2012

SENSING DEVELOPMENT OF A SOYBEAN CANOPY UNDER P OR K NUTRITIONAL STRESS

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SENSING DEVELOPMENT OF A SOYBEAN CANOPY UNDER P OR K NUTRITIONAL STRESS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Agriculture
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By

Martin M. Navarro

Director: Dr. John H. Grove, Professor

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ABSTRACT OF THESIS

SENSING DEVELOPMENT OF A SOYBEAN CANOPY UNDER P OR K NUTRITIONAL STRESS

The normalized difference vegetative index (NDVI) has been correlated with physiological plant parameters and used to evaluate plant growth. There is little information about the use of this technique to detect soybean nutrient deficiencies. The objective of this work was to determine the ability of the NDVI sensor to detect P and K deficiencies, and grain yield reduction, in soybean. During 2010 and 2011, NDVI measurements were made on a soybean field trial site known to exhibit yield responses to both P and K nutrition. Four replicates of 8 levels each of P and K nutrition were evaluated. The NDVI measurements were made with an active proximal sensor held parallel to the soil surface every seven days after V2, and until R2. At each measurement a mean NDVI value was found for each plot. Phosphorus deficiency was detected with the first NDVI measurement. Potassium deficiency was first detected just after V4. Differences in NDVI values due to P or K nutrition increased with continued crop development. There were significant R1 leaf composition and grain yield responses to improved P or K nutrition. The active proximal sensor was able to detect soybean growth differences due to P or K deficiencies in soybean.

Keywords: NDVI, soybean, phosphorus, potassium, proximal sensing

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July 10, 2012

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CHAPTER ONE

Introduction

Soybean (*Glycine max* (L.) Merr.) is a species of legume native to East Asia, widely grown for its edible bean, which has numerous uses. Soybean is considered by many agencies to be a source of complete protein. A complete protein is one that contains significant amounts of all the essential amino acids that must be provided to the human body because of the body's inability to synthesize them. Approximately 85 % of the world's soybean crop is processed into meal and vegetable oil (USDA).

The United States (US), Brazil, Argentina, China and India are the world's largest soybean producers, together representing more than 90 % of global production. The US produced more than 90 million tons of soybean in 2011, of which more than one-third was exported. Soybean is second only to corn (*Zea mays* L.) in US agricultural export value. The average worldwide soybean yield, in 2010, was 2.5 tons per hectare (USDA).

Total nutrient uptake by soybean depends on the yield obtained, which will vary with season, cultivar, soil, and cultural practices. Soybean takes up relatively small amounts of nutrients early in the season, but with further growth the daily rate of nutrient uptake increases. Soybean needs an adequate supply of nutrients at each developmental stage for optimum growth. High-yielding soybean removes substantial nutrients from the soil, and this should be taken into account in an overall nutrient management plan. Soybean contains a larger amount of potassium (K), and about the same amount of phosphorus (P), in the grain as does wheat, corn, or grain sorghum and thus removes more K.

Phosphorus fertilizer recommendations are based on soil tests. Consistent responses to direct P fertilization generally have been restricted to soils testing very low or low in available P. With medium testing soils, responses have been erratic and are normally quite small. As with P, a soil test is the best index of K needs. Soils testing very low or low should be fertilized with K. Yield increases from K are comparable to those with P at very low and low soil test levels.

Phosphates are a major contributor to lake and stream pollution, and high water P concentrations cause over-production of algae and water weeds. Improper or excessive use of P or nitrogen (N) fertilizer can lead to pollution of ground or surface water. The precise contribution of agriculture to eutrophication of surface water and contamination of groundwater is difficult to quantify. Isermann (1990) calculated that European agriculture is responsible for 60 % of the total riverine flux of N to the North Sea, and 25 % of the total P loading.

One component of a comprehensive nutrient management plan is determining proper fertilizer application rates. The goal is to limit fertilizer to an amount necessary to achieve a realistic yield goal for the crop. Yearly soil sampling may be necessary for determining plant nutrient needs and to make accurate fertilizer recommendations. However, more information than soil analysis should be used to determine and describe the spatial variation in P and K soil levels across a field. A complete system is needed to increase fertilizer use efficiency and minimize environmental damage. Components of this system often include farming practices that are not strictly related to fertilizer management; such as conservation tillage, utilization of yield maps and remote sensing tools, and creation of buffer strips close to surface water.

The results of this experiment will be important to a better understanding of soybean P and K nutrition management. Furthermore, the results of this experiment will help researchers and farmers improve P and K fertilization recommendations for soybean, thus improving profit potential and minimizing environmental risk due to excessive P application.

Literature Review

Soybean is one of the major crops grown in the United States (US) and the world. The US is the largest world soybean producer, followed by Brazil and Argentina. Soybean production in the US increased from 57 million tons in 1985 to 91 million tons in 2010. Soybean is the main world source of vegetable protein. Soybean protein meal consumption represents 69 % (176 million tons) of total world vegetable protein meal consumption (USDA). Soybean oil represents 29 % (42 million tons) of total world vegetable oil consumption.

Fertilizer consumption in the US has reached a plateau (Figure 1.1). There was an important consumption increase between 1960 and 1980, but after 1980 fertilizer consumption has been nearly constant with little year-to-year variation. However, fertilizer prices have increased greatly during the last 5 years (Figure 1.2). Fertilizer price volatility affects the profitability of corn, soybean and small grains, where fertilizer accounts for a relatively large proportion of production costs. The prices of raw fertilizer input materials contributed to the surge in fertilizer prices. Prices of phosphate rock, sulfur, and ammonia, raw input materials used to produce diammonium phosphate and other fertilizers, increased sharply after January 2005. Rising energy prices have also increased the cost of producing and delivering fertilizers. Higher fertilizer prices may encourage the cultivation of more soybean (the crop has a lower fertilizer requirement) and result in less acreage planted to corn, wheat, and other feed grains. This situation encourages the use of new technologies to improve nutrient use efficiency; increasing the benefit of each unit of nutrient applied to the crop.

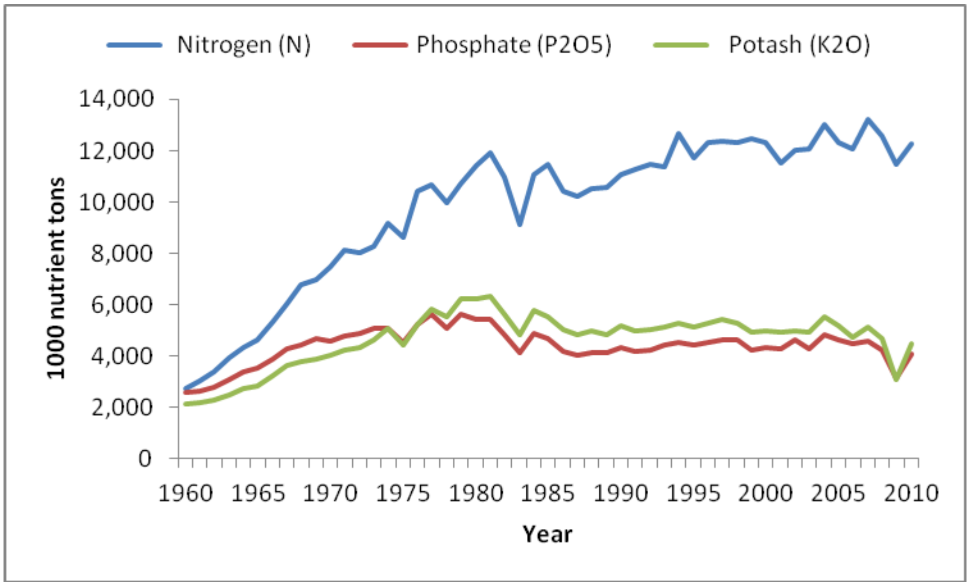

Figure 1.1: *Fertilizer consumption in the US (USDA).*

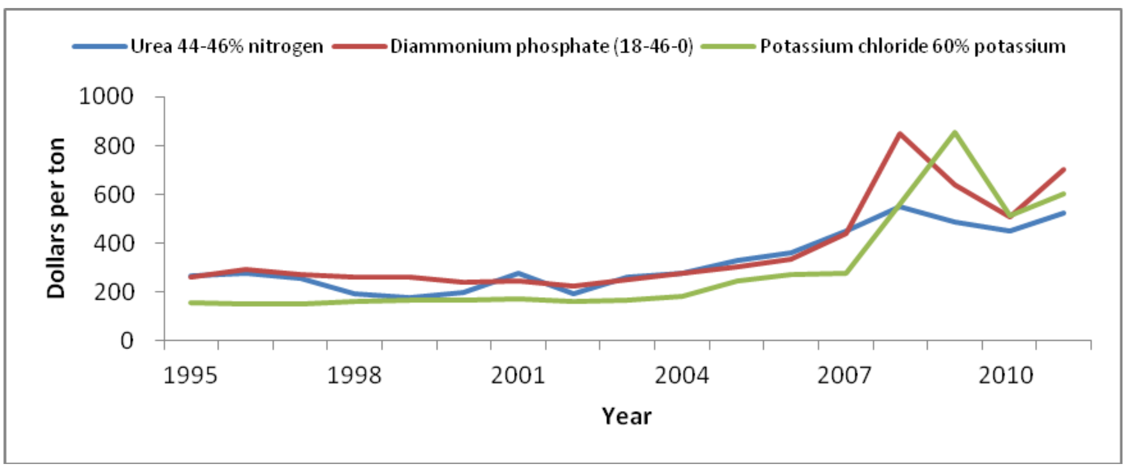

Figure 1.2: *Evolution of fertilizer prices in the US (USDA).*

Among environmental constraints, nutrient availability can be critically limiting to plant productivity (O'Hara et al., 1988). Phosphorus and K are two important soybean nutrients. Phosphorus is one of the major nutrient factors affecting plant growth and productivity. Phosphorus is involved in storing and transferring the energy produced by photosynthesis, for use in plant growth and development. The consequences of soybean P deficiency include a decline in tissue N concentration due to a reduction in N-metabolism activity and a resulting reduction in plant dry weight (Gunawardena et al., 1992). Although biological N fixation (BNF) by soybean can provide significant N nutrition, potential BNF depends, in part, on soil P supply (Rotaru, 2009). Legumes appear to be especially vulnerable to P and Fe deficiencies because of the special needs for these elements to support symbiotic N fixation.

Relatively large amounts of P are needed for soybean growth and development. Total P accumulation by soybean follows a pattern very similar to that of dry matter, with slow accumulation during early vegetative growth stages, and an almost constant, but more rapid, P accumulation at later vegetative and early to mid-reproductive stages. After about growth stage R5, P is rapidly lost from the leaves, petioles, stems and pods and repartitioned into the developing soybean seed. Approximately half of the P in mature seeds comes from these other plant tissues. At harvest, approximately 65 to 75 % of total soybean P is in the mature seed (Hanway, 1971).

Uptake of P may be reduced in cool, wet soils. Soybean P deficiency symptoms are not always clear. Leaves may turn dark green or bluish green, and the leaf blade may curl up and appear pointed. Phosphorus deficiency can delay blooming and maturity.

Critical soil test P (STP) concentrations indicate values above which P fertilization no longer results in an economic yield response. Reported critical concentration values/ranges vary with the soil-test method, soil sampling depth, year (season) region, and also with the model fit to the yield versus STP relationship (Dahnke and Olson, 1990; Mallarino and Blackmer, 1992). In eastern regions of the USA, research

(Beegle and Oravec, 1990) found critical Mehlich III concentrations for corn and soybean ranging from 18 to 41 mg P kg^{-1}, depending on the model used.

Soils commonly contain more than 20 g total K kg^{-1} (Liebhardt, 1977). Nearly all of this K is a structural component of soil minerals and is unavailable to plants. Plants can only use the exchangeable K found on the surfaces of soil particles and the K dissolved in the soil solution. Changes in soil test K levels are dependent on soil cation exchange capacity (CEC). Soil test K (STK) changes more slowly in high CEC soils than in low CEC soils. Soil test levels can vary with time of year (Liebhardt, 1977). Higher STK levels tend to occur in spring, as compared to fall.

The K accumulation by soybean follows a pattern very similar to that of dry matter, with slow accumulation at early vegetative growth stages, and an almost constant, more rapid, K accumulation at later vegetative and early to mid reproductive stages. After about growth stage R5 (beginning seed) (Fehr and Caviness, 1977), K is rapidly lost from the leaves, petioles, and stems and repartitioned into the developing beans. Approximately half of the K in mature seeds comes from these other plant fractions. At harvest, approximately 56 % of the total K in the plant is in the mature seed (Hanway, 1971). So, the K removal by soybean is important, and can cause a continued decline in soil K content.

The exact function of K in plant growth has not been clearly defined. Potassium is associated with movement of water, nutrients, and carbohydrates in plant tissue. If K is deficient or not supplied in adequate amounts, growth is stunted and yields are reduced. Various research efforts have shown that K stimulates early growth, increases protein production, improves the efficiency of water use and raises resistance to disease and insect pressure (Yin, 2004). These roles or functions are general; but all are important to profitable crop production. Potassium deficient soybeans exhibit yellow leaves, beginning at the margins and moving inward over the leaf. Deficiency symptoms occur first on older lower leaves. In severe cases, all but the newest emerged leaves may show K deficiency symptoms.

Soil tests are widely used to determine if the soil nutrient supply will be enough for the crop to reach maximum yield. Chemical solutions that mimic root and soil processes influencing nutrient availability are added to soil samples. The chosen nutrient extracting solution should simulate the natural processes found in different types of soils. Some extractants and methods are better suited for particular soils and the lab results must be correlated with local field research (Sparks, 1996). To have meaning, soil test levels must be correlated with yield response (Black, 2000). Correlation data are collected from many study sites and years. At a particular site and year (site-year), initial soil test levels and yield responses to incremental rates of applied P and/or K are recorded. Most soil tests for K are based on ammonium acetate, or a similar chemical, extraction (Mellich, 1984). This provides an estimate of the potential of a soil to supply plant-available K and is the basis for fertilizer K recommendations, also based on individual crop requirements. Soils in western states and provinces (Canada) generally have higher plant available K levels than those in the eastern part of North America. The higher K levels in the west reflect the less-weathered status of most soils in the region (Potash & Phosphate Institute, 2005).

Tissue analysis can show the nutrient status of plants at the time of sampling. Plant tissue analysis can detect unseen deficiencies and confirm visual deficiency symptoms. Toxic levels of many elements may also be detected. The most important use of plant analysis is as a monitoring tool for determining the adequacy of current fertilization practices. Sampling a crop periodically during the season, at least once each year, provides a record that can be used through the growing season or from year to year. With soil test information and a plant analysis report, a producer can more closely tailor field fertilization practices to specific soil-plant needs. It may also be possible to prevent nutrient stress in a crop if plant analysis indicates a potential problem developing early in the season. Combined with data from a soil analysis, a tissue analysis is an important tool in determining the nutrient requirements of a crop.

Soil testing and plant tissue analysis are similar in that they both measure nutrients necessary for plant growth. Soil tests are most useful before planting to predict lime and fertilizer needs; tissue tests are best used during the growing season to monitor plant nutrient uptake. When growth problems occur, both tests are necessary to provide a complete diagnosis of a crop's nutritional status and the best corrective action. Soil tests measure levels of specific nutrients in a soil. They cannot indicate whether plants growing in that soil are able to take up the nutrients.

Plant tissue analysis indicates whether adequate concentrations of essential plant nutrients are present at the time of sampling. Alone, plant analysis does not provide enough information to explain why nutrient levels may be high or low. In combination, however, soil test and plant analysis results often reveal the reason.

Remotely sensed data have been used to study, monitor and provide a better understanding of crop conditions. The Normalized Difference Vegetation index (NDVI) has been used to monitor biomass production, crop nutritional condition, and forecast crop yield. The NDVI is an indirect measurement of photosynthetic activity and ranges between -1 (low) and +1 (high) (Onema et. al., 2009). The NDVI is based on the differential reflection of radiation by green vegetation (Figure 1.3) in two spectral wavebands, red (RED; 0.58-0.60 μm) and near-infrared (NIR; 0.725-1.1 μm) (Mkhabela et. al., 2011).

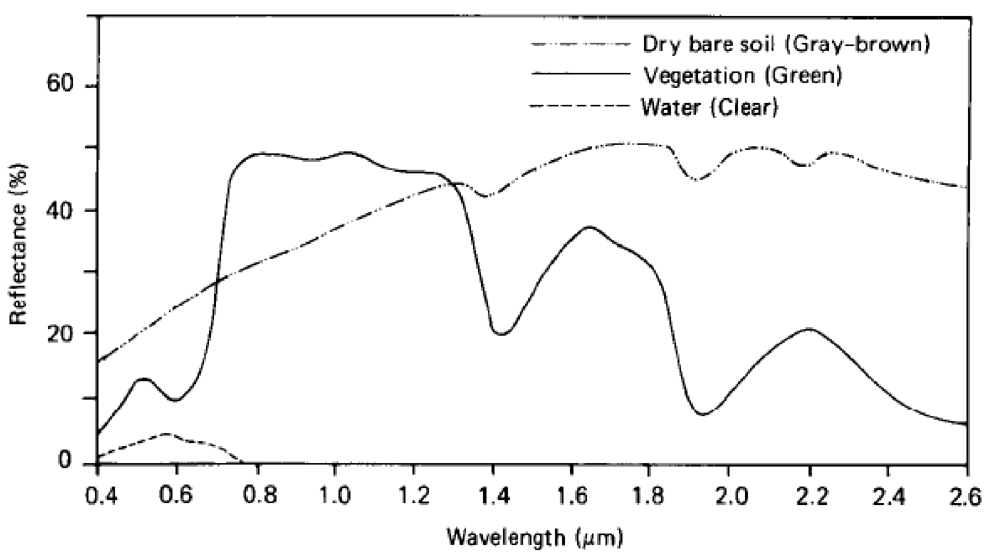

Figure 1.3: *Typical reflectance for vegetation, soil and water (Lillesand and Kiefer, 1994).*

Vegetative surfaces are characterized by high absorption of RED radiation and low absorption of NIR. Chlorophyll reflectance is about 20 % in the RED and 60 % in the NIR, and the contrast between the crop's reflectance responses to both bands allows the quantification of the energy absorbed by chlorophyll, providing levels indicative of different vegetation surfaces (Tucker and Sellers, 1986). The NDVI is defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

With tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort), NDVI was positively correlated ($r^2 = 0.68$) with biomass, also determined by destructive harvesting (Flynn, 2008). Seed yield is positively correlated with biomass accumulation, both below- and above-ground. Huang et al. (2009) measured the correlation between soybean biomass and yield. The peak correlation occurred at seed-filling (growth stage R5-R6) with a correlation coefficient of 0.76 ($P < 0.01$) for below-ground biomass and 0.79 ($P < 0.01$) for above-ground biomass. On the Canadian Prairies, Mkhabela (2011) evaluated the possibility of using NDVI measurements during the growing season to forecast crop yield. The model functions developed for each crop accounted for 48 to 90 %, 32 to 82 %, 53 to 89 % and 47 to 80 % of the grain yield variability for barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), field peas (*Pisum sativum* L.) and spring wheat (*Triticum aestivum* L.), respectively. Mkhabela (2011) found that the cumulative average NDVI explained 61, 68 and 51 % of the maize yield variation in the Swaziland regions of Middleveld, Lowveld and Lubombo Plateau, respectively.

