 4-4.5 and 6 than at Haun 2 (Table 4). At Haun 4-4.5 and Haun 6, grain protein and YLNS were correlated positively to all indices whereas YLWS was correlated negatively to the indices. Degree of correlation was stronger for YLNS and YLWS at Haun 4-4.5 and stronger for protein at Haun 6. Yield was correlated negatively to all indices at Haun 4-4.5 but correlated positively at Haun 6. These differences were a



consequence of averaging years with different response functions and datasets. For example, Haun 4 contained data from 2003 and 2005, whereas Haun 6 contained data from 2002 and 2005.

The chlorophyll indices of CGreen and CRedEdge at Haun 4-4.5 and Haun 6 generally had higher positive correlation to YLNS than most of the vegetation indices. These results suggest that the chlorophyll indices provided more reliable information about N stress than vegetation indices. In addition, these two chlorophyll indices were correlated negatively to YLWS at these two growth stages, indicating that N stress and water stress differentially influenced canopy reflectance.

### **Predicting N and Water Stress**

Regression models for predicting yield, grain protein, YLNS, YLWS, and grain  $\delta^{15}\text{N}$  were developed using spectral bands and selected indices (Table 5). Index  $\text{BNDVI}_w$  was not significant in any model and is not discussed further. Overall, models explained from 26 to 93 % of the variability. Models for Haun 2 explained 46% of the yield variability, which was similar with the models at other growth stages. However at Haun 2, less variance was explained for the YLNS, YLWS, protein, or  $\delta^{15}\text{N}$  parameters compared with models at later growth stages. These results were expected at this growth stage because of a large percentage of soil that was still exposed.

At later growth stages (Haun 4-4.5, 6, and 10-10.2), regression modeling became more effective in predicting all variables except yield. At Haun 6, the models explained 93%, 70%, and 57% of the variability observed in the YLNS, protein, and YLWS data, respectively. The CGreen and CRedEdge were the only parameters used in the models for prediction of all three, although the coefficients for YLNS were positive values for CGreen and negative values for CRedEdge, compared with negative values of CGreen and positive values of CRedEdge for YLWS and protein. These results suggest that in-season remote sensing fairly early in wheat growth can provide reasonable estimates of N and water stress.

### **SUMMARY AND CONCLUSIONS**

Yield losses due to N stress (YLNS) decreased with increased fertilizer application that also increased yield. Yield loss to water stress (YLWS) was alleviated but not eliminated with irrigation and generally increased as fertilizer rate increased. Multivariate regression prediction models explained more variance in protein and YLNS at Haun 6 than at Haun 4-4.5 and Haun 10-10.2. Wavebands most used often in developing the prediction models for YLNS and protein at Haun 4-4.5 were wideband canopy reflectance in green (560 nm) and NIR (830 nm) and narrow band canopy reflectance in red edge (710 nm) and NIR (810 nm) for CRedEdge (grain protein only). At Haun 6, YLNS and grain protein were predicted using narrow band canopy reflectance at red edge (710 nm) and NIR (810 nm) for CRedEdge, and green (568) and NIR (810 nm) for CGreen. At Haun 10-10.2 (heading), canopy reflectance in the wide blue band (440-530 nm) was a

component in prediction models for all end of season parameters.

The results from this study are sufficiently promising to suggest that spectral bands together with chlorophyll indices, which do not saturate as readily as vegetation indices, may be good regression estimators of YLNS and grain protein. This remote sensing information may be used for determination of wheat N status early in the growing season and applying in-season N topdress applications to improve yield and grain protein.

