SAE TECHNICAL PAPER SERIES

961757

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The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

1996 SAE Symposium on
Off-Highway and Engines Conference
Indianpolis, Indiana
August 26, 1996

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ABSTRACT

A review of papers and patents related to sensor based variable rate technology (sVRT) is presented. The rationale for an sVRT system using optical sensing to vary top-dress nitrogen fertilization of winter wheat is presented. The current OSU sensor is presented with some of the calibration results for the 1996 crop season. Reasonable correlations for use of radiance based NDVI (Perry et al. 1984) for detecting vegetative nitrogen mass are presented.

INTRODUCTION

Variable rate fertilization technologies have great promise to improve profitability in agriculture but create some difficult problems for producers. Variable rate fertilizer application based on field mapping is constrained because comprehensive field mapping of soil tests is needed Wollenhaupt (1994). The labor required and large number of soil tests that must be analyzed impose a significant management load on producers and diminish returns. Additionally, yield variability records cannot be used to predict availability of mobile nutrients such as nitrogen during the reproductive phase of winter wheat and similar crops (Singh et al., 1994). Sensor based variable rate technology (sVRT) offers good potential as a solution to variable rate nitrogen fertilization.

Sawyer (1994) indicated that there are various factors which limit the application of map-based variable rate technology (VRT). These include 1) cost of implementation (sampling, mapping, equipment, personnel), 2) lack of expected increase in crop yield and 3) lack of input savings. Sawyer (1994) further suggested that in order to effectively implement map-based VRT, within-field variation must be accurately identified and reliably interpreted.

Sawyer (1994) also pointed out that for most soil chemical properties, sVRT is still futuristic. The goal of sVRT is to avoid traditional costs (such as soil sampling, chemical analysis, data management, and recommendations) and to adjust the application rate based on sensor measurements of fertility as an applicator travels across the field (Sawyer, 1994). Cassman and Plant (1992) found that increases in fertilizer nutrient use efficiency due to spatially variable application depended on both crop response to fertilizer and the variance and skewness of the native nutrient levels in the soil. Chancellor and Goronea (1994) noted that simulated advantages of input efficiency were obtained with spatially variable applications at low and intermediate application rates. They found that advantages decreased with spatial sampling intervals longer than 1 m.

Solie et. al. (1995) demonstrated that spatial variability of nitrogen in the vegetative component of winter wheat had a fundamental field element length of between 0.86 and 1.5 meters. Solie also demonstrated that neighboring field elements could not be used to predict each other with reasonable accuracy. Based on their work (Solie et al., 1995), sVRT systems in winter wheat must sense and apply to approximately 1 meter field elements to achieve the greatest agronomic effect. Whitney et al. (1995) used machine configuration simulations of sVRT fertilization equipment for winter wheat to determine the spatial resolution for best economic return. The simulations demonstrated that returns were much more sensitive to fertilizer savings and yield improvements than to machine costs. They concluded that the economic field element length was slightly less than 1 meter.

Work by Wood et al. (1992) found high correlation between field chlorophyll measurements and corn tissue N concentration at V10 (tassel begins to develop rapidly and the stalk is continuing rapid elongation) and midsilk growth stages using the SPAD-502 chlorophyll meter, Minolta Camera Co., Ltd., Japan. The chlorophyll meter which they used measures the difference in attenuation of transmitted light at wavelengths 430 and 750 nm. The 430 nm wavelength is a spectral transmittance peak for both chlorophyll a and b, while the 750 nm wavelength is in the NIR region where low transmittance occurs (Wood et al., 1992).