The NDVI is often used to detect nitrogen deficiencies in corn and wheat. Teal (2006), working with maize, found a poor exponential relationship between NDVI measured at the V6–V7 growth stage and grain yield. By V8, a strong relationship (R^2=0.77) between NDVI and grain yield was observed. Freeman et al. (2007) found that using an index of NDVI by plant height provided the highest correlation with plant-by-plant forage yield, on an area basis. Martin et al. (2006) reported that maize NDVI increased until a plateau was attained at V10, and then decreased after the VT growth stage. They stated that the highest correlation of NDVI with corn grain yield was found at the V7 to V9 growth stages. In 1996, Stone and colleagues investigated the use of hand-held sensors to detect and predict forage N uptake and grain yield in winter wheat (Stone et al., 1996). These sensors measured RED and NIR reflectance from the crop, which was used to calculate NDVI. They found NDVI was highly correlated with wheat forage N uptake and grain yield. Katsvairo et al. (2003) studied how biomass, tissue N concentration, and N uptake might be used to facilitate variable N rate management. They found that these factors had no spatial structure to their variability at the V6, R1, and R6 growth stages. However, they did find that plant height exhibited significant spatial variability, but did not consistently correlate with corn yield in a dry year. They recognized that more research should be conducted on plant height measurements.

Soybean yield is dependent on light interception, radiation use efficiency, partitioning of assimilates and the length of seed filling period. Plant density directly affects light interception, limiting production when falling below a critical level. Increments in seed yield of soybean planted in narrow rows or higher densities have been attributed to the development of a full canopy with upwards of 95 % light interception before seed filling (Herbert and Litchfield, 1984). Remote sensing techniques, in particular multispectral reflectance, can provide an instantaneous, nondestructive, and quantitative assessment of the crop’s ability to intercept radiation and an estimate of crop stress and potential yield (Ma et al., 1996). Mandal et al. (2009) studied the effect of NPK fertilizer and organic (manure) additions on biomass production potential and biomass partitioning into different plant parts; grain yield of field-grown soybean; crop growth rates; and leaf area development. Stem, petiole and leaf biomass were significantly greater with NPK and manure treatments, and the relative contribution of these plant parts to total biomass at physiological maturity were 29, 9, and 17 %, respectively. Pod and seed constituted 46 % of plant biomass at physiological maturity. Quadratic regression models best represented the stem, petiole and leaf biomass relation with NPK nutrition. A maximum LAI of 4.88, total biomass of 633 g m^{-2}, and a CGR of 18.4 g m^{-2} d^{-1} were recorded for the NPK and manure treatments. Grain yield increased by 72.5 and 98.5 %, and stover yield by 56.0 and 94.8 % in NPK and NPK + manure treatments, respectively, relative to the control. Normalized difference vegetation index most accurately predicted LAI and light interception (r^2=0.93 to 0.97). Light interception and LAI were linked to NDVI by strong linear regression models, and did not show the quadratic response reported by other authors (Board et al., 2007).

Using different seeding rates, Ma et al. (2001) correlated plant canopy reflectance and aboveground biomass so as to predict soybean yield at early reproductive growth stages. Canopy reflectance was measured with a hand-held multispectral radiometer on three sampling dates (approximately R2, R4, and R5) at two locations. Soybean grain yield was highly positively correlated with canopy reflectance, expressed as NDVI, at all sampling dates. Regression analyses showed a positive relationship between NDVI and grain yield, with R^2 values up to 0.80 ($P < 0.01$) and progressive improvement with measurements from the R2 to the R5 growth stages. However, these measurements were done too late to take corrective action.

Assessing the N nutritional status of cotton (*Gossypium hirsutum* L.) with spectral reflectance has, in many cases, been confined to analysis of individual leaves. Lough and

Varco (2001) used spectral reflectance to assess the N and K status of cotton leaves. They reported that reflectance at 550 nm and a shift in the edge of red reflectance separated N and K fertilizer treatments, respectively. Field reflectance studies, performed to assess the N status in cotton by Bronson et al. (2003), found that simple vegetative ratio indices of NIR to red or green reflectance estimated in-season cotton N status and predicted the need for N fertilization. Bronson et al. (2005) concluded that regressions with NDVI, using either green or red (passive or active) reflectance, related poorly or not at all with leaf N, biomass, or lint yield. However, NDVI reflected the leaf N response or lack of response to added N fertilizer. Partial least squares regression estimated leaf N reasonably well (R^2=0.64) in the 2 years when N fertilizer response was observed. Bronson et al. (2005) concluded that the lack of consistency in the standardized estimates of the partial least square regressions probably limits their usefulness in predicting in-season leaf N.

Precision agriculture offers the promise of increasing yield and quality of agricultural products while minimizing environmental contamination. Variable rate technology (VRT) is an important part of precision agriculture, causing application of production inputs, such as fertilizers or seed, at rates specific to the management zone. Generally, a VRT system contains a fertilizer rate decision sub-system and variable-rate implementation sub-system. Classified according to the fertilizer rate decision method, there are two types of VRT systems; map-based and sensor-based (Ess et al., 2001). The map-based VRT is implemented with a prescription map generated from field grid sampling analysis and/or a field yield map and/or manually setting different rates according to experience (indigenous knowledge), and then utilizing said map to control/drive a variable-rate applicator. Fields with the greatest potential to benefit from variable-rate nutrient application are those with low average yield potential, high spatial variability, positively skewed potential yield distributions, and exhibiting good response to the applied nutrient(s). The NDVI measurements can be used to vary the rate of fertilizer nitrogen in a sensor-based VRT system. Studies with wheat by Stone et al. (1996) and Lukina et al. (2001) showed that NDVI was exponentially related to plant N uptake, regardless of production year, growth stage and variety. Moges (2004) recorded an average savings of just over $34 per ha using variable nitrogen rate technology, reaching the same yield level as that achieved with traditional N application systems.

Chlorophyll meters (SPAD meters) have been successfully used to determine in-season N status, since plant chlorophyll is often highly correlated with leaf N concentration (Wolfe et al., 1988; Schepers et al., 1992). With the chlorophyll meter, researchers developed an N Sufficiency Index [(as-needed treatment/ well-fertilized treatment) * 100] from which recommendations were made for in-season N fertilizer applications when the index values fell below 95 % (Blackmer and Schepers, 1995; Varvel et al., 1997). Varvel et al. (1997) reported that maximum corn grain yields were attained when early season sufficiency indexes ranged between 90 and 100 % up to the V8 growth stage. If the sufficiency index fell below 90 % at V8, maximum yields were not realized due to early season N deficiency. Peterson et al. (1993) indicated that variation in chlorophyll meter measurements can range up to 15 % from plant to plant, requiring a considerable number of measurements in order to determine a representative average for the field at each sampling date. Another drawback of the chlorophyll meter is that these leaf chlorophyll readings are not associated with a measure of plant biomass, as would be done with other remote sensing technologies.

Variable-rate P and K applications are generally based on dense soil sampling in order to derive the maximum possible potential from variable-rate fertilization. Mallarino (2006) conducted strip trials on 11 Iowa fields (six for P and seven for K), and each field was evaluated for one to three cycles in a 2-year corn-soybean rotation. The treatments applied to replicated strips (experimental areas of 10 to 25 acres) within each field were a non-fertilized control, a variable-rate method based on soil tests from samples taken using dense grid soil sampling, and a single-rate method based on the average soil test value for each experimental area. Treatments were replicated three to five times. Strip width was usually 20 to 25 m and the length varied from 250 to 650 m. The results strongly suggested that variable-rate P application could reduce P runoff loss, compared with a uniform application over low-testing and high-testing field areas, and could result in improved water quality. The results of these on-farm trials suggested that the most significant issue to effective use of variable-rate fertilization is the soil sampling method and the fertilization rate recommendation map on which P and K VRT should be based. Maine et al. (2007) studied the corn yield and profitability response to variable-rate application of P in South Africa. Variable rate treatments resulted in higher profits than single rate treatments.

Maleki et al. (2008) designed and implemented a soil sensor-based fertilization system for on-the-go application of P during maize planting. A visible (VIS) and NIR soil sensor with a measurement range of 305-1711 nm was installed at the front of a planter-applicator for on-the-go measurement of soil P. Alternate plots were used for VRT application and for uniform-rate (UR) treatments. The number of plant leaves and grain yield were measured as growth indices influenced by P deficiency. Lower variation in plant leaf number was observed in VRT plots, indicating more uniform P nutrition. Corn yield was significantly higher (336 kg ha^{-1}), and less variable, on VRT plots. Other studies used yield map information to determine variable fertilizer application rates. Norton et al. (2004), working with cotton, reduced P fertilizer use by 27 % with a VRT application technique.

Very little experience has been gained regarding the monitoring of field crop nutrition for elements other than N using remotely sensed data. Preliminary work has shown the effect of several different macronutrient deficiencies on canopy reflectance, but was limited to pot experiments in controlled environments (Ponzoni and Goncalves, 1999). Since P and K are the two most important macronutrients required by plants, after N, the ability to monitor crop nutritional status for these elements through remote sensing would be an important step forward. As was discussed previously, previous research has shown that NDVI measurements were able to detect changes in biomass production and leaf area development. There are several studies explaining the effect of P and K nutrition on biomass and leaf area production. However, there is little work regarding the early detection of soybean P and K deficiencies using NDVI measurement.

Objectives

The objectives of this study were: a) to evaluate the use of NDVI for early detection of P and K deficiencies in soybean; and b) to compare NDVI detection with other nutrient stress indicators, such as soil test P and K levels and leaf P and K concentrations.

CHAPTER TWO

Materials and Methods

The experiment was conducted at the West Kentucky Research and Education Center (picture 2.1), near Princeton, KY (370 N latitude, 87 0 W longitude), located within a long-term corn-soybean soil fertility experiment first begun in 1983.

Figure 2.1: *Soil survey map locating the experiment in Caldwell County, Kentucky (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).*

The soil was an eroded Sadler silt loam (map unit = SaB2), with a 2 to 6 % slope. The parent material was fine-silty non-calcareous loess over loamy residuum weathered from sandstone and/or siltstone. The elevation is around 137 m above sea level; the mean annual precipitation is between 1100 and 1500 millimeters; the mean annual air temperature is between 8.3 and 20.5 degrees C; and the frost-free period is between 191 and 240 days. The soil is moderately well drained, with a depth to restrictive feature (a fragipan) of 0.5 to 1.0 meters and a profile depth of 1.3 to 2.0 meters to lithic bedrock. Permeability is moderate above the fragipan and slow or very slow in the fragipan. The land capability classification (non-irrigated) is 2e (USDA).

Management practices suggested for the Sadler silt loam include minimum tillage or no-till planting, farming on the contour, grassed waterways, and winter cover crops to reduce the risk of soil erosion. Planting later in spring, when the water table has receded, helps to prevent crusting and rutting of the soil surface. Nutrient management practices, such as soil tests, returning crop residue to the soil, and proper timing of fertilizer and other chemical treatments, help to improve soil productivity (USDA).

Soybean was grown without tillage during the two years (2010 and 2011) of the experiment. Before this experiment started the experimental area was under no-tillage, in a corn-soybean rotation. However, during the experiment only soybean was planted. Treatments consisted of four levels of P fertilizer, four levels of K fertilizer and two levels of manure (poultry litter) in a semi-factorial treatment arrangement (Table 2.1). Treatments were hand broadcast to the corn part of the rotation (every other year) since the first corn crop in 1983, so different soil P and K levels existed within the experiment prior to the this study. In 2009, fertilizer P (0, 16.8, 33.6 and 50.4 kg P_2O_5 ha^{-1} as commercial monocalcium phosphate, 0-46-0) and K (0, 33.6, 67.3 and 100.9 kg K_2O ha^{-1} as commercial potassium chloride, 0-0-60) were applied to appropriate plots, and lime (1170 kg dolomite ha^{-1}) was applied to all plots. In 2011, fertilizer P (58.5 kg P_2O_5 ha^{-1} as commercial monoammonium phosphate, 11-52-0) and K (67.7 kg K_2O ha^{-1} as commercial potassium chloride, 0-0-60) were applied in lieu of the usual manure treatment.

Table 2.1: *Experimental treatments.*

Treatment	**Manure**	***Fertilizer P**	***Fertilizer K**
		kg P ha^{-1}	kg K ha^{-1}
1	No	0.0	50.4
2	Yes	0.0	50.4
3	No	8.4	50.4
4	Yes	8.4	50.4
5	No	16.8	50.4
6	Yes	16.8	50.4
7	No	25.2	50.4
8	Yes	25.2	50.4
9	No	25.2	33.6
10	Yes	25.2	33.6
11	No	25.2	16.8
12	Yes	25.2	16.8
13	No	25.2	0.0
14	Yes	25.2	0.0

*Fertilizer P and K applied only to corn – every other year.

Treatments were randomized within each of four blocks. Plot size was 10.6 m by 3.6 m. Soybean (Asgrow 4703 RR) was planted at 500,000 seed ha^{-1}, at a 76 cm row spacing, on 26 May 2010 and 21 May 2011, using a John Deere 1750 no-till planter. Each plot had 4 rows. Weed control was appropriate for the weed species present and consisted of both pre- and post-emergence herbicide applications.

Soil samples were taken before soybean was planted in 2010 and after harvest in 2010 and 2011 by compositing 10 cores per plot. Cores were taken to a depth of 10 cm, except for the final sampling, which was done at 0 to 7.5 and 7.5 to 15 cm. Bioavailable P and K were determined with the Mehlich III extractant (Mehlich, 1984) and both soil solution and buffer pH were determined according to procedures used by the University of Kentucky's Regulatory Services Soil Test Laboratory. Soil carbon and nitrogen were determined by dry combustion using a LECO CN-2000 Carbon Nitrogen Analyzer. Soil carbon was multiplied by 1.72 to give soil organic matter.

Leaf tissue samples consisted of 15 uppermost mature leaves from each plot. Leaf samples were collected at growth stage R1 (Fehr and Caviness, 1977) in 2010 and at V2, V4, V7 and R1 in 2011. Tissues were dried at 60 C and then ground to pass a 0.5 mm screen opening. The tissue P was determined with an automated version of the Fiske and Subbarow (1925) method, after a micro-Kjeldahl wet acid digestion. The tissue K determination was done by atomic emission spectroscopy after combustion in a muffle furnace. Tissue N was determined colorimetrically after a micro-Kjeldahl digestion.

Chlorophyll meter (Minolta SPAD-502) readings were done at R1 in 2010 and every week, between V2 and R1, in 2011. Chlorophyll meter readings are based on the measurement of transmittance of red (650 nm) and infrared (950 nm) radiation that passes through the leaf. Chlorophyll adsorbs red radiation but not infrared radiation. The chlorophyll meter calculates a value on the basis of the transmission of these two wavelengths, a value which is strongly and positively associated with leaf chlorophyll content (Markell et al., 1995).

Canopy NDVI measurements were done every week, between V2 and R1, in both years. A handheld GreenSeeker (N Tech Industries Inc., Ukiah, CA; Patent No. 5389781) proximal active reflectance sensor was used (Figure 2.2). The GreenSeeker is an active sensor that emits light at 660 nm (RED) and 780 nm (near-infrared; NIR) at high frequency. The reflected light is filtered, and the filtered signal is measured.

Figure 2.2: *Handheld GreenSeeker proximal active reflectance sensor.*

Vegetation surfaces are characterized by high absorption of RED radiation and low absorption of NIR. Chlorophyll reflectance is about 20 % in the RED and 60 % in the NIR and the contrast in the reflectance responses in both bands allows quantification of the energy absorbed by chlorophyll, providing levels indicative of different vegetation surfaces (Tucker and Sellers, 1986). The NDVI is defined as:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

The reflectance readings were taken by holding the sensor parallel to the canopy surface, at both 1 m and 1.5 m above the canopy. The sensor was centered over one crop row, and NDVI was always measured on the same row for the duration of the season. The investigator walked the length of the plot, continuously taking NDVI data. A mean NDVI value was found for each plot, for each height, at each sensing date. The GreenSeeker unit uses internal illumination so it can be used in any lighting condition, day or night.