Table 5. Growth stage dependent remote sensing multiple regression models for predicting yield, yield loss due to N stress (YLNS), yield loss due to water stress (YLWS), grain protein, and grain  $\delta^{15}\text{N}$ .

|   | Spectral Band |         |        | Spectral Index |        |        |                   |                   |                    |                    |          |          | R <sup>2</sup> |
|---|---------------|---------|--------|----------------|--------|--------|-------------------|-------------------|--------------------|--------------------|----------|----------|----------------|
|   | Intercept     | Blue    | Green  | Red            | NIR    | MIR    | NDVI <sub>w</sub> | NDVI <sub>n</sub> | GNDVI <sub>w</sub> | GNDVI <sub>n</sub> | CGreen   | CRedEdge |                |
| <b>Growth Stage: Haun 2 (05/20/2003)</b>                      |               |         |        |                |        |        |                   |                   |                    |                    |          |          |                |
| Yield   | -4555.8       | 2108.8  |        |                | -576.6 |        |                   |                   | -21501.0           |                    | 13276.00 |          | 0.46**         |
| YLNS  | 10193.0       | -2644.7 |        | 1318.2         |        |        |                   | 27056             |                    |                    | -11565.0 |          | 0.42**         |
| YLWS  | -4300.4       |         |        |                |        |        |                   | -6070.1           | 15559.0            |                    |          |          | 0.27*          |
| Protein   | 4.6           |         |        |                |        |        | -101.5            |                   |                    |                    | 34.2     |          | 0.26*          |
| $\delta^{15}\text{N}$   | -4.6          |         |        |                |        | 0.2    |                   | 90.2              |                    |                    |          | -59.4    | 0.28*          |
| <b>Growth Stage: Haun 4-4.5 (06/04/2003 &amp; 05/29/2005)</b> |               |         |        |                |        |        |                   |                   |                    |                    |          |          |                |
| Yield   | -1939.5       |         |        |                |        |        |                   |                   |                    | 11706.0            |          | -995.4   | 0.48***        |
| YLNS  | 4285.7        |         |        |                | 79.0   |        |                   |                   | -8396.6            |                    |          |          | 0.73***        |
| YLWS  | 2936.9        |         | -287.6 |                |        |        |                   | -1205.6           |                    |                    |          |          | 0.36***        |
| Protein   | -9.0          |         |        |                |        |        |                   |                   | 38.9               |                    |          | -1.9     | 0.60***        |
| $\delta^{15}\text{N}$   | -13.1         |         | 2.6    |                | -0.5   |        |                   |                   |                    |                    |          |          | 0.40**         |
| <b>Growth Stage: Haun 6 (06/14/2002 and 06/06/2005)</b>       |               |         |        |                |        |        |                   |                   |                    |                    |          |          |                |
| Yield   | 11846.0       |         |        |                |        | -130.6 |                   | 6983.3            | -17988.0           |                    |          | 501.6    | 0.43**         |
| YLNS  | 1364.1        |         |        |                |        |        |                   |                   |                    |                    | 1128.8   | -2073.7  | 0.93**         |
| YLWS  | 112.8         |         |        |                |        |        |                   |                   |                    |                    | -310.3   | 611.7    | 0.57**         |
| Protein   | 12.6          |         |        |                |        |        |                   |                   |                    |                    | -1.4     | 3.1      | 0.73***        |
| $\delta^{15}\text{N}$   | -6.5          |         |        |                |        |        |                   | 18.2              |                    |                    | 1.7      | -5.4     | 0.54***        |
| <b>Growth Stage: Haun 10-10.2 (06/24/2002 and 06/29/2003)</b> |               |         |        |                |        |        |                   |                   |                    |                    |          |          |                |
| Yield   | 6173.6        | -1978.7 |        |                |        | 81.9   |                   |                   |                    |                    |          |          | 0.48**         |
| YLNS  | 425.6         | -4030.7 | 2029.1 |                |        |        |                   |                   |                    |                    |          |          | 0.64**         |
| YLWS  | -1524.3       | 612.4   |        |                |        |        |                   |                   |                    |                    | 85.4     |          | 0.30**         |
| Protein   | 18.7          | 17.3    | -9.4   |                |        |        |                   |                   |                    |                    |          |          | 0.70***        |
| $\delta^{15}\text{N}$   | 8.48          | -1.79   |        |                |        |        |                   |                   |                    |                    |          | -1.06    | 0.36**         |

\* Significant at  $P=0.01$ ; \*\* Significant at  $P=0.001$ ; \*\*\* Significant at  $P=0.0001$ .

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