Near infrared diffuse reflectance spectrophotometry has been used to measure protein, moisture, fat and oil in agricultural products (Wetzel, 1983). Early work by Thomas and Oerther, (1972) noted that leaf reflectance at 550 and 675 nm could be used to estimate the N status of sweet peppers. Blackmer et al. (1994) found that measurement of light reflectance near 550 nm could be used to detect N deficiencies in corn leaves. The NIR spectral region has also been used for predicting organic C and total N in soils (Dalal and Henry, 1986; Sudduth, 1991). The NIR spectral region is dominated by weak overtones and combinations of vibrational bands of light atoms that have strong molecular bonds such as H attached to atoms of N, O or C (Dalal and Henry, 1986). Each constituent of a complex organic mixture has unique absorption properties in the NIR region (700-2500 nm) due to stretching and bending vibrations of molecular bonds between elements (Morra et al., 1991). Diffuse-reflectance properties of the NIR spectrum of a sample can be correlated to changes in the chemical composition of a sample measured by other means (Morra et al., 1991).

Elliott et al. (1987) found that the concentration of NO_3-N in basal stems of spring wheat could be used to define the N status during tillering and for predicting grain yield responses to applied N. Vaughan et al. (1990) indicated that stem and whole-plant NO_3-N concentrations were highly variable and had limited use for N recommendations. Their work suggested that total N in the whole plant or leaves collected between Feekes 5 and 7 (Large, 1954) could be used for establishing critical N levels. Similar work by Roth et al. (1989) noted that whole-plant total N (between Feekes 3 and 6) could be used to predict N fertilizer requirements in winter wheat.

Wuest and Cassman (1992) found that late-season applied N has greater uptake efficiency and is more effective in increasing grain N levels than N applied at planting. Similar work by Boman et al. (1995) found significant increases in grain yield from topdress N applied in January. Early-season N must be managed to optimize grain yield, but adding excess N at that time reduces overall partitioning efficiency (Wuest and Cassman, 1992).

Optical techniques for automated detection of weeds follow closely optical techniques for biomass detection. Nitsch et al. (1991) determined reflectance curves in the visible and NIR bands and used the data to select vegetative indices (VIs) and wavelengths for weed detection. They examined interferences from soil type, soil surface moisture, and surface organic matter and examined two weed types. The (VIs), NIR/Red and NDVI ((NIR-Red)/(NIR+R)) were evaluated and NDVI with long NIR wavelengths (800 nm ,850 nm) was found to be most effective in detecting living plant matter.

Several patents exist for apparatus to detect and spray weeds. Beck and Vyse (1995) patented the use of modulated light at several wavelengths to differentiate between plant and soil. Modulation was used to allow detectors to determine reflectance by detecting selected radiance due to a source provided in the system. The detected level is then a fraction of the maximum. They concluded that wavelengths of 670 nm and 720-750 nm were optimum for differentiation. McCloy and Felton (1992) patented a weed sprayer controller which determines reflectance based on measurement of irradiance in both the NIR and Red bands and radiance from the target plant in the same bands. Their controller uses a stored lookup table to allow computation of the existence of the plant.

Stone (1994) reported the use of Artificial Neural Networks to process the information from a three band optical sensor for weed detection. After selection of a best performing network for training conditions, the unit was able to detect 92% of the cases where weeds were presented to it and rejected 80% of the cases where weeds were not presented to it. Low sensitivity was found for low light conditions in the field. In addition, situations where the conditions were beyond the training set of data, for example near dawn or dusk resulted in poor performance.

Empirical relationships between vegetative indices and plant biomass have been reported by several researchers. Wanjura and Hatfield (1987) compared three VIs, the ratio of red to NIR reflectance, the normalized difference of red and NIR reflectance, and the sum of the red and NIR reflectance for cotton (Gossypium hirsutum L.), soybeans (Glycine max L.), sunflower (Helianthus annus L.), and grain sorghum (Sorghum bicolor L.). The normalized difference and greenness ratios were better predictors of biomass during the vegetative growth phase, while the red-NIR ratio was a better predictor during the maturation phase. Coefficients of determination for a power function ($y = a\,x^b$) were generally higher than for a linear function. Kleman and Fagerlund's (1987) data indicate that the NIR/red ratio was related to fresh spring barley (Hordeum distichum L.) biomass by a sigmoidal function. They indicated that the function shifts with time and information on growth stage is needed. Walburg et al. (1982) presented tabular data relating NIR/red ratios to biomass at several growth stages. There were no clear trends indicating whether a linear or exponential function was preferred when relating the two variables. Thomas and Oerther (1972) related the inverse of reflectance measurements at 530 nm and 675 nm to the inverse of leaf nitrogen content of sweet pepper (Capsicum annum L.). Blackmer et al. (1994) measured leaf reflectance from 400 to 700 nm of four corn hybrids at four nitrogen rates. Two of the four hybrids clearly exhibited an exponential or power relationship between N application rate and radiance. In a later study, Blackmer et al. (1996) refined the selection of wavelengths to 550 and 710 nm. Their studies were done comparing nonlimited N reference plots to plots with limited N availability. Results were expressed as relative reflectance between the two plots. Strong relationships between N application rates on the limited plots and spectral indices were found over two seasons. They suggested that an in field reference could be used with inexpensive sensors to implement an sVRT system.