All NDVI data was processed in an IPAQ (Compaq pocket PC) using the NTech Capture© program for Pocket PC™ program. The NTech Capture© is a software program developed to capture readings from the GreenSeeker hand held sensor, display the current reading, and store readings for later data analysis. There are two available data logging modes. The strip logging mode is for collecting readings from large strips. The plot logging mode is for collecting readings from individual plots, in studies with many plots, and is better suited to data analysis. This latter mode was used to collect the NDVI data in these studies. Three files were created when data were saved (at each sampling date); the filename.txt file containing all collected data, the filenameavg.txt file containing only an average NDVI value for each plot, and the filenamediag.txt file containing all sensor diagnostic information (an empty file in this experiment).

Soybean yield was determined by combine harvest of the center two rows from each plot. Harvest grain samples were placed in a dryer at 60 C until no further change in mass occurred and a final weight was then recorded. Grain yields were adjusted to a uniform 13.5 % moisture content. Samples were taken from harvested grain, for each plot. Grain P, K and N concentrations were determined as outlined previously for leaf tissue.

All data was statistically evaluated using appropriate analysis of variance procedures (SAS, 1993). The LSD test was used to separate treatment means. Regression and correlation analysis was applied to estimate the nutritional stress predictive value of different diagnostic methods.

Relative NDVI was calculated using as 100 % the highest result at each growth stage across the 14 treatments, using treatment mean. Relative yield was calculated using as 100 % the highest yield in each year, across the 14 treatments.

Rainfall and Temperature

In the 2010 season, rainfall was considerably lower than normal (Table 2.2), especially during late July, all of August and early September. This stressful period coincided with soybean reproductive stages, which are very sensitive to stress (Jiang and Egli, 1995). As such, there was normal vegetative growth in 2010, until R1, when water stress began. The resulting important yield reduction severally affected all treatments. The average daily temperature was about normal. However, during the water stress period, temperatures were higher than normal, further negatively affecting yield. During 2010 there were 58 days with maximum temperatures higher than 32 degrees C.

In 2011 rainfall was greater than normal (Table 2.3), especially during April and June. Vegetative growth and yield were normal for the 2011 season. The average daily temperature was lower. During 2011 there were 44 days with maximum temperatures higher than 32 degrees C.

Table 2.2: *2010 crop growing season temperatures and rainfall.*

DATE RANGE	Air temperature (C)			Days			Precipitation (mm)	Days		
	Average Max	Average Min	Day Average	Max =>32	Min <=-18	Min <= 0	Total	=>2.54	=>12.7	=>25.4
Mar 27 - Apr 10	22	9	16	0	1	0	64.0	3	1	1
Deviation	0	2.3	2				3.0			
Apr 11 - Apr 25	23	9	17	0	0	0	30.0	4	1	0
Deviation	0.6	0.6	0.6				-31.0			
Apr 26 - May 10	22	12	17	0	0	0	165.1	4	2	2
Deviation	-1.6	0	-1				104.1			
May 11 - May 25	26	16	21	0	0	0	54.6	3	1	1
Deviation	-1	1.3	0.3				-6.4			
May 26 - Jun 9	30	19	24	1	0	0	90.4	8	3	1
Deviation	0.3	1.3	1				36.6			
Jun 10 - Jun 24	32	22	27	9	0	0	76.5	6	3	1
Deviation	1	2.6	1.3				27.7			
Jun 25 - Jul 9	31	20	26	5	0	0	8.6	2	0	0
Deviation	-0.3	-0.6	0.3				-42.7			
Jul 10 - Jul 24	32	22	27	7	0	0	47.2	5	2	0
Deviation	0	2	1				-5.6			
Jul 25 - Aug 8	34	22	28	12	0	0	17.8	2	1	0
Deviation	1.3	2	1.6				-33.0			
Aug 9 - Aug 23	34	22	28	11	0	0	55.1	3	2	1
Deviation	2	2.3	2.3				5.8			
Aug 24 - Sep 7	31	17	24	5	0	0	4.6	2	0	0
Deviation	0.6	0.3	0.3				-41.4			
Sep 8 - Sep 22	30	16	23	6	0	0	23.1	2	1	0
Deviation	1.6	1	1.3				-19.1			
Sep 23 - Oct 7	25	8	17	2	0	0	0.8	1	0	0
Deviation	0	-2.3	-1				-39.4			
Average	**27**	**15**	**21**			**Total**	690.4	**Deviation**	-86.9	

Table 2.3: *2011 crop growing season temperatures and rainfall.*

DATE RANGE	Air temperature (C) Average Max	Average Min	Day Average	Days Max =>32	Min <=-18	Min <= 0	Precipitation (mm) Total	Days =>2.54	=>12.7	=>25.4
Mar 22 - Apr 5	14.4	4.4	9.4	0	0	0	63.8	6	1	1
Deviation	-2.1	0.0	-1.2				3.0			
Apr 6 - Apr 20	22.8	11.7	17.2	0	0	0	128.5	5	4	2
Deviation	0.9	2.4	1.5				67.6			
Apr 21 - May 5	20.0	10.6	15.6	0	0	0	371.9	10	7	5
Deviation	-2.1	0.3	-0.9				310.9			
May 6 - May 20	23.3	13.3	18.3	0	0	0	9.7	4	0	0
Deviation	-1.8	0.3	-0.9				-51.3			
May 21 - Jun 4	28.9	18.3	23.9	5	0	0	47.8	3	2	1
Deviation	0.3	1.5	0.9				-9.9			
Jun 5 - Jun 19	31.1	19.4	25.0	8	0	0	58.2	5	2	1
Deviation	0.3	1.2	0.9				9.4			
Jun 20 - Jul 4	28.9	19.4	24.4	2	0	0	67.3	6	2	0
Deviation	-1.2	0.6	-0.3				17.3			
Jul 5 - Jul 19	31.7	21.7	26.7	6	0	0	27.7	2	1	0
Deviation	0.0	1.5	0.6				-25.1			
Jul 20 - Aug 3	33.9	22.2	28.3	13	0	0	39.4	1	1	1
Deviation	0.9	1.8	1.5				-12.7			
Aug 4 - Aug 18	30.0	20.0	25.0	3	0	0	28.4	5	1	0
Deviation	-0.6	0.9	0.0				-20.8			
Aug 19 - Sep 2	31.7	18.3	25.0	5	0	0	71.9	1	1	1
Deviation	0.9	0.9	0.9				23.6			
Sep 3 - Sep 17	25.6	14.4	20.0	2	0	0	21.8	2	1	0
Deviation	-1.5	-0.6	-0.9				-20.3			
Sep 18 - Oct 2	22.2	12.2	17.2	0	0	0	76.2	7	2	1
Deviation	-2.1	-0.3	-1.2				34.5			
Average	25.8	14.7	20.3			**Total**	**1046.7**	**Deviation**	**284.0**	

CHAPTER THREE

Soil Analysis

There was initial variation in 2010 soil test values due to the treatments (Table 3.1). That variation was related to the history of different fertilizer and manure treatments. The University of Kentucky considers 1 to 2.5 mg kg^{-1} a very low level of soil test P (Mehlich III extraction) for soybean; 3 to13.5 mg kg^{-1} a low level; 14 to 30 mg kg^{-1} a medium level; and a soil test P level greater than 30 mg kg^{-1} a high level (AGR-1, 2010). Based on the pre-2010 season soil test P results (Table 3.1), yield response to improved P nutrition was expected, creating an experimental setting for evaluation of NDVI as a tool for P stress detection.

The initial soil test K also varied significantly (Table 3.1). University of Kentucky fertilizer K recommendations (AGR-1, 2010) consider a very low level of soil test K (Mehlich III extraction) to fall between 0 and 50 mg kg^{-1} , a low level between 50 and 95 mg kg^{-1}, a medium level between 95 and 150 mg kg^{-1} and a high level greater than 150 mg kg^{-1}. Based on the pre-2010 season soil test K results, a significant yield response to better K nutrition was expected.

Treatments with a manure application history exhibited higher soil test P (STP) and soil test K (STK) values (Table 3.1). The higher nutrient supplies in the manure treatments were partially counteracted by higher nutrient removals in earlier crops. One of the biggest impacts of previous manure application was on STP levels. Poultry litter was the manure source. In general, poultry litter has a higher P content, relative to N and K, as compared to other animal manures.

Table 3.1: Soil test results prior to the 2010 growing season.

Treatment			Soil Test								
P rate kg/ha	**K rate kg/ha**	**Manure (Y/N)**	**Mehlich III-P-(g/kg)**	**Mehlich III-K-(g/kg)**	**Organic Matter (g/kg)**	**pH-KCL**	**pH-Buffer**	**Total N-g/kg**	**Zn-(g/kg)**	**Cu-(g/kg)**	**B-(g/kg)**
0	50.4	N	4.9	76	21.1	4.65	6.83	1.23	0.70	0.89	0.50
0	50.4	Y	6.5	77	23.3	5.24	7.00	1.36	1.81	2.54	0.59
8.4	50.4	N	5.8	66	21.3	4.95	6.97	1.22	0.84	1.09	0.54
8.4	50.4	Y	9.4	79	24.2	5.18	6.98	1.40	1.96	2.74	0.49
16.8	50.4	N	9.5	68	25.7	4.98	6.92	1.51	0.96	1.07	0.54
16.8	50.4	Y	16.1	73	26.5	5.15	6.96	1.51	2.55	3.20	0.57
25.2	50.4	N	9.8	60	22.5	4.84	6.92	1.34	0.75	0.86	0.37
25.2	50.4	Y	22.7	71	24.2	4.99	6.93	1.37	2.06	2.86	0.54
25.2	33.6	N	12.4	53	23.5	4.87	6.88	1.37	0.80	0.87	0.37
25.2	33.6	Y	25.1	58	26.8	5.10	6.89	1.54	2.18	2.73	0.55
25.2	16.8	N	14.1	52	22.7	4.69	6.83	1.33	0.75	0.88	0.52
25.2	16.8	Y	20.2	60	22.5	4.97	6.91	1.31	1.80	2.39	0.56
25.2	0	N	16.1	43	21.5	4.87	6.92	1.24	0.80	0.95	0.47
25.2	0	Y	24.3	52	23.4	5.15	7.02	1.38	2.11	2.70	0.57
		LSD (0.10)	7.6	15	3.5	0.32	0.13	0.20	0.45	0.48	0.17

Manure (Y/N)	Mehlich III-P-(g/kg)	Mehlich III-K-(g/kg)	Organic Matter (g/kg)	pH-KCL	pH- Buffer	Total N (g/kg)	Zn (g/kg)	Cu (g/kg)	B (g/kg)
Yes	17.8 a	67 a	24.4 a	5.11 a	6.96 a	1.43 a	2.07 a	2.74 a	0.55 a
No	10.4 b	60 b	22.6 b	4.83 b	6.90 b	1.28 b	0.80 b	0.94 b	0.47 b

Table 3.2: *Soil test results in January, 2012, after the 2011 growing season.*

Treatment			Soil Test						
P rate kg/ha	**K rate kg/ha**	**Manure (Y/N)**	**Mehlich III-P-(g/kg)**	**Mehlich III-K-(g/kg)**	**pH-KCL**	**pH-Buffer**	**Zn (g/kg)**	**Cu (g/kg**	**Mn (g/kg)**
0	50.4	N	4.6	84	4.67	6.77	0.8	1.1	227
0	50.4	Y	6.9	87	4.96	6.88	2.1	3.1	206
8.4	50.4	N	6.5	82	4.89	6.85	1.2	1.4	220
8.4	50.4	Y	9.6	91	4.86	6.81	2.4	2.4	204
16.8	50.4	N	5.5	65	4.76	6.80	0.9	0.9	195
16.8	50.4	Y	11.1	80	4.92	6.83	2.3	2.3	227
25.2	50.4	N	10.6	64	4.60	6.71	0.9	0.9	212
25.2	50.4	Y	21.0	80	4.79	6.79	2.4	2.4	206
25.2	33.6	N	10.7	59	4.70	6.76	0.9	0.9	216
25.2	33.6	Y	21.6	71	4.65	6.73	2.2	2.2	180
25.2	16.8	N	12.2	65	4.53	6.67	0.9	0.9	196
25.2	16.8	Y	19.8	65	4.89	6.83	2.1	2.1	222
25.2	0	N	13.7	52	4.67	6.74	1.0	1.0	222
25.2	0	Y	18.0	61	4.83	6.82	2.1	2.1	195
		LSD (0.05)	6.3	15	0.30	0.12	0.6	0.7	51

Manure (Y/N)	**Mehlich III-P-(g/kg)**	**Mehlich III-K-(g/kg)**	**pH-KCL**	**pH- Buffer**	**Zn (g/kg)**	**Cu (g/kg**	**Mn (g/kg)**
Yes	15.4 a	76 a	4.84 a	6.81 a	2.22 a	2.38 a	205 a
No	9.1 b	67 b	4.69 b	6.75 b	0.94 b	1.00 b	212 a

Manure application increased pH, soil organic matter (SOM), total N, and extractable zinc (Zn), boron (B) and copper (Cu) (Table 3.1). Manure is not only a source of macronutrients like P and K, but also provides micronutrients such as Cu, Zn and B.

Soil samples taken in early 2012 (Table 3.2), after the 2011 harvest, but before 2012 fertilizer and manure applications, also exhibited great variation, similar to what was observed pre-2010. The range in STP was smaller and, on average, STP levels were lower than those observed prior to the 2010 season (Table 3.2). Early 2012 STK levels (Table 3.2) were higher than those in early 2010 (Table 3.1).

Similar to what was observed in early 2010, treatments with a history of manure application exhibited higher levels of STP and STK, with the greater effect on STP in early 2012 (Table 3.2). Manure application also again significantly and positively affected pH, and extractable Zn and Cu (Table 3.2).

In 2010, soybean yields were lower than normal, due to significant water stress after R1. However, there were significant differences in yield due to the treatments (Table 3.3). The 2011 season resulted in higher yields. However, differences between treatments were lower, on a relative basis, than those in 2010. The fertilizer application in 2011 to replace/simulate manure nutrients produced an important yield effect and resulting in more equal yields among more of the treatments.

Treatment 1 (no manure and 0 P fertilizer) resulted in the lowest yield both years. So the effect of P stress was greater than the effect of K stress. Treatment 13 (no manure and 0 K fertilizer) caused the second lowest yield in both years. So, with an important reduction in yield potential due to a water deficit in 2010; and with normal environmental conditions in 2011, nutrient deficiencies significantly affected yields.

Table 3.3: *Average soybean yield for 2010 and 2011.*

P rate kg/ha	K rate kg/ha	Manure (Y/N)*	Treatment N	2010 yield kg/ha	2011 yield kg/ha
0	50.4	N	1	830	1490
0	50.4	Y	2	1210	3100
8.4	50.4	N	3	1240	2360
8.4	50.4	Y	4	1320	2910
16.8	50.4	N	5	1170	2530
16.8	50.4	Y	6	1280	3120
25.2	50.4	N	7	1460	2580
25.2	50.4	Y	8	1430	2760
25.2	33.6	N	9	1300	2520
25.2	33.6	Y	10	1310	2900
25.2	16.8	N	11	1180	2120
25.2	16.8	Y	12	1280	3020
25.2	0	N	13	1100	2060
25.2	0	Y	14	1180	2850
			LSD (0.05)	200	600

*Manure applied at 1 to 1.5 Mg ha^{-1}, every other year (prior to 2009).

Pre plant soil test P was not a good predictor of yield in 2010 (Fig 3.1). Maximum soybean yield was reached with an STP of 17 ppm. This critical P concentration was lower than expected. University of Kentucky recommendations assume a soybean yield response to added P at Mehlich III STP levels up to 30 ppm (AGR-1, 2010). Michigan State University found a critical STP concentration of 15 ppm, similar to the results obtained in this experiment. Similar critical STP concentrations were observed in Ohio and Indiana (Vitosh, 1995).

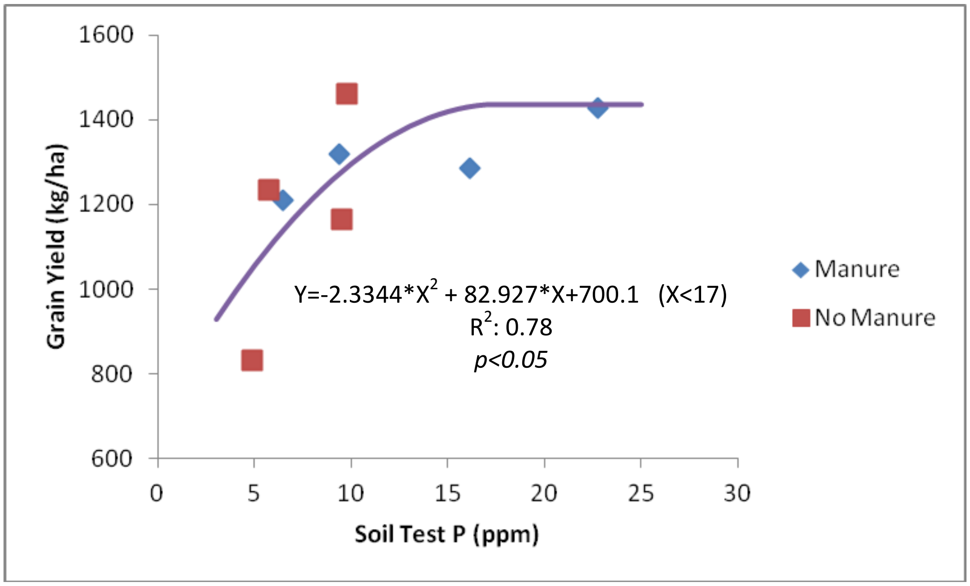

Figure 3.1: *Relationship between pre-plant soil test P and 2010 soybean yield.*

Soybean receiving P fertilizer in 2011 equivalent to a manure P application did not exhibit yield differences (Fig. 3.2). The added P compensated for the different levels of STP prior to the addition. Treatments without manure exhibited a positive relationship between STP and soybean yield, similar to what was observed in 2010.

Pre-plant STK was a very good predictor of yield (Fig 3.3). Maximum yield was reached at STK values around 70 ppm. This critical K concentration was lower than expected. University of Kentucky recommendations (AGR-1, 2010) expect soybean yield response to K fertilization when STK values fall below 150 ppm. Similar critical K concentrations were observed in Indiana, Ohio and Michigan (Vitosh, 1995).

Post-harvest, 2012, soil test K was a good predictor of yield in treatments without a manure history (Fig. 3.4). Treatments that received the K fertilizer equivalent to the K in a manure application (manure treatments) did not exhibit a yield response – the K fertilizer compensated for the different STK levels. There was a general K deficiency across all treatments. All the treatments that received manure exhibited higher grain yield

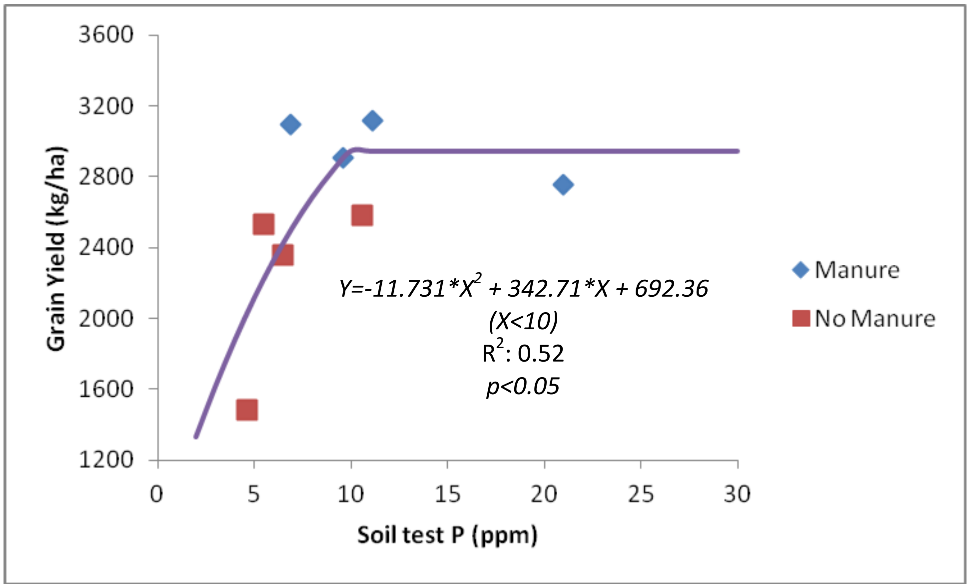

Figure 3.2: *Relationship between post-harvest soil test P and 2011 soybean yield.*

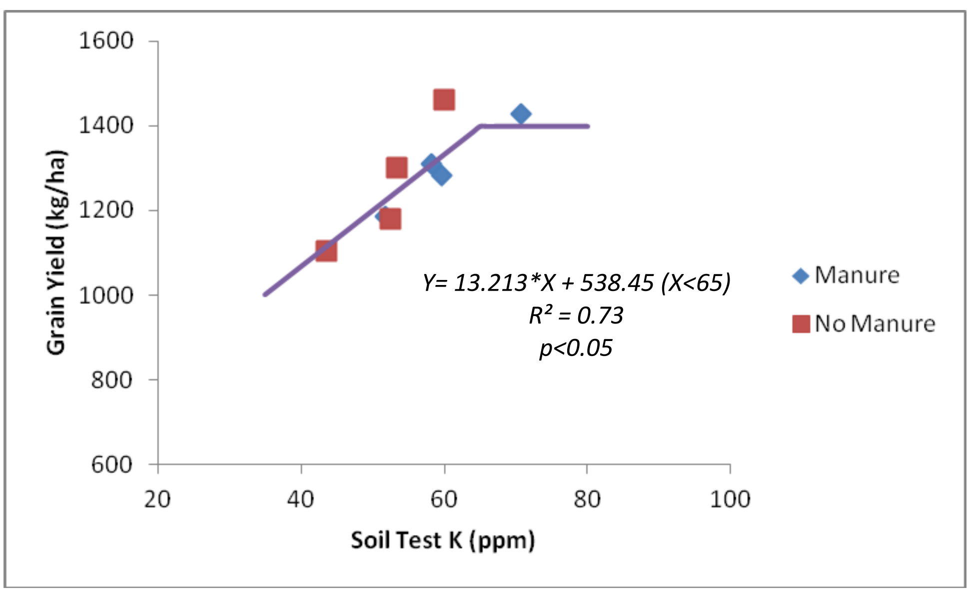

Figure 3.3: *Relationship between pre-plant soil test K and 2010 soybean yield.*

than the treatments that did not receive earlier manure applications, across both P and K treatments (Fig. 3.2 and 3.4).

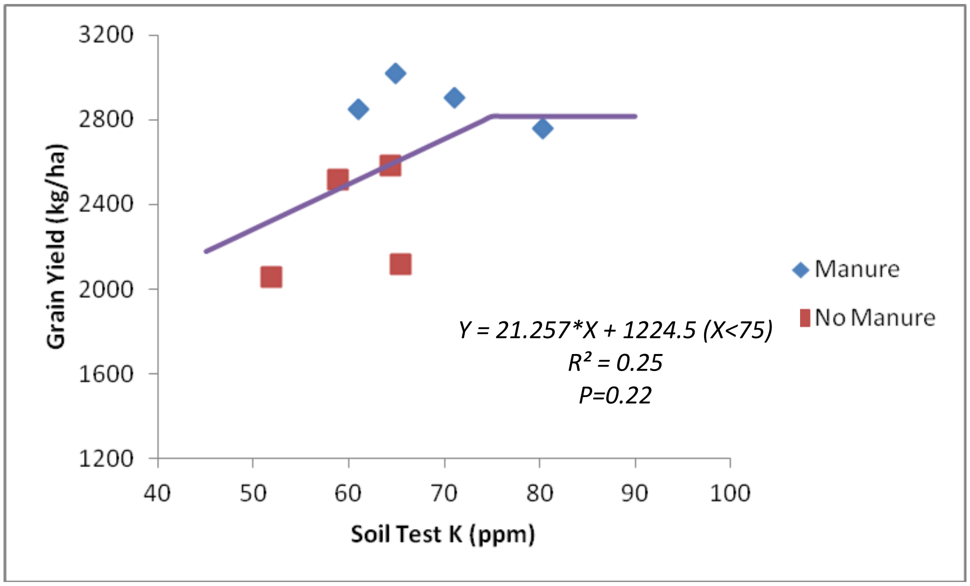

Figure 3.4: *Relationship between post-harvest soil test K and 2011 soybean yield.*

Soil conditions can limit crop root growth. Potassium moves slowly within soil, so roots must continually exploit additional soil volume for K. If root growth is inhibited by dry soil, as in 2010, K uptake could be decreased. Potassium moves through moisture films that surround soil particles/aggregates. Under drought conditions the moisture films are thinner and the path length for ion diffusion is increased. This results in less K movement to the roots. Weather conditions severely affected yield in 2010. This could also affect the relationship between soil nutrient level and soybean yield, changing nutrient critical levels.

Low to medium STK (Table 3.1) was initially observed across all 14 treatments, suggesting a general K deficiency. Treatments that received K fertilizer in place of manure in 2011 exhibited a higher yield than any no manure treatment.

Critical STP concentrations in this experiment were lower than those described by University of Kentucky recommendations, which consider a level between 15 and 20 ppm as ‘medium’. The treatments that exhibited the lowest STP exhibited a delay in development, about 5 days with the most severe deficiency. This study found an effect of P and K fertilization on growth and yield of soybean in both 2010 and 2011.

Leaf Tissue Analysis

Healthy plants contain predictable concentrations of the nutrients required for normal growth and development. Plants need macro-nutrients (N, P, K, Ca, Mg, and S) in greater quantities and micronutrients (Fe, Mn, Zn, Cu, B, Mo, and Cl) in very small amounts. Plants get all these nutrients from fertilizer and/or the soil. Standard plant analysis measures concentrations of 11 essential elements (N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, and B). Additional tests can be requested so as to measure Cl and Mo.

Tissue analysis can be used to monitor nutrient status or diagnose existing nutrient problems. Monitoring involves sampling healthy crops to fine-tune fertilization strategy. Diagnostic analysis involves taking samples from unhealthy or discolored plants to find out if any nutrient concentrations are too high or too low. Interpretation of the results is based on sufficiency ranges, established for each crop.

Nutrient levels within the tissue change as the plant or plant part ages (Table 3.4). Nutrient concentrations in vegetative parts of the plant tend to decrease as the plant grows because nutrients are being exported to younger and reproductive tissues and/or are diluted with greater total amounts of plant biomass.

Table 3.4: *Dry matter and nutrient accumulation by soybean at various growth stages (adapted from Flannery, 2002).*

Growth Stage	V3	V6	Full Bloom	Pod Dev.	Soft Green	Mature
Days	40	51	67	82	103	119
Dry Matter (kg/ha)	879	1777	5332	10642	18942	18599
N (kg/ha)	34	52	192	345	614	554
N (g/kg)	38.3	29.0	35.9	32.4	32.4	29.8
P_2O_5 (kg/ha)	7	13	45	83	148	126
P_2O_5 (g/kg)	3.4	3.3	3.7	3.4	3.4	3.9
K_2O (kg/ha)	30	64	167	328	485	445
K_2O (g/kg)	29.1	30.46	26.5	26.1	21.6	20.2

Leaf tissue nutrient concentrations for 2010 soybean at R1 are displayed in Table 3.5. There was a significant positive response to the addition of P and K fertilizer. Leaf P concentration varied between 1.97 and 5.65 g/kg. Leaf K concentration varied between 11 and 23 g/kg. There was greater variation in leaf P than leaf K concentrations. This greater leaf P variation was related to the greater range in soil test P levels. Leaf N concentrations varied with the different P nutrition treatments. However, leaf N was almost constant across the K nutrition treatments. There was a positive interaction between P and N nutrition.

Manure application increased leaf N, P, and Zn concentrations (Table 3.6). The higher nutrient supply in the manure treatment is partially offset by greater nutrient uptake and removal by previous crops. Not all nutrients in manure are immediately plant available. Organic nutrient forms must be mineralized into inorganic forms. Manure N and P are usually present as a mix of organic and inorganic compounds that varies among manure sources, production systems, and with differences in bedding, storage, and handling. This variability in manure N and P forms contributes to greater uncertainty in manure nutrient management, compared to that with fertilizers.

Table 3.5: *Soybean leaf nutrient concentrations at R1 in 2010.*

P Rate (kg/ha)	K Rate (kg/ha)	Manure (Y/N)	Treat-ment N°	Leaf N (g/kg)	Leaf P (g/kg)	Leaf K (g/kg)	Leaf Cu (mg/kg)	Leaf Zn (mg/kg)
0	50.4	N	1	41	2.4	22	7.3	32
0	50.4	Y	2	46	3.2	21	7.4	32
8.4	50.4	N	3	48	3.3	20	7.9	32
8.4	50.4	Y	4	51	3.9	22	8.1	32
16.8	50.4	N	5	50	3.7	17	7.4	30
16.8	50.4	Y	6	56	4.5	21	7.6	31
25.2	50.4	N	7	54	4.4	20	7.5	30
25.2	50.4	Y	8	55	5.1	19	7.7	32
25.2	33.6	N	9	54	4.5	18	7.8	31
25.2	33.6	Y	10	56	5.3	20	8.1	32
25.2	16.8	N	11	54	4.7	15	7.8	31
25.2	16.8	Y	12	56	5.1	18	7.8	32
25.2	0	N	13	54	5.0	14	7.6	30
25.2	0	Y	14	57	5.0	14	8.0	31
			LSD (0.05)	2.8	0.4	2.2	0.7	1.3

Table 3.6: *Mean 2010 R1 soybean leaf nutrient concentrations, with and without manure.*

Manure (Y/N)	Leaf N (g/kg)	Leaf P (g/kg)	Leaf K (g/kg)	Leaf Cu mg/kg	Leaf Zn mg/kg
Yes	53.9 a	4.6 a	19.3 a	7.81 a	31.7 a
No	50.7 b	4.0 b	18.0 a	7.60 a	30.7 b

Table 3.7 shows the 2011 crop's leaf tissue nutrient concentrations at V2, V4, V7 and R1. The P and K fertilizer increased leaf P concentrations, which varied between 2.3 and 5.2 g kg^{-1}. The differences between treatments were higher in the later growth stages.

Table 3.7: *Leaf nutrient concentration at V2, V4, V7 and R1 soybean in 2011.*

P rate kg/ha	K rate kg/ha	Manure (Y/N)	Treatment Number	Leaf N (g/kg) V2	Leaf P (g/kg) V2	Leaf K (g/kg) V2	Leaf N (g/kg) V4	Leaf P (g/kg) V4	Leaf K (g/kg) V4	Leaf N (g/kg) V7	Leaf P (g/kg) V7	Leaf K (g/kg) V7	Leaf N (g/kg) R1	Leaf P (g/kg) R1	Leaf K (g/kg) R1
0	50.4	N	1	42.8	3.0	26.3	44.6	2.6	25.5	41.5	2.3	22.4	46.2	2.8	24.0
0	50.4	Y	2	44.1	4.2	28.3	43.2	3.6	26.0	44.8	3.6	21.7	57.6	4.2	22.2
8.4	50.4	N	3	44.7	3.5	26.8	44.8	2.8	22.4	44.8	3.0	18.4	51.7	3.3	20.4
8.4	50.4	Y	4	46.1	4.2	29.3	45.0	3.7	25.6	45.4	3.8	20.4	58.9	4.7	20.9
16.8	50.4	N	5	46.6	4.2	22.0	45.8	3.2	20.8	42.7	3.0	16.2	50.4	3.4	17.5
16.8	50.4	Y	6	44.8	4.1	29.0	44.1	3.9	25.2	44.0	3.7	20.1	60.0	4.9	20.4
25.2	50.4	N	7	47.8	4.2	25.8	45.0	3.5	21.5	43.5	3.6	17.1	57.3	4.2	15.9
25.2	50.4	Y	8	45.7	4.2	28.8	43.9	4.4	26.8	50.4	4.4	20.4	58.5	5.2	19.9
25.2	33.6	N	9	48.7	4.3	22.8	45.5	3.8	19.3	49.0	4.0	14.6	57.7	4.5	14.5
25.2	33.6	Y	10	46.4	4.5	26.3	45.5	4.0	24.1	48.2	4.3	18.2	61.0	5.2	18.3
25.2	16.8	N	11	49.0	4.3	18.5	46.9	3.8	16.0	46.6	3.9	12.2	59.4	4.7	11.5
25.2	16.8	Y	12	46.1	4.3	25.9	46.3	4.3	24.1	48.9	4.2	18.6	60.1	5.2	18.4
25.2	0	N	13	48.9	4.4	17.6	45.8	4.2	17.7	49.1	4.2	13.0	60.0	5.1	12.6
25.2	0	Y	14	45.0	4.2	24.4	46.6	3.9	22.5	48.2	4.0	18.9	60.7	5.2	17.9
			LSD (0.05)	1.4	0.4	3.1	2.7	0.3	2.3	2.6	0.3	2.3	4.0	0.4	2.2

Table 3.8: *Mean leaf nutrient concentrations at V2, V4, V7 and R1 soybean in 2011, with and without manure.*

Manure (Y/N)	Leaf N (g/kg) V2	Leaf P (g/kg) V2	Leaf K (g/kg) V2	Leaf N (g/kg) V4	Leaf P (g/kg) V4	Leaf K (g/kg) V4	Leaf N (g/kg) V7	Leaf P (g/kg) V7	Leaf K (g/kg) V7	Leaf N (g/kg) R1	Leaf P (g/kg) R1	Leaf K (g/kg) R1
Yes	45.4 a	4.2 a	27.4 a	44.9 a	3.9 a	24.9 a	47.1 a	3.9 a	19.7 a	59.5 a	4.9 a	19.7 a
No	46.9 b	4.0 b	22.8 b	45.5 a	3.4 b	20.5 b	45.3 b	3.4 b	16.3 b	54.7 b	4.0 b	16.6 b

Leaf K concentration varied between 11 and 29 g/kg. The highest leaf K concentrations were observed at the earlier growth stages. As well as in 2010, there was a significant positive response to manure application in leaf N, P, and K concentrations, across all growth stages (Table 3.8).

There was a strong positive correlation between STP and leaf P at R1 in 2010 (Fig. 3.5). Small and Ohlrogge (1973) reported that the soybean plant sufficiency range for P was 2.6 to 5.0 g/kg. University of Kentucky recommendations state that the sufficiency range for leaf P is between 3.0 and 6.0 g/kg (AGR-1, 2010). Mallarino (2006) observed significant average manure and fertilizer effects for corn, an average manure effect for soybean, and no significant manure by fertilizer interactions, between fertilizer rate and P uptake, similar to these results.