Dusek et al. (1985) examined vegetative indices composed of visible, NIR, and Mid IR bands. They found that VIs including a mid IR band were much more effective than NIR/Red reflectance or NDVI in predicting mass of vegetative matter in winter wheat. They also found ratios including 3 to 5 bands more accurately predicted mass of vegetative matter than simpler ratios.

Stone et al. (1995) demonstrated that with top dress applied N in winter wheat, variable rate treated plots based on a spectral index, resulted in a total N savings between 32 and 57 kg N ha^{-1} compared to the fixed topdress N rates. Their results were based on a spectral index using red (671±6 nm) and NIR (780±6 nm) wavelengths. They found good correlation between vegetative N mass per unit area and the spectral index.

Numerous researchers have found increased fertilizer N use efficiency in winter wheat when N was applied at lower rates (Campbell et al., 1993; Welch et al., 1966; and Olson and Swallow, 1984). The implementation of variable rate technology should capitalize on this work by reducing the total field N rate, while also having the potential to optimize N use efficiency at a much finer resolution (defined area for which N rates can be adjusted on-the-go, but potentially the agronomic optimum area). Considering that spring applied N has resulted in increased N use efficiency when compared to fall applied N in winter wheat (Welch et al., 1966; Olson and Swallow, 1984), sensor based variable rate technology will likely be increasingly beneficial when using spring plant N as an indicator variable.

Plant canopy architecture has been shown to have a significant effect on canopy reflectance. Moran et al. (1989) found that alfalfa has a more erectophile (vertical) leaf architecture when under water stress. The plants also tended to have a lower NIR reflectance when under stress which tended to support the evidence found in modeling winter wheat (Jackson and Pinter, 1986.)

Variable cloud cover and solar angle have been examined to determine the effect on vegetative indices. Pinter et al. (1987) found that cloud cover had a minimal effect on the vegetative indices, NIR/Red and NDVI. Where individual reflectances in the NIR and red bands were effected, reflectances in both bands were similarly effected. Pinter (1993) also investigated the effects of sun angle on vegetative indices and found sun angle had a strong affect. NDVI was computed from NIR and Red measurements observed with a nadir orientation under various sun angles. NDVI for new regrowth alfalfa cover changed from .42 to .7 over a sun angle change between 27^{o} to 72^{o}.

A foundation exists in the literature for the use of an optical based sensor which can determine a spectral index and use that information to determine nitrogen fertility levels. Fertilization can then be directly controlled using the sensor information. In particular, the following studies reported above form the basis of that foundation:

- Wood et al. (1992) found high correlation between field chlorophyll measurements and tissue N concentration.
- Several researchers have found good correlation between tissue biomass and spectral indices. (Wanjura and Hatfield, 1987; Kleman and Fagerlund, 1987; Dusek et al., 1985)
- Roth et al. (1989) noted that whole-plant total N (between Feekes 3 and 6) could be used to predict N fertilizer requirements in winter wheat.
- Sensor based VRT strategies have been demonstrated in the field. (Blackmer et al., 1994; Stone et al., 1995, Blackmer et al., 1996)
- Plant canopy architecture and solar angle have been found to have significant influences on spectral indices though cloud cover appears not to be significant. (Moran et al., 1989; Pinter et al., 1987)