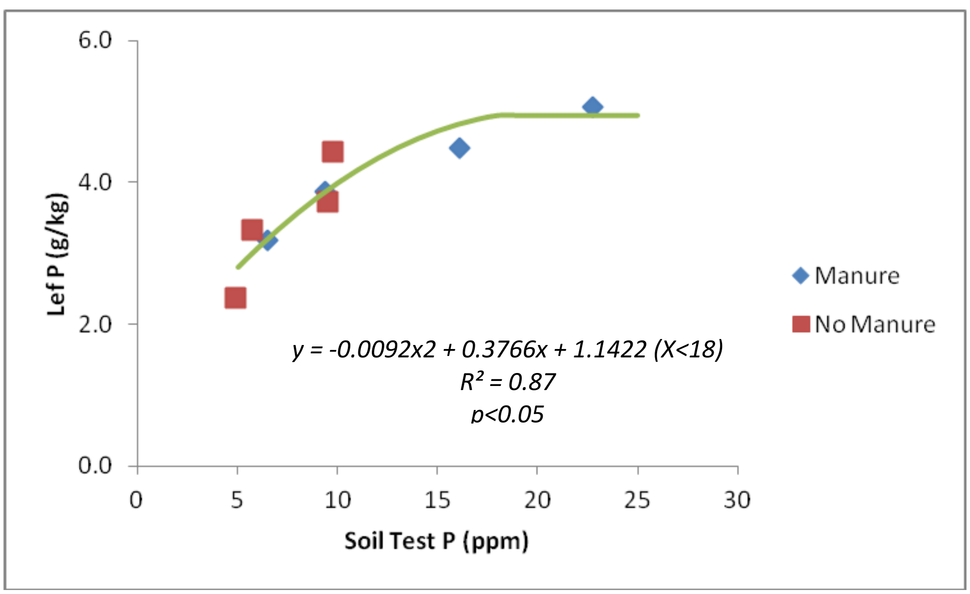

Figure 3.5: *Relationship between soil test P and leaf P concentration at R1 in 2010.*

Soil test K increased leaf K at the R1 growth stage in 2010 (Fig. 3.6). Nelson (2005) found a positive relationship between leaf K at R1, STK at planting, and the K fertilizer rate. A quadratic-plateau model was used to model these relationships. The K sufficiency range for soybean at initial flowering was estimated to be 17.5 to 25.0 g/kg by Plank (1979) in Georgia. The critical leaf K value for soybean at the early pod stage was found to be approximately 20.0 g/kg in Florida (Sartain et al., 1979). Most leaf K concentrations in these experiments were similar to those earlier reports. However, the lowest leaf K concentrations in these experiments were lower than those previously observed. This is related to the low STK level and the duration of the experiment. University of Kentucky recommendations report the sufficiency range for soybean leaf K concentration to be between 14.0 and 20.5 g/kg (Schwab, 2007).

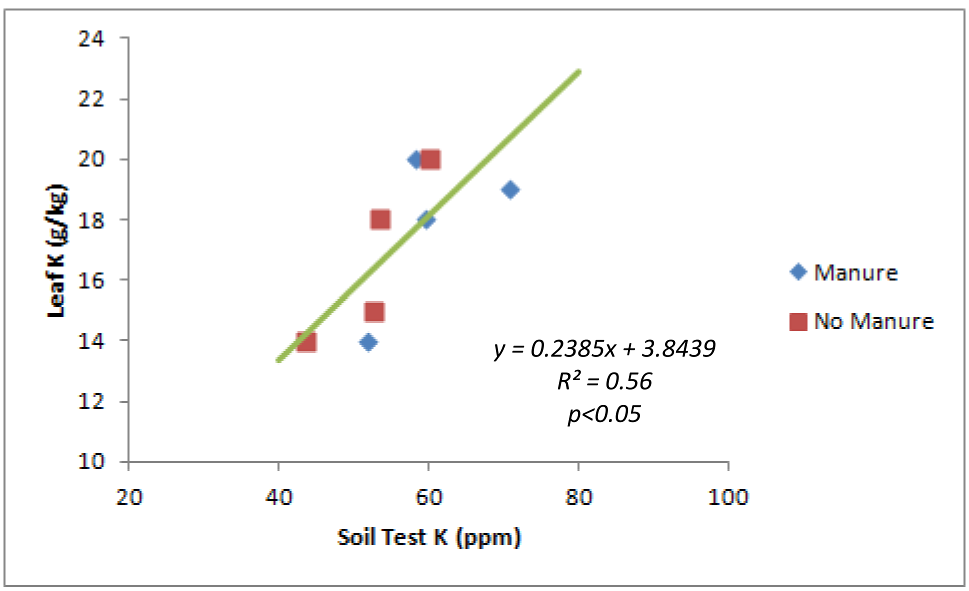

Figure 3.6: *Relationship between soil test K and leaf K concentration at R1 in 2010.*

Slaton et al. (2010) found that leaf K concentration increased significantly, positively, and linearly as HNO_3 and Mehlich-III extractable soil K increased. The linear-plateau model using Mehlich-III extractable soil K was also significant and predicted that leaf K reached a plateau of 16.5 g kg^{-1} when Mehlich-III soil K was ≥113 mg K/kg. In this experiment, in 2010, maximum leaf K using the quadratic model was around 20 g/kg, reached with 140 ppm STK.

Figure 3.7 shows the relationship between post-harvest STP and leaf P at R1 in 2011. There was a positive and strong correlation between post-harvest STP and leaf P at R1 in 2011 (Fig 3.7). Manure history (recent P addition) produced a positive increment in leaf P concentration.

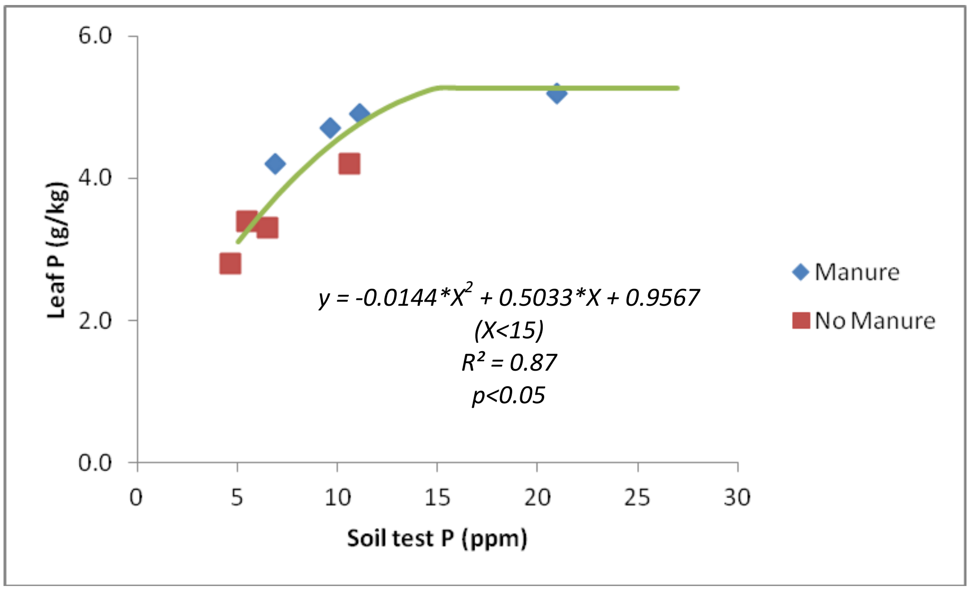

Figure 3.7: *Relationship between soil test P and leaf P concentration at R1 in 2011.*

There was a positive correlation between STK level and leaf K (Fig. 3.8). Manure history (recent K addition) produced a positive increment in leaf K concentration, regardless of STK level, that caused leaf K to be independent of STK in these treatments. As was discussed previously, all treatments were generally K deficient. The addition of K in the manure treatments positively affected K leaf concentration, regardless of the previous STK level.

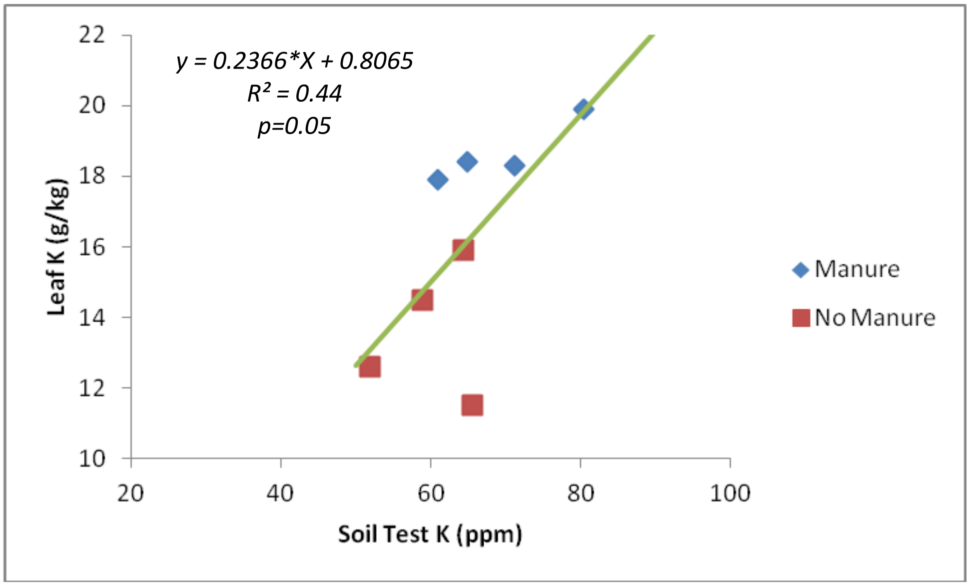

Figure 3.8: *Relationship between soil test K and leaf K concentration at R1 in 2011.*

There was a positive, strong relationship between leaf P and N concentrations at R1 (across P treatments) in 2010 (Fig. 3.9). In the mid-western United States, 40 to 50 % of soybean N comes from BNF (Ham, 1978). Phosphorus has a critical role in the growth and activity of nodules. Phosphorus fertilization has been shown to increase nodule number and mass (Jones et al., 1977). Soybean appears to be especially vulnerable to P deficiency because of the need to support BNF. Biological N_2 fixation has a higher P requirement for maximum activity than plant growth supported by nitrate assimilation because of the high energy requirements in the reduction of atmospheric N_2 by the nitrogenase system (Sinclair and Valdez, 2002). The consequences of P deficiency in soybean are directly related to declines in both plant dry matter and N nutrition.

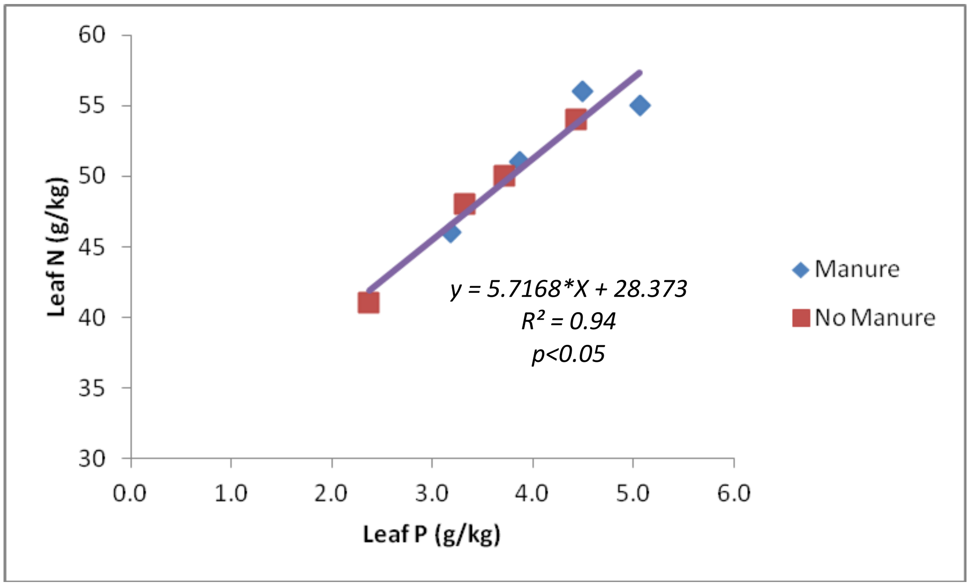

Figure 3.9: *Relationship between leaf P and leaf N concentration at R1 in 2010.*

Sinclair and Valdez (2002) found a positive correlation between N accumulation, nodule mass, and nodule P and Fe concentrations. However, there was no linear correlation between either nodule P or Fe concentration and nodule mass. These results imply that, to a large extent, nodule mass may be a consequence of plant growth rather than altered nodule mass resulting in changed shoot growth.

Leaf P and N concentrations at R1 in 2011 were positively correlated (Fig. 3.10). The relationship was similar to that observed in 2010. However, leaf N concentrations were, on average, higher than in 2010. This could be related to the better soil moisture conditions during 2011, which helped to improve BNF.

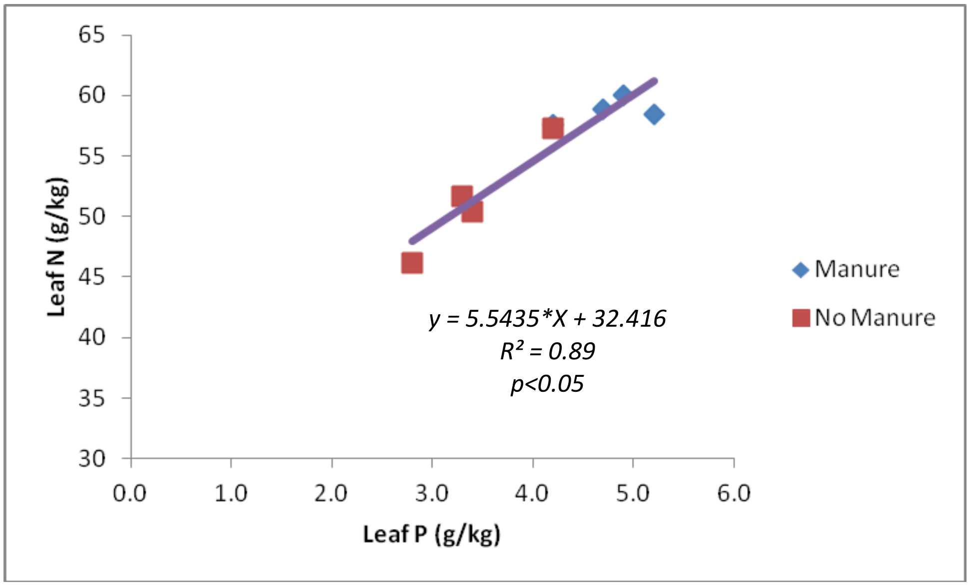

Figure 3.10: *Relationship between leaf P and leaf N concentration at R1 in 2011.*

Figure 3.11 shows the relationship between leaf P and N concentrations at different vegetative growth stages in 2011. Between V2 and V4 there was no relationship between leaf P and leaf N. Either there was little variation in leaf P (V2) or leaf N (V4). At V7 there was a significant and positive correlation (r= 0.83). As shown previously, at R1, there was a strong positive correlation. This result could be related to the soil N supply. At the beginning, N from the soil and N from BNF was adequate for soybean growth in all treatments. After V7, low P treatments, with consequently low BNF, began to show N deficiency. More information is needed to confirm this theory.

Figure 3.12 shows the relationship between leaf P at R1 and relative yield for both 2010 and 2011. Both years exhibit a positive and strong correlation. Yields in 2011 doubled the yields of 2010. However, using relative yields, both years followed a similar model. The critical leaf P concentration was around 4.5 g/kg in both years, and was independent of different factors affecting yield potential (especially water).

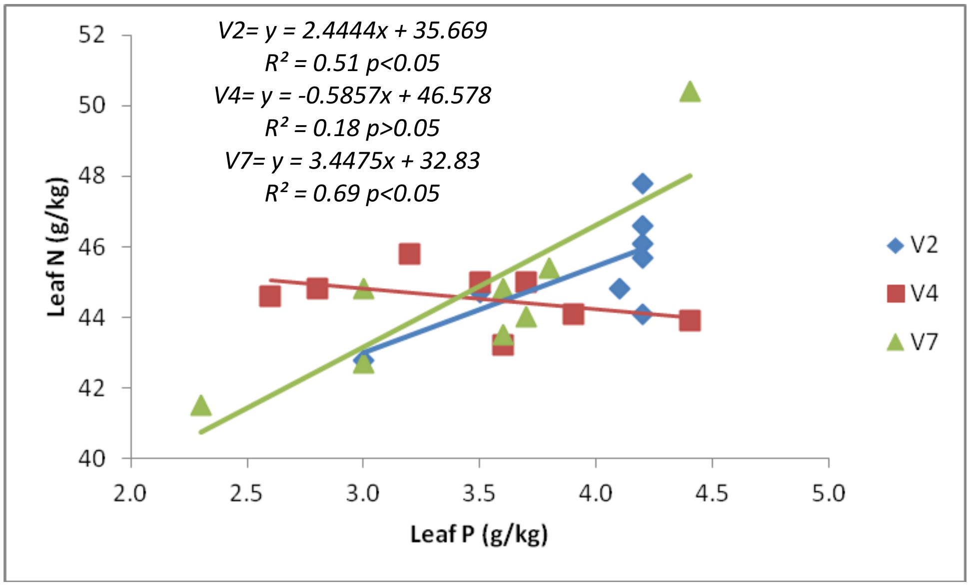

Figure 3.11: *Relationship between leaf P and leaf N concentration at different vegetative growth stages in 2011.*

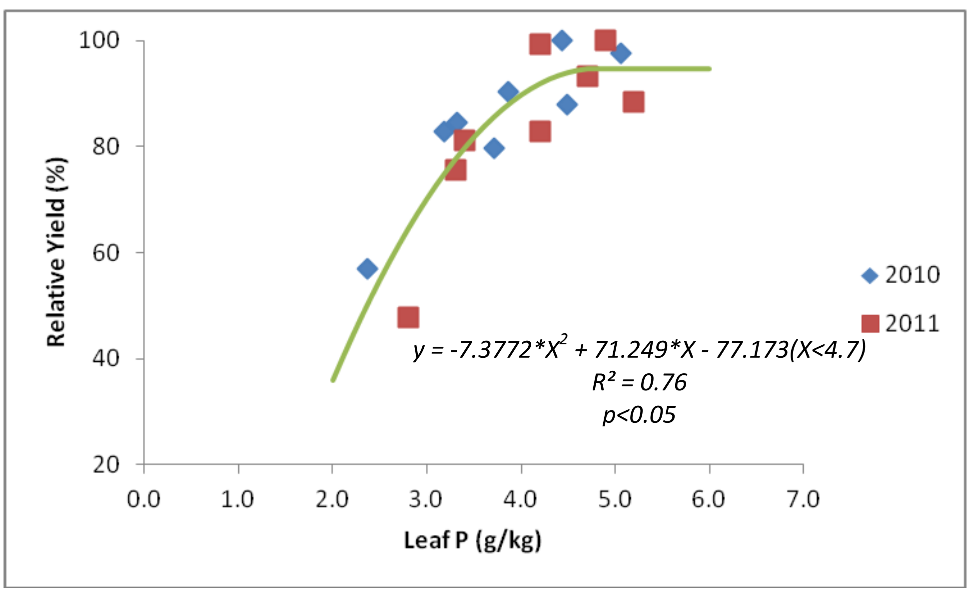

Figure 3.12: *Relationship between leaf P at R1 and relative soybean yield in 2010 and 2011.*

University of Kentucky recommendations define the P sufficiency range between 3.0 and 6.0 g/kg (Schwab, 2007). Our results do not support those recommendations.

Figure 3.13 shows the relationship between leaf K at R1 and relative yield in 2010 and 2011. Both years gave a positive and strong correlation. A linear model best fit the relationship. Yields in 2011 doubled the yields of 2010. However, using relative yields, both years were similar. A critical leaf K concentration was not established. The relationship exhibits continued yield increase with ever higher leaf K concentration. University of Kentucky recommendations define the K sufficiency range between 15.0 and 22.5 g/kg (Schwab, 2007). Our results do not support current recommendations.

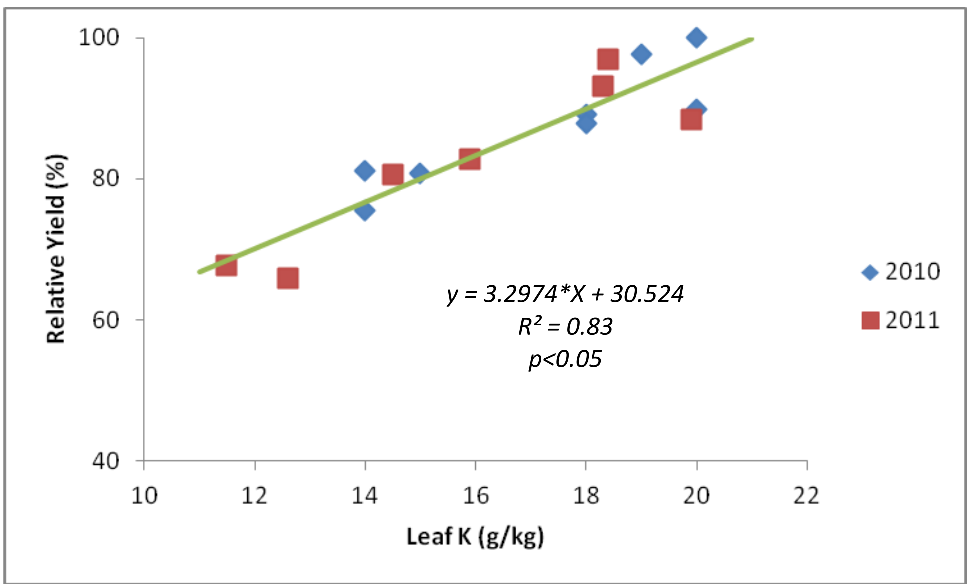

Figure 3.13: *Relationship between leaf K at R1 and relative soybean yield in 2010 and 2011*.

In farm research could be a good option to determine the optimal leaf nutrient concentration. There are two conditions that greatly affect nutrient response, field to field or point to point within a field variability (spatial variability) and year-to-year variability over time (temporal variability). There could be also an effect of the cultivar that we are using. Reference strips have been developed to allow evaluation and determination of whether an in season N application is needed for corn (Desta, et al., 2011). However, there is no experience working with P and K in soybeans.

At R1, leaf N and relative yield were positively correlated both years (Fig. 3.14). Both relations were similar of what previously showed between P and relative yield. Yields in 2011 doubled the yields of 2010. Using relative yields, both years followed a model similar in shape (linear response). However, in 2011 there was greater relative yield reduction at the same leaf N levels than in 2010. Maximum yield was reached with 55 g/kg and 58 g/kg for 2010 and 2011, respectively. University of Kentucky recommendations indicate that the soybean leaf N sufficiency range is between 32.5 and 50.0 g/kg (Schwab et al., 2007). These results indicate that the range may be too low.

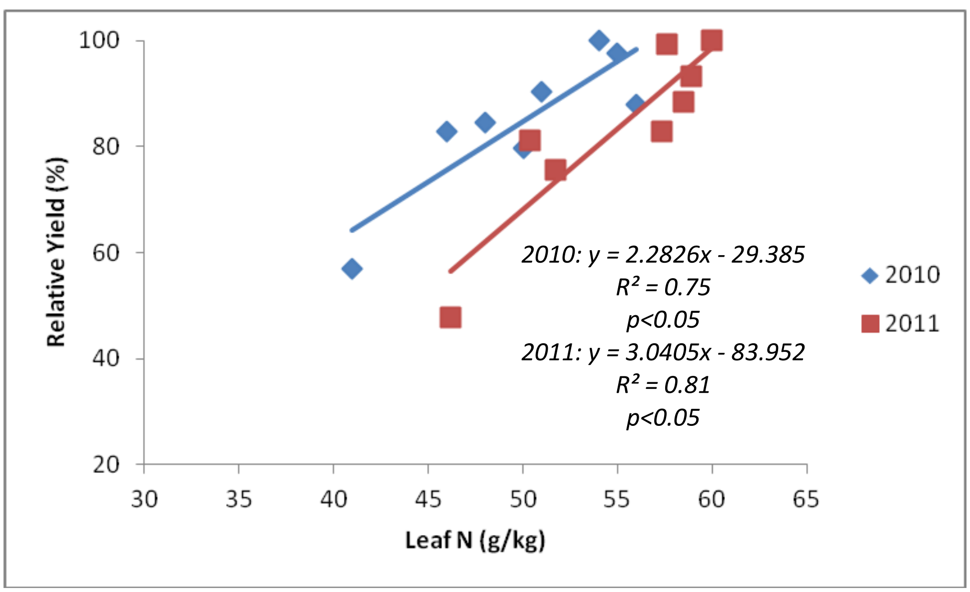

Figure 3.14: *Relationship between leaf N at R1 and relative soybean yield (in the P nutrition treatments) in 2010 and 2011.*

The nutrient content of a plant varies with the chosen plant part, and with stage of development. There are also varietal differences which can affect nutrient concentrations. Plant analysis interpretation is based on a comparison of the nutrient concentration found in a particular plant to known desired values or ranges. Results from this experiment did not agree with current University of Kentucky published values. On farm research could be a good option to improve the use of plant tissue analysis as a diagnostic tool.

Figure 3.15 shows the relationship between leaf P, measured at the different vegetative growth stages, and relative soybean yield in 2011. At V2, only two treatments caused a lower leaf P concentration and also gave the lowest yields. The other six treatments exhibited nearly the same leaf P concentration (4.2 g/kg). At V4, the treatments exhibited greater leaf P variation, and the critical level was around 3.7 g/kg. There was even greater variation at V7, with a critical level around 3.6 g/kg.

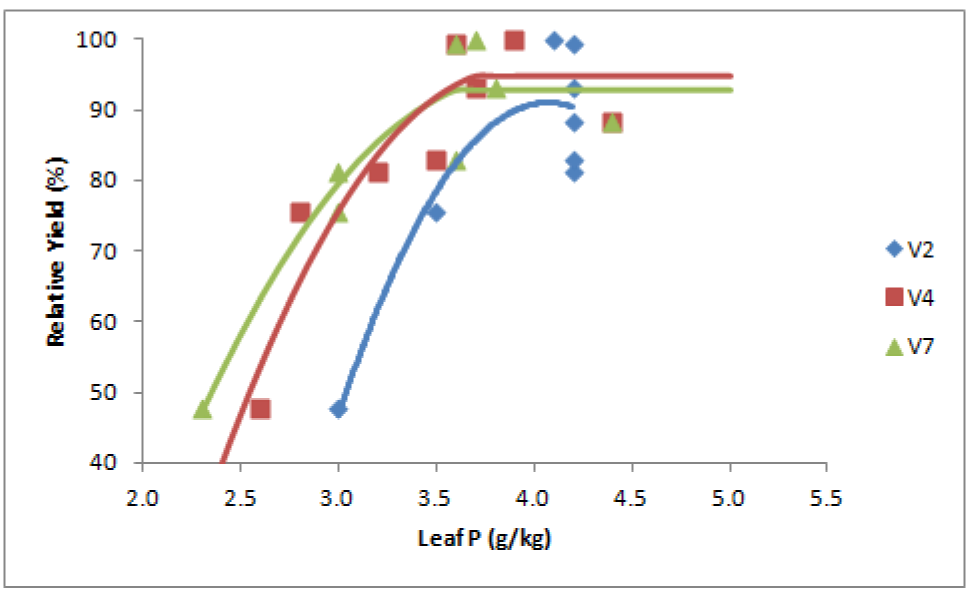

Figure 3.15: *Relationships between leaf P at V2, V4 and V7 and relative soybean yield in 2011.*

Figure 3.16 shows the relationship between leaf K, measured at V2, V4 and V7, and relative soybean yield in 2011. The average leaf K concentration at V2 was higher than at the other growth stages. There were differences between treatments. The critical concentration was around 27 g/kg. At V4, with lower leaf K concentrations than at V2, the critical level was around 25 g/kg. At V7, with the lowest average leaf K, the critical level was around 19 g/kg.

Table 3.9 shows the regression analyses between leaf P or K, at the different growth stages, and relative soybean yield in 2011. Quadratic-plateau models described the relationships between leaf P and relative yield. Linear-plateau models described the relationships between leaf K and relative yield. The regression coefficient was greatest with leaf P or K measured at R1. However, models for earlier growth stages were good enough - earlier sampling could be used to determine soybean nutrient deficiencies.

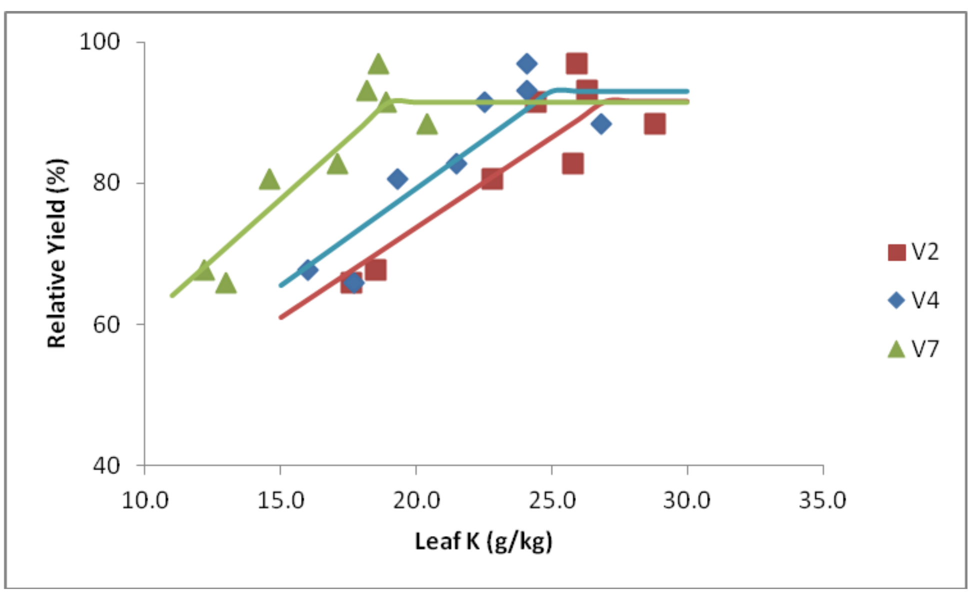

Figure 3.16: *Relationships between leaf K at V2, V4 and V7 and relative soybean yield in 2011.*

Table 3.9: *Regression analysis for leaf nutrient concentrations, at the different growth stages, and relative soybean yield in 2011.*

Growth Stage	Leaf P vs. Relative Yield		Leaf K vs. Relative Yield	
	Model	R^2	Model	R^2
V2	y = -38.481x2 + 313.44x - 547.24 (X<4.2)	0.84	y = 2.5508x + 22.751 (X<27)	0.73
V4	y = -25.425x2 + 197.89x - 289.23 (X<3.7)	0.89	y = 2.7409x + 24.434 (X<25)	0.76
V7	y = -18.811x2 + 146.22x - 189.93 (X<3.6)	0.90	y = 3.4407x + 26.163 (X<19)	0.82
R1	y = -14.852x2 + 134.99x - 210.76 (X<4.2)	0.90	y = 3.4293x + 27.787 (X<18)	0.87

DRIS Analysis

Critical leaf nutrient concentrations have frequently been used to diagnose the nutritional causes of under-performing crops. However, the critical concentration approach is somewhat erroneous in that ‘critical nutrient concentrations’ are not independent, but can vary in magnitude as the background concentrations of other nutrients increase or decrease in crop tissue (Walworth and Sumner, 1986). Nutrient ratios, rather than single nutrient concentrations, are, in certain situations, more reliable as diagnostic criteria. However, this approach only assesses the sufficiency status of a single nutrient on the basis of its abundance relative to one or more other nutrients. The Diagnosis and Recommendation Integrated System (DRIS) employs a minimum of three nutrient ratios per diagnosis. In other words, the sufficiency status of an individual nutrient in plant tissue is diagnosed on the basis of its abundance relative to at least two other plant nutrients, considering nutrient balance within plant tissue. The DRIS has been used successfully to interpret the results of foliar analysis for a wide range of crops, including soybean and sugarcane (Beaufils and Sumner, 1976).

The DRIS is a system of calculations by which tissue nutrient concentration ratios for a given sample are compared to "optimum" values for the same ratios generated from a population of samples taken from high-yielding plots, treatments or fields. Those optimums are called norms. The system of calculation gives an index for each nutrient. Essentially, this nutrient index is a mean of the deviations of the ratios containing a given nutrient from their respective optimum or DRIS norm values (Bailey et al., 1997). The DRIS norm values for soybean were calculated at R1 (Beverly et al., 1986). No one has calculated DRIS soybean norms at other, earlier, growth stages.

The relative abundance of each nutrient was evaluated by comparing all ratios containing that nutrient with the corresponding DRIS norms. The mean and coefficient of variation (CV) values for the selected nutrient ratios (N/K; N/P; P/K), from the high-yielding population, were used in calculating DRIS indices. In theory, an index value of zero would indicate an optimum level of the nutrient, but, in practice, an optimum range is more appropriate. Following the precedent of Beaufils (1973), a nutrient index within 1.33 standard deviations (SD) of the high-yield group's zero index value was considered to be sufficient for high-yield production, and ±1.33 SD would encompass 80 % of high-yield soybean fields, assuming a normal distribution.

The N, K and P nutrient indices are calculated as follows (Walworth and Sumner, 1987):

$$\text{Index N} = [f\,(N/K) + f\,(N/P)]/2$$

$$\text{Index K} = [f\,(K/N) + f\,(K/P)]/2$$

$$\text{Index P} = [f\,(P/N) + f\,(P/K)]/2$$

and given that when N/K is equal to or larger than n/k (norm for the N/K ratio);

$$f(A/B) = \left(\frac{N/K}{n/k} - 1\right) \frac{100}{CV}$$

or that when N/K is smaller than n/k;

$$f(A/B) = \left(1 - \frac{n/k}{N/K}\right) \frac{100}{CV}$$

At every growth stage in 2011, positive P indices were associated with relative yields greater than 80 % (Fig. 3.17). The DRIS analysis was able to detect P deficiency at every growth stage. However, P index values varied with growth stage.

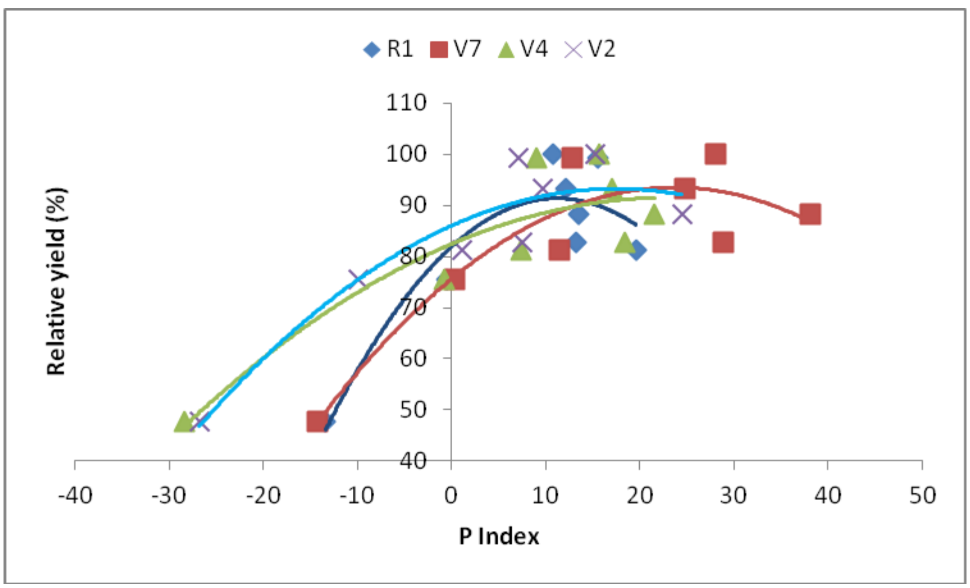

Figure 3.17: *Relationship between the DRIS P index, at different growth stages, and relative soybean yield in 2011.*

During 2010 only one leaf sampling was done, at R1. The P index exhibited a trend similar to that found in 2011 (Figure 3.18). In general, the higher the P index the greater the yield, with the exception of one treatment. Positive P indices were associated with relative yields higher than 80 %.