OSU SENSOR DESIGN

We undertook development of optical based sensors for detection of N availability in winter wheat at OSU in fall 1994. The sensor technology used was based on earlier work with weed detection. The earliest weed detection sensors incorporated photodiode sensing elements, fixed gain amplifiers, and a multiplexed 8 bit A/D converter connected to an embedded computer. A simple aperture was used to control the view of the photodiodes. A vehicle area network was incorporated into the electronic control unit (ECU) serving the sensor to allow the ECU to gather ground speed information and if necessary solar irradiation information. The original weed detection sensor used NIR specific photodiodes to collect NIR radiance, and visible sensitive photodiodes with filters to detect red and green wavelengths. broadband colored glass filters were used to select green and red wavelengths. The original weed detection sensor had inadequate radiance resolution and though the broadband filters appeared to work adequately their performance was difficult to characterize and repeat in later designs. In addition, there was a large inherent variation in the photodiode and amplifier components in the original sensor and considerable effort was required to tune each new sensor to repeat the previous sensor.

A modified sensor was constructed for use in nitrogen detection and for further weed detection studies in early 1995. The general physical schematic is shown in Figure 1.

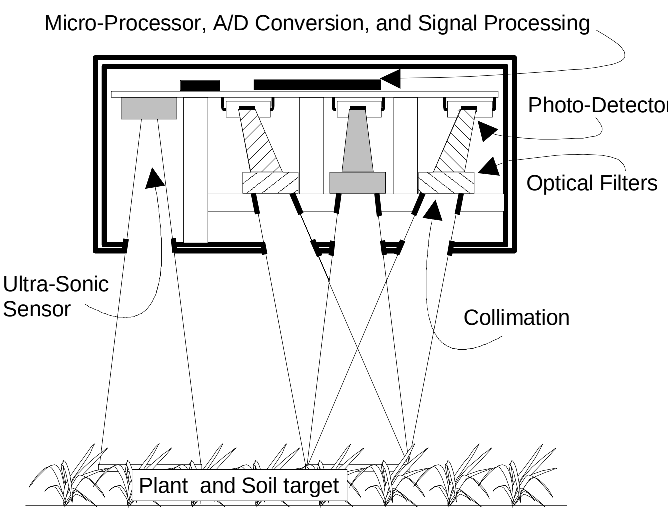

Figure 1. Schematic of the current OSU optical sensor.

Several changes were made based on the earlier experience. A micro-processor controlled variable gain amplifier with 256 gain levels was incorporated to give the sensor better resolution at low light levels and greater dynamic range. Integrated photodiode/amplifiers were included. These devices have smaller inherent variability from part to part and feature amplifiers that are well matched to the photodiodes. The silicon integrated circuit was used for green, red, and NIR bands. Interference filters were substituted for the original uncharacterized glass filters. This allowed use of the same filter arrangement for all three optical bands. The cost of the interference filters may be too high for production instruments but were used here because they are well characterized. The interference filters were chosen at wavelengths of 550±6 nm (green), 671±6 nm (red) and 780±6 nm (NIR). Figure 2 shows reflectance in the visible and NIR bands in both wheat and an average for 10 soils from across Oklahoma. The NIR reflectance rises in the 780 nm band and falls in the 670 nm band for increasing N availability. Weaker response has been found in the 550 nm band. The collimated view of the soil and plant surface was set at 0.46 m wide by 0.075 m long (along the direction of travel).