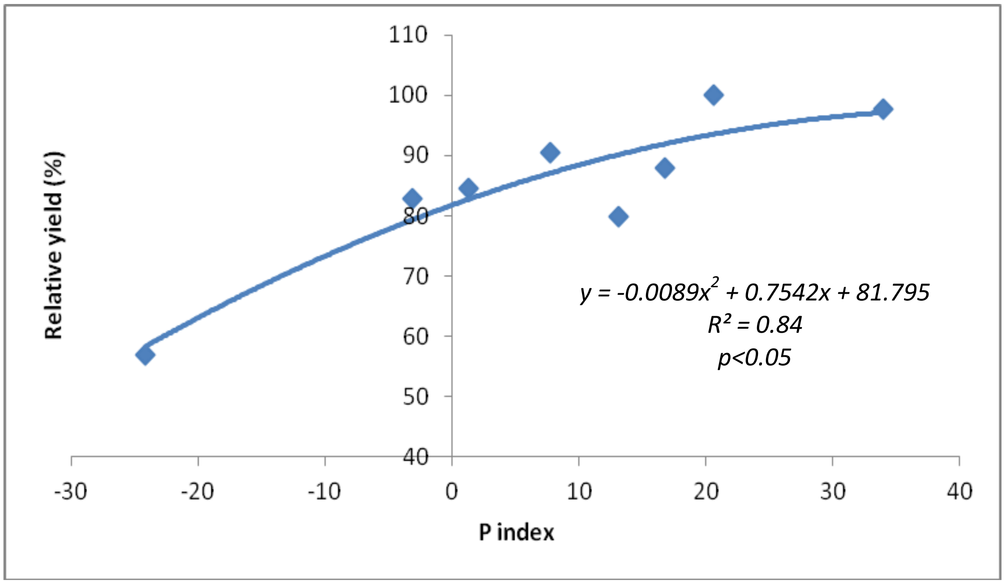

Figure 3.18: *Relationship between the DRIS P index and relative soybean yield in 2010.*

Figure 3.19 shows the relationship between the DRIS K index, determined using leaf K at each growth stages, and relative soybean yield in 2011. At V2 and V4, positive K indices were associated with higher yields and negative to near zero K indices were associated with lower yields. However, at V7 and R1 all treatments exhibited negative K index values, though less negative values were associated with higher yields. One possible explanation for these results could be that the norms used to determine the K index did not represent the high yielding population, though these were established by Beverly et al. (1986) using, in part, information from Kentucky. Another possibility is that the study suffered from general K deficiency. However, given previous soil test results, this seems implausible. The DRIS analysis was able to detect K deficiency at every growth stage though K index values varied with growth stage.

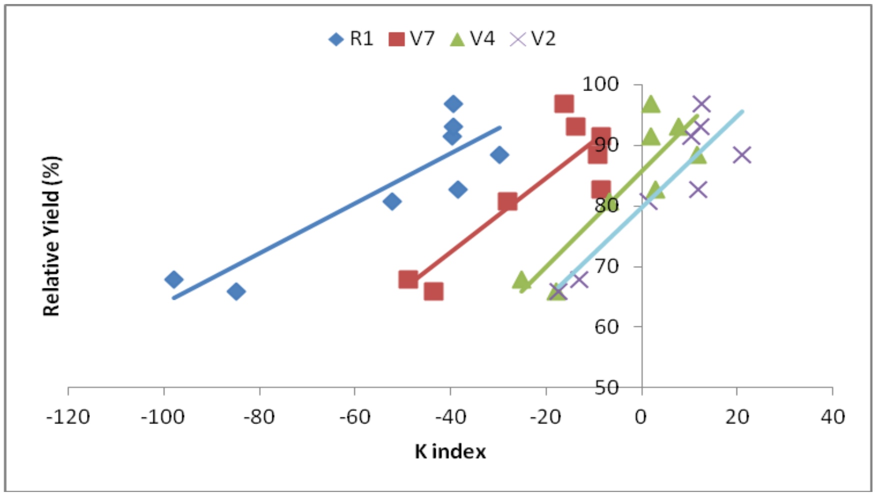

Figure 3.19: *Relationship between the DRIS K index, at different growth stages, and relative soybean yield in 2011.*

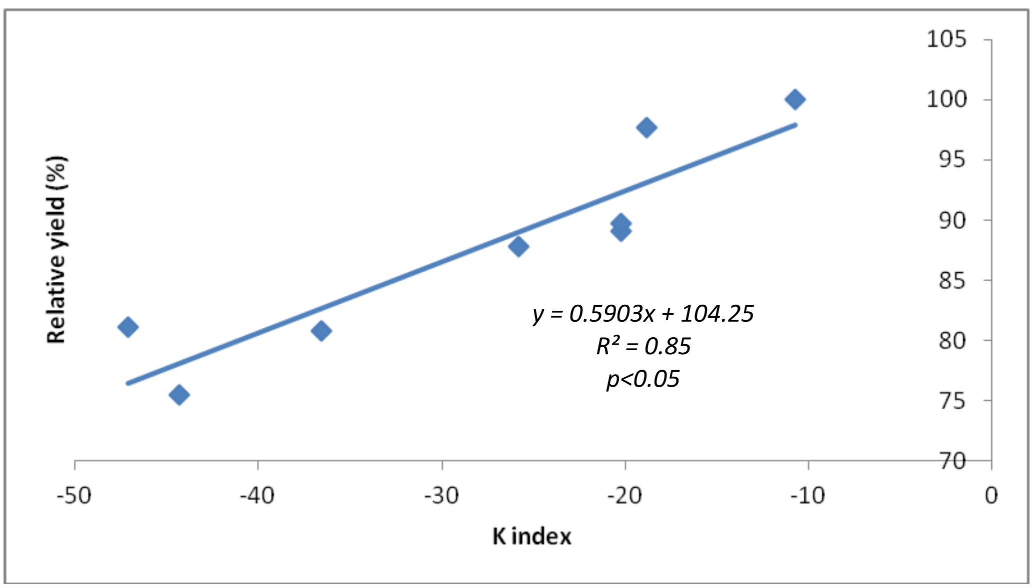

Figure 3.20: *Relationship between the DRIS K index and relative soybean yield in 2010.*

For 2010, the DRIS K index exhibited a similar trend to that seen in 2011 (Fig. 3.20). In general, the higher the K index the greater the yield. However, as was seen in 2011, all K treatments gave a negative K index. The correlation between the K index and relative yield was high.

The DRIS analysis shows relative nutrient limitation to yield and the degree of yield limitation. However, more nutrients could be included in the analysis. The DRIS norms, for different growth stages, could give early nutrient deficiency detection.

The sum of the absolute DRIS index values is used to assess nutritional imbalance. The greater the imbalance, the greater the sum of the absolute values. Using all the treatments (Fig. 3.21) there was no relationship between the sum of the DRIS indices and relative soybean yield. However, when using only the K treatments, the sum of the absolute DRIS indices was negatively correlated to relative yield (Fig. 3.22).

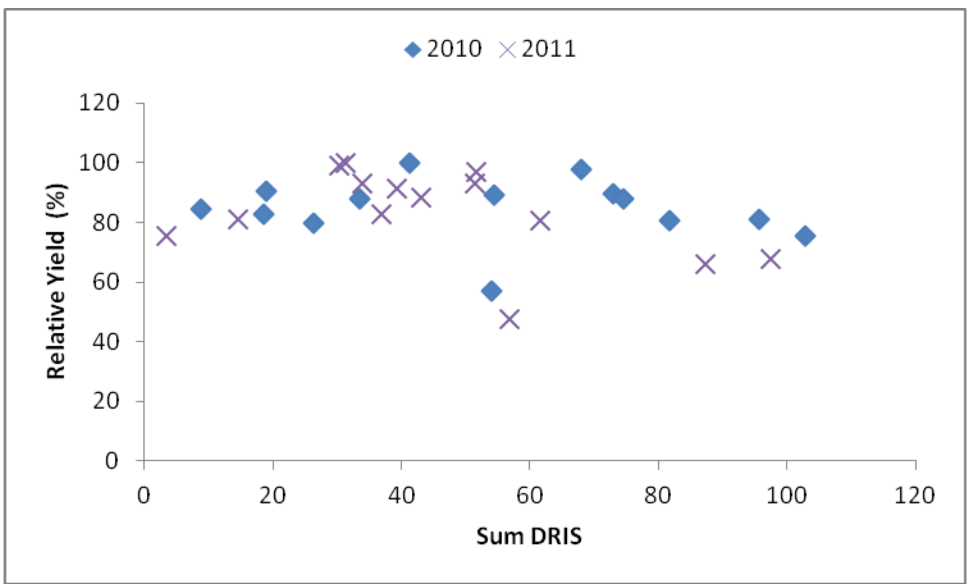

Figure 3.21**:** *Relation between the sum of the DRIS indices for R1 leaf tissue and relative soybean yield in 2010 and 2011 using all fourteen treatments.*

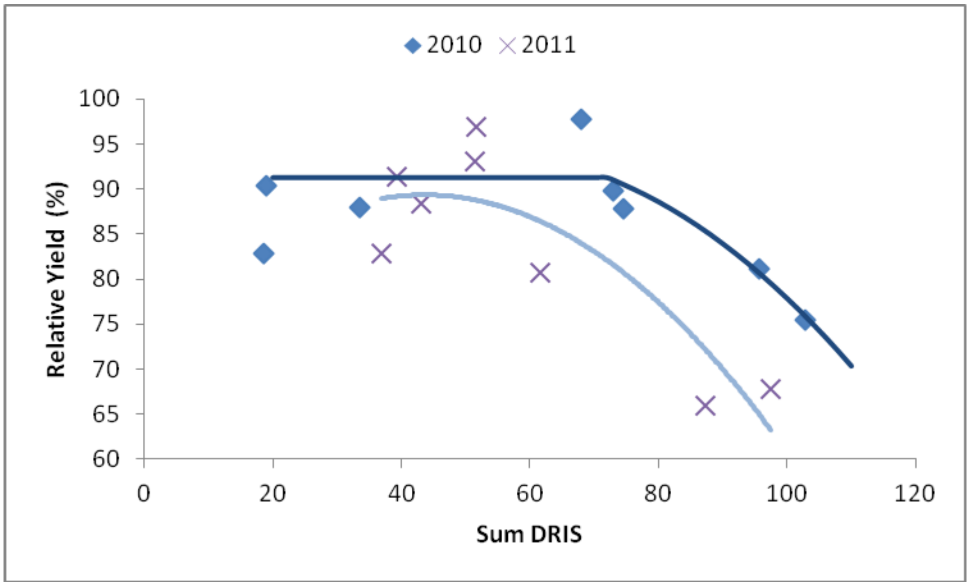

Figure 3.22**:** *Relation between the sum of the DRIS indices for R1 leaf tissue and relative soybean yield in 2010 and 2011 using only the eight K treatments.*

CHAPTER FOUR

Grain Nutrient Concentration and Removal

Messiga et. al. (2012) observed that grain P concentrations were significantly ($P < 0.05$) increased by P additions during a 17-year study. Across the years, soybean grain P concentration varied from 5.0 g kg^{-1} in the control to 5.8 g kg^{-1} in the treatment that received the highest P rate. However, the experiment was conducted on a soil that originally possessed a high available P level, and which did not give a significant yield response to applied P. In this study, during 2010 and 2011, there was a positive grain P concentration response to the addition of P (Tables 4.1, 4.2, 4.3, and 4.4). The range in grain P concentration varied between 3.0 and 6.0 g/kg, and was similar between years. However, yields in 2011 were double those of 2010. There was a similar grain P concentration across the K treatments. However, in 2011, where the nutrient equivalent of manure was applied as fertilizer, all treatments that received extra nutrition exhibited higher grain P. Treatment 1, under severe P stress, exhibited the lowest grain P concentration. On average, grain P concentrations in 2010 were higher than those in 2011. Those results are related with the higher yields in 2011, which produced a dilution effect.

Soybean grain P removal varied across treatments (Tables 4.1, 4.2, 4.3, and 4.4). Grain P removal differences were influenced by two factors, grain P concentration and grain yield. Grain P removal ranged between 2 and 7 kg P/ha in 2010, and between 4 and 16 kg P/ha in 2011. The difference between years is explained by weather conditions that severely reduced yields in 2010. Across K treatments, the variation in P removal was explained mainly by differences in grain yield.

Grain K concentration exhibited a positive response to K addition as manure or fertilizer (Tables 4.1, 4.2, 4.3, and 4.4). The range in grain K concentrations was between 13.5 and 17.0 g/kg. The variation was relatively smaller than that in grain P concentration. Grain K concentrations were similar across years. Treatments that received K (fertilizer for manure) in 2011 gave higher K concentrations than in 2010. There were no significant differences in grain K concentration in 2011 across K fertilizer rate treatments without a manure history (Treatments 9, 11 and 13). However, the yields associated with these treatments exhibited a response to K nutrition. These results were similar to what Yin and Vyn (2004) observed. Potassium fertilizer consistently increased soybean leaf K concentration, grain K concentration and K removal by the crop.

The treatment differences in K removal were influenced by two factors, grain K concentration and grain yield (Tables 4.1, 4.2, 4.3, and 4.4). Grain K removal ranged from 11 and 20 kg K/ha in 2010 and between 22 and 45 kg K/ha in 2011. That difference between years is due to the dry weather conditions that severely reduced yields in 2010. Across the P treatments the variation in K removal was explained mainly by differences in grain yield. The eight K treatments showed the importance of both grain K concentration and grain yield to K removal. However, grain yield was the main factor explaining K removal.

Table 4.1: *Grain nutrient concentration and removal in 2010.*

P rate kg/ha	K rate kg/ha	Manure (Y/N)	Treatment Number	Grain N (g/kg)	Grain P (g/kg)	Grain K (g/kg)	N removal (kg/ha)	P removal (kg/ha)	K removal (kg/ha)
0	50.4	N	1	65.2	3.4	16.6	47	2.5	12.0
0	50.4	Y	2	67.8	4.1	17.0	71	4.3	17.8
8.4	50.4	N	3	66.7	4.0	16.3	71	4.2	17.5
8.4	50.4	Y	4	67.0	4.7	16.7	76	5.4	19.0
16.8	50.4	N	5	69.6	4.6	16.0	70	4.6	16.1
16.8	50.4	Y	6	67.9	5.5	16.9	75	6.1	18.8
25.2	50.4	N	7	68.5	5.1	15.9	87	6.4	20.1
25.2	50.4	Y	8	69.4	6.1	16.5	85	7.5	20.3
25.2	33.6	N	9	69.5	5.5	15.9	78	6.2	17.9
25.2	33.6	Y	10	68.9	6.0	16.4	78	6.8	18.6
25.2	16.8	N	11	70.0	5.8	14.8	71	5.9	15.1
25.2	16.8	Y	12	70.2	6.0	15.6	78	6.7	17.3
25.2	0.0	N	13	70.8	6.0	14.4	67	5.7	13.7
25.2	0.0	Y	14	69.4	6.0	14.7	71	6.1	15.1
			LSD (0.05)	2.2	0.3	0.8	11	0.9	2.8

Table 4.2: *Mean grain nutrient concentration and removal, with and without manure, in 2010.*

Manure (Y/N)	Grain N (g/kg)	Grain P (g/kg)	Grain K (g/kg)	N removal (kg/ha)	P removal (kg/ha)	K removal (kg/ha)
Yes	68.6 a	5.48 a	16.2 a	76 a	6.11 a	18.1 a
No	68.6 a	4.91 b	15.7 b	70 b	5.09 b	16.1 b

Table 4.3: *Grain nutrient concentration and removal in 2011.*

P rate kg/ha	K rate kg/ha	Manure (Y/N)	Treatment Number	Grain N (g/kg)	Grain P (g/kg)	Grain K (g/kg)	N removal (kg/ha)	P removal (kg/ha)	K removal (kg/ha)
0	50.4	N	1	63.0	3.1	17.3	81	3.9	22.1
0	50.4	Y	2	65.7	4.1	17.0	176	11.0	45.5
8.4	50.4	N	3	63.1	3.4	16.4	129	7.0	33.4
8.4	50.4	Y	4	65.8	4.7	16.5	165	11.8	41.6
16.8	50.4	N	5	64.1	3.7	15.9	141	8.0	34.9
16.8	50.4	Y	6	66.7	5.2	17.4	180	14.0	46.9
25.2	50.4	N	7	66.1	4.3	15.1	148	9.7	33.6
25.2	50.4	Y	8	67.3	5.9	17.2	161	14.0	40.9
25.2	33.6	N	9	65.7	4.7	14.2	143	10.2	31.0
25.2	33.6	Y	10	67.5	5.9	16.7	169	14.6	42.1
25.2	16.8	N	11	67.3	5.3	14.0	123	9.6	25.7
25.2	16.8	Y	12	70.3	5.9	16.0	183	15.5	41.8
25.2	0.0	N	13	68.6	5.6	13.5	122	9.9	24.2
25.2	0.0	Y	14	67.5	5.9	16.0	166	14.6	39.5
			LSD (0.05)	1.9	0.3	0.7	14	1.2	3.6

Table 4.4: *Mean nutrient concentration and removal, with and without manure, in 2011.*

Manure (Y/N)	Grain N (g/kg)	Grain P (g/kg)	Grain K (g/kg)	N removal (kg/ha)	P removal (kg/ha)	K removal (kg/ha)
Yes	67.2 a	5.36 a	16.7 a	171 a	13.6 a	42.6 a
No	65.4 b	4.29 b	15.2 b	126 b	8.3 b	29.3 b

Grain N concentration exhibited some variation across treatments (Tables 4.1, 4.2, 4.3, and 4.4). All the treatments that received the highest P rate possessed similar grain N concentrations. There was no influence of K nutrition treatments on grain N concentration. However, there was an interaction between P nutrition and plant N composition. Treatments resulting in low grain P concentrations also exhibited low grain N concentrations.