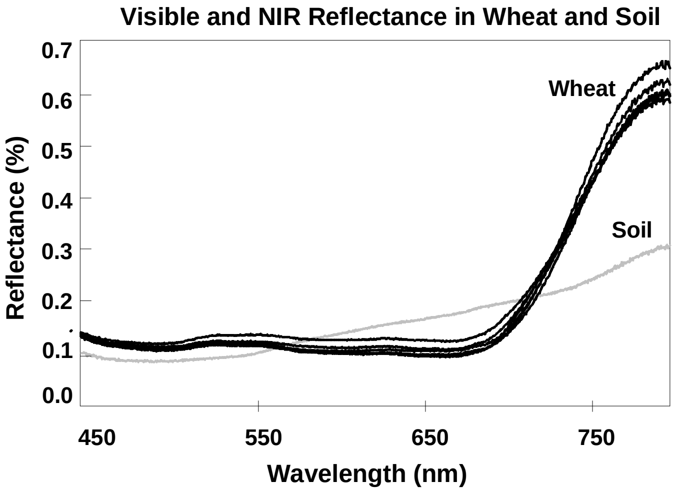

Figure 2. Reflectance in Oklahoma wheat and soil samples

The sensor described above was used in early 1995, and several further changes were made for the 1996 season. The variable gain element in the amplifier had large variability from sensor to sensor. Three high resolution A/D converters were substituted for the variable gain device and original A/D with one A/D converter and amplifier for each optical channel. The sensor was incorporated into the sensor ECU housing and the power supply for the analog portion of the sensor was isolated from the computer. The collimated view was increased to 0.75 m wide by 0.25 m long. The width was increased to match the sensor with nozzles suitable for fertilizer. The 0.25 m length along the direction of travel allowed sampling to a finer resolution than that expected to be necessary based on the work by Solie et al. (1995).

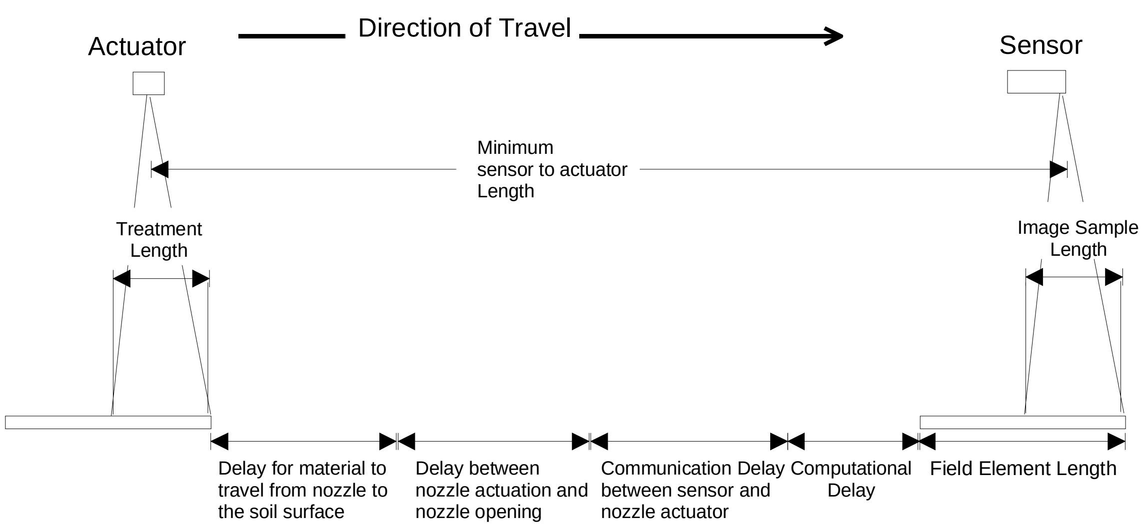

Figure 3. Factors affecting sensor to actuator distance

Dynamic response of the sensor was an issue with earlier sensor versions. A 15 km/hr speed, or slightly more than 4 m/s, is currently not unusual for fertilizer applicators. At that speed, and a view of 0.1 m length along the direction of travel, the digitization is 41 Hz for non-overlapping images. The amplifier and sensor element combination should have at least twice the bandwidth of the sampling rate, making a 100 Hz bandwidth suitable. With the very large gains associated with photodiode amplification, it becomes critical to carefully optimize the photodiode/amplifier design. In addition, variability of components and temperature compensation become issues when amplifier designs are close to maximum design limits. The current integrated photodiode/amplifier ICs avoid this problem and provide bandwidths greater than 1 kHz.

Simultaneous acquisition of each of the spectral inputs is important in the sensor design. Each detector is arranged to view the same soil and plant surface. Acquisition of each spectral input at the same time allows the same view to be captured by each photodiode. Rations of the bands are used to compute spectral indices making coincident views necessary. A compromise in hardware design results in sequential acquisition with a time skew of approximately 0.1 ms which corresponds to an error of approximately 0.5 mm at 15 km/hr. This issue prevents the use of ICs which incorporate voltage to frequency conversion. At low light levels, the frequency is low and effective conversion time is too long.

Operation of the sensor at other than the required sensor to target (plant/soil surface) distance results in views that are not perfectly overlapping. The sensor current is “focused” at a design sensor to target distance of 1 meter. Variation in the actual distance is currently ignored. A 10 cm variation in sensor to target distance causes approximately 1 cm of error along the 25 cm axis. Control of boom height in commercial systems implementing this technology will be necessary.

An ultrasonic height measuring transducer was tested with the sensor. We expected that as wheat biomass increased per unit area and the crop became taller, that more of the crop would be obscured from view by the sensor. Testing has not proved that ultrasonic height measurement improves biomass or nitrogen sensing significantly. Wheat during the growth stages of interest for topdressing nitrogen is relatively planophile. Measurements during later stages of growth (before jointing) continued to show a strong relationship between NDVI and N mass. The architecture of the plant may organize itself to more efficiently absorb red wavelengths and avoid obscuring leaves from the sun.

Sensor to actuator distance is an important factor affecting sensor design as well as technical feasibility of the sVRT concept. Figure 3 illustrates the lengths associated with critical timing components of sVRT design. Lengths shown in the diagram are associated with times required for each factor. From right to left, the field element must be completely measured before computation to determine action by the actuator is done. Some computational delay after the field element is sensed will occur. This delay may be distributed to an actuator computer but will exist in the system.

Computational delay in the OSU design is distributed between sensor and actuator and the total delay is 10 ms. Some significant delay may be associated with communication of information from sensor to actuator. For the SAE J1939 network used on the OSU sprayer this time is on the order of 0.5 ms. Once the actuator has received the information, there is some delay while the actuator is changing state. In the OSU sprayer, this action is opening or closing of a nozzle (liquid UAN is being used). Nozzle opening or closing time is on the order of 20 to 50 ms for the OSU sprayer. Finally, time is required for fertilizer to reach the target after it is dispensed. In the OSU sprayer this time is between 200 and 400 ms. The maximum total delay in the OSU system can be nearly 0.5 sec, meaning that at 15 km/hr, the minimum sensor to actuator distance should be at least 2 m. The current OSU design employs a SAE J1939 based network to communicate between sensors and actuators, and two booms, a front boom for sensors and a rear boom for actuators and nozzles. The sensor to actuator distance is primarily controlled by drop flight time which can be significantly be improved by lowering the spray boom and by employing an alternative nozzle system. The possibility exists that a single boom design could be developed.

SENSOR PERFORMANCE

Figure 4 presents correlations between N uptake and NDVI for the 1996 season in Oklahoma. The NDVI values are based on unscaled radiance measurements rather than reflectance. The 1996 growing season has been characterized by drought and large variations in biomass existed. In addition, freeze damage and other potential factors related to drought may have caused error in the data. Reasonable correlations were still obtained between N uptake and NDVI. Slopes of the correlations were similar except for the January data. We speculate that the slope difference is due to the earlier growth stage in the January data. This effect also occurs in the data taken one year earlier. The data taken after January show considerable variation in intercept. The variation does not appear to be a soil background effect as some of the data are from the same location. Time of day did vary for sampling but was kept between 10 AM and 3 PM. During the period the data were taken, sun angle increases dramatically at the same time of day and may have some effect. The data taken in April shows significantly higher NDVI values as well as N uptake. This increase is expected based on other measurements in the literature.

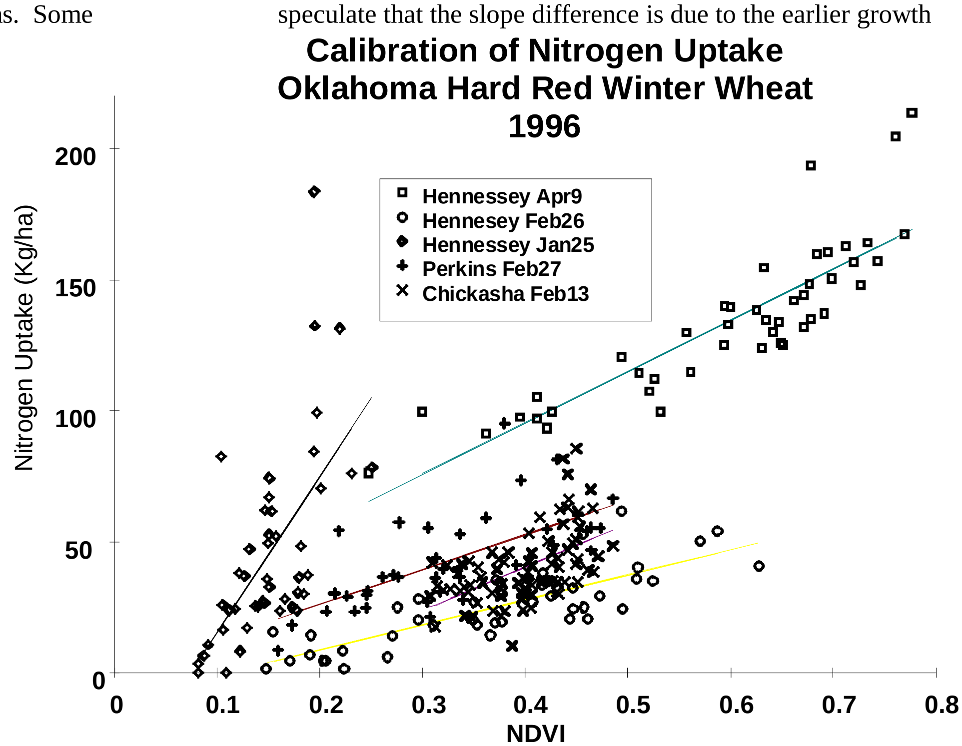

Figure 4. Calibration of NDVI to Nitrogen uptake in 1996 Oklahoma Wheat.

One of the reasons that biomass is correlated to spectral indices is because chlorophyll acts as a strong absorber of red light and greater biomass concentrations within a view results in greater amounts of chlorophyll absorption. With the same argument, though, increasing nitrogen content causes increased chlorophyll as shown by Wood above. Total chlorophyll mass in vegetative material is the product of chlorophyll concentration and vegetative mass. It is reasonable to expect then that spectral absorption in red wavelengths should be proportional to the product of tissue nitrogen concentration and vegetative mass. A wheat plant with greater nitrogen availability (assuming other factors are not limiting and yield potential has not been reached) will produce greater biomass. The expectation based on these arguments is that as wheat plants have increasing nitrogen availability, red absorption should increase more than linearly with nitrogen uptake. This would be reflected in flattening of the upper end of the curves in Figure 3. Many other factors effect the relationship between NDVI and nitrogen uptake and an effective non-empirical model of the system is not available.

SUMMARY

Design of a sensor for an sVRT system to place topdress fertilizer on winter wheat was presented. A continuing effort has been undertaken at OSU to refine the sensor and fertilizer application strategy based on use of sensors to determine nitrogen uptake and hence nitrogen availability to the plant. The current sensor technology can be used to detect nitrogen uptake in the wheat plant under the adverse conditions existing for the 1996 crop in Oklahoma. Research and innovation is needed to develop techniques to eliminate interfering signals and optimize the detection of nitrogen uptake. The interference of solar angle must be evaluated. The current sensing with inherent problems can be used with site specific calibrations to apply topdress nitrogen to winter wheat.

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