Grain N removal variation across treatments was mainly due to grain yield differences (Tables 4.1, 4.2, 4.3, and 4.4). Grain N removal varied between 47 and 87 kg N/ha in 2010 and between 80 and 170 kg N/ha in 2011. Again, the difference between the two years is explained by weather conditions that severely reduced yield in 2010. Across the P treatments the variation in N removal was explained mainly by differences in grain yield. However, there was also some variation in grain N concentration. The K treatments gave similar grain N concentrations, and N removal differences among these treatments were explained by differences in grain yield.

There was a positive and strong correlation between leaf P concentration at the different growth stages and grain P removal (Figure 4.1). However, at V2 the correlation was not strong because there was less variation in leaf P concentration. After V4, the correlation was stronger. Leaf P concentration was a good indicator of P removal by the crop because leaf P was strongly related to grain yield and grain P concentration.

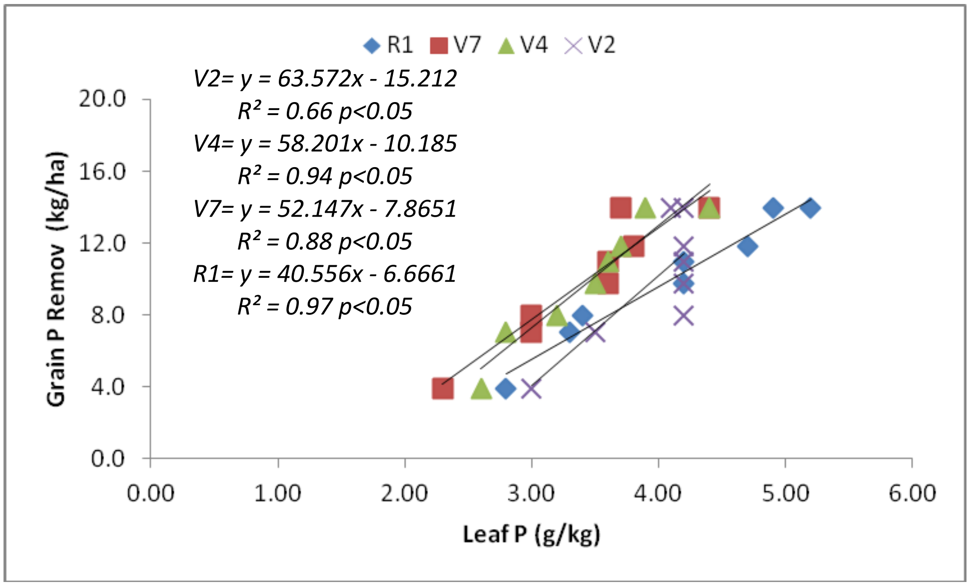

Figure 4.1: *Relationship between leaf P concentration and grain P removal in 2011.*

There was a positive and strong correlation between leaf K concentration at the different growth stages and grain K removal (Figure 4.2).

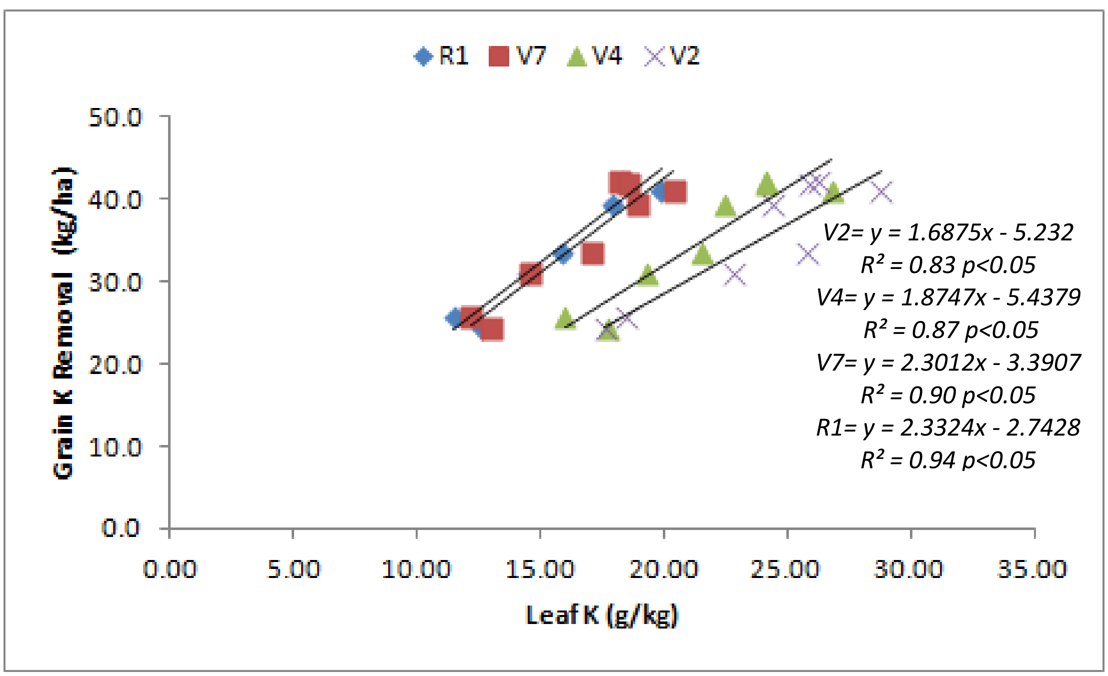

Figure 4.2: *Relationship between leaf K concentration and grain K removal in 2011.*

The correlation was similar across the different growth stages. Leaf K concentration was a good indicator of K removal by the crop because leaf K was strongly related to grain yield and grain K concentration. However, variation in removal of K by the crop was explained more by differences in yield than by differences in K concentrations in the grain. The relative variation in grain K concentration was smaller than the relative variation of grain yield.

A high N harvest index is characteristic of soybean (Eaglesham et al., 1982), causing much crop N to be exported in grain. Chien et. al. (1993) found P application to soybean increased the amount of atmospheric-derived N by BNF. Therefore, the application of P should increase the N concentration of grain and N removal. There was a positive and strong correlation between leaf N concentration at R1 and grain N removal, across the eight P treatments (Figure 4.3).

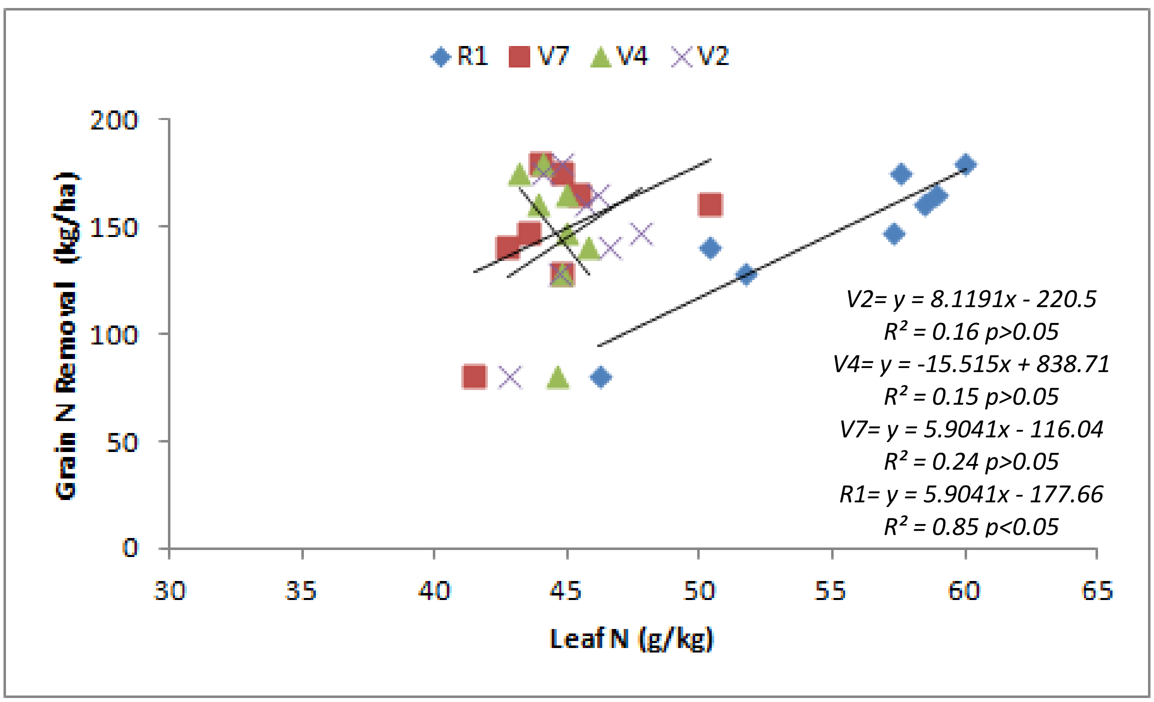

Figure 4.3: *Relationship between leaf N concentration and grain N removal in 2011.*

However, there was no correlation with leaf N determined at earlier growth stages. Leaf N at R1 was a good indicator of grain yield and grain N concentration. Grain yield was the main factor explaining differences in grain N removal. Across the K treatments, there was no correlation between leaf N, at any growth stage, and N removal.

CHAPTER FIVE

NDVI – Leaf P – P Stress Relationships

Increased reflectance at visible wavelengths (400-700 nm) is generally the most consistent response to stress within the 400-2500 nm range (Carter, 1993). Narrow wavebands between 480 and 680 nm are recommended for early detection of forest damage (Hoque and Hutzler, 1992). However, reflectance at 690-700 nm is particularly sensitive to early, stress-induced, reductions in leaf chlorophyll content (Carter, 1993).

In 2010, leaf samples were only taken at R1, and in 2011, leaf samples were taken at V2, V4, V7 and R1. In 2011, there was a positive and strong correlation between relative NDVI measured 1 m above the canopy and leaf P measured at V2 (Figure 5.1).

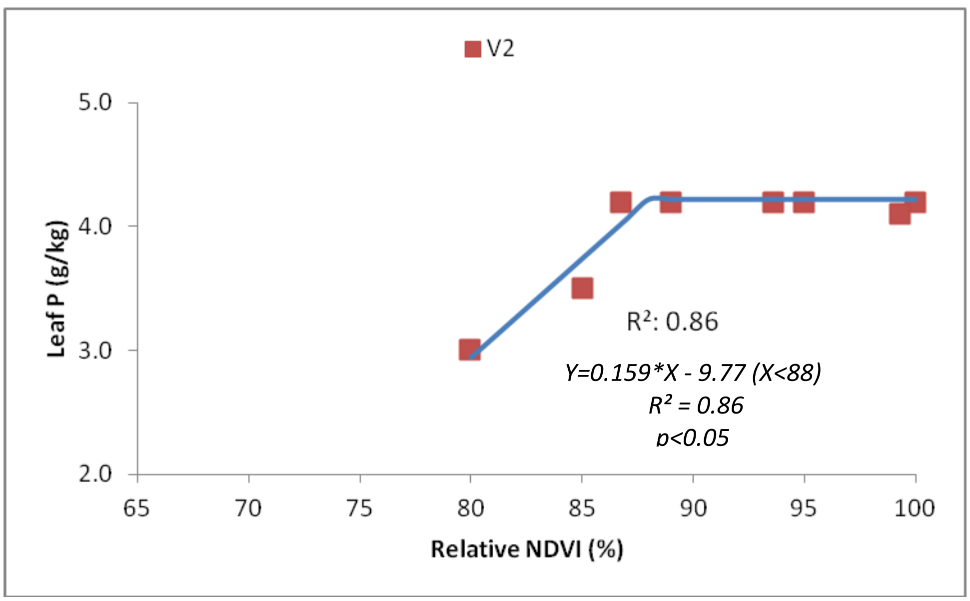

Figure 5.1: *Relationship between relative NDVI and leaf P concentration at V2 in 2011.*

Only two treatments exhibited lower leaf P concentrations. Most treatments exhibited the same leaf P concentration, around 4 g/kg. However, NDVI measurement detected differences between treatments that were related to something other than leaf P concentration. Those differences in NDVI values among the treatments may be related to differences in biomass production or leaf area. Board et al. (2007) used NDVI to detect differences in LAI and light interception among different soybean varieties. In 2004, differences in LAI and light interception were created by manual defoliation, whereas in 2005 LAI/light interception differences occurred with different cultivars and planting dates (Board et al., 2007). Board et al. (2007) found that across canopies ranging from very low LAI to canopy closure (95% light interception), NDVI accurately predicted LAI and light interception with strong linear regression models (r^2 = 0.93 to 0.97).

In this study, there was a positive and strong correlation between NDVI measured 1 m above the canopy at V2 and leaf P at R1 in both 2010 and 2011 (Fig. 5.2). There were no significant differences in NDVI at V2, or any other growth stage, due to measurement height (data not shown). The NDVI measurements at V2 were a good predictor of leaf P at R1.

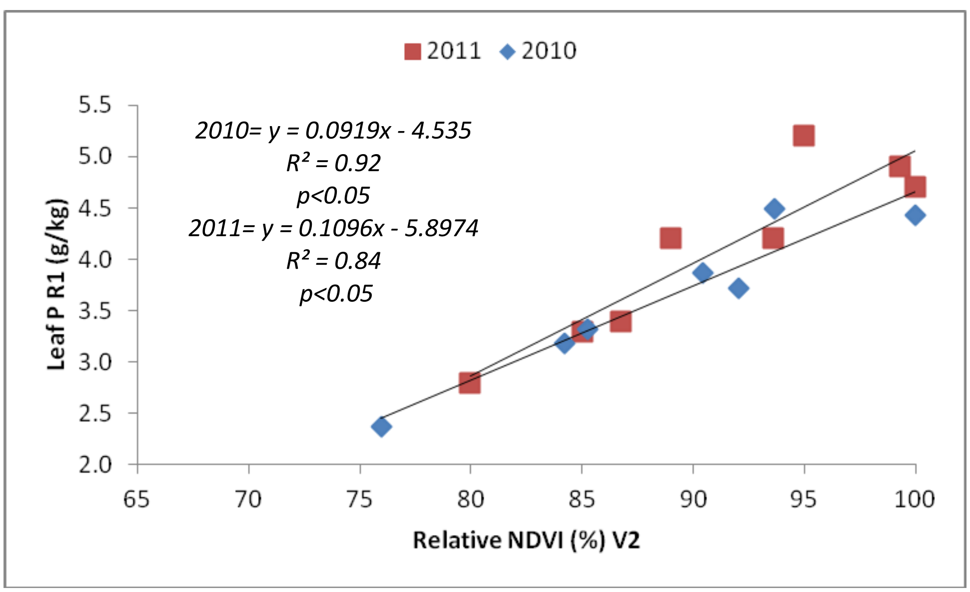

Figure 5.2: *Relationship between relative NDVI at V2 and leaf P concentration at R1.*

The NDVI is a good predictor of biomass production or leaf area (Board et al., 2007). At V2, the plants exhibited similar leaf P concentrations across the treatments. However, there were differences in biomass production and/or leaf area that NDVI was able to detect at this early growth stage (Fig 5.2).

There was a positive and strong correlation between relative NDVI at V4 and leaf P concentration at V4 (Fig. 5.3). By V4 there was greater variation in leaf P due to the treatments. At V2 only two treatments exhibited leaf P differences (Figure 5.1), but at V4 the greater range in leaf P leaf resulted in a linear model between relative NDVI and leaf P (Fig. 5.3). These results indicate that there is an opportunity for early detection (V4) of nutritional deficiencies using NDVI and/or leaf tissue analysis (to understand which nutrient is limiting plant growth).

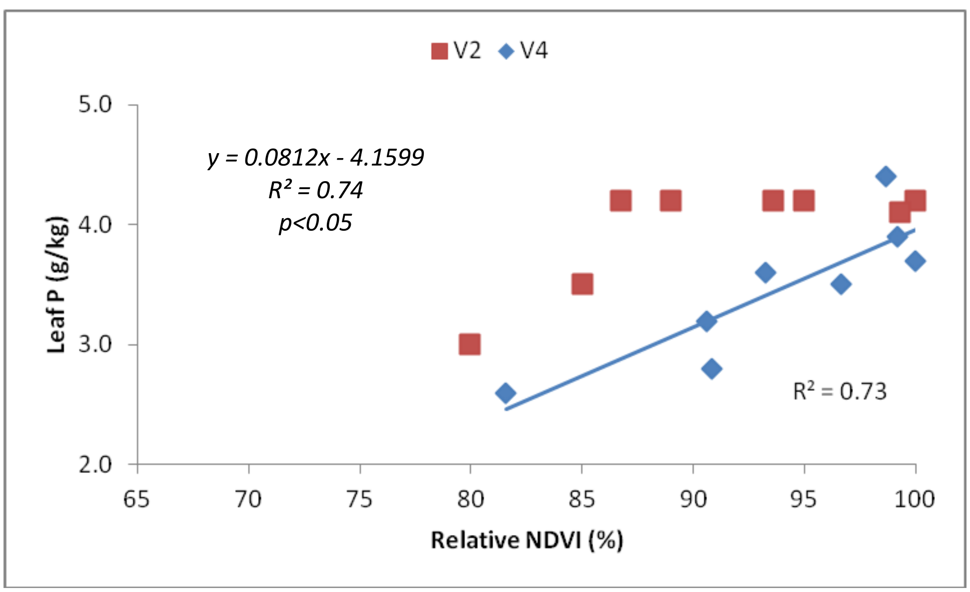

Figure 5.3: *Relationship between relative NDVI and leaf P concentration at V4 in 2011.*

In both 2010 and 2011, there was a positive and strong correlation between relative NDVI at V4 and leaf P at R1 (Fig. 5.4). These relationships were equal in quality to those between NDVI at V2 and leaf P at R1 (Figure 5.2).

There was also a positive and strong correlation between NDVI and leaf P at V7 (Fig. 5.5). The NDVI measurements taken at V7 were a good predictor of leaf P at that growth stage. There was greater variation in leaf P between treatments and a greater range in NDVI values than at V2 and V4, and the regression coefficient at V7 was higher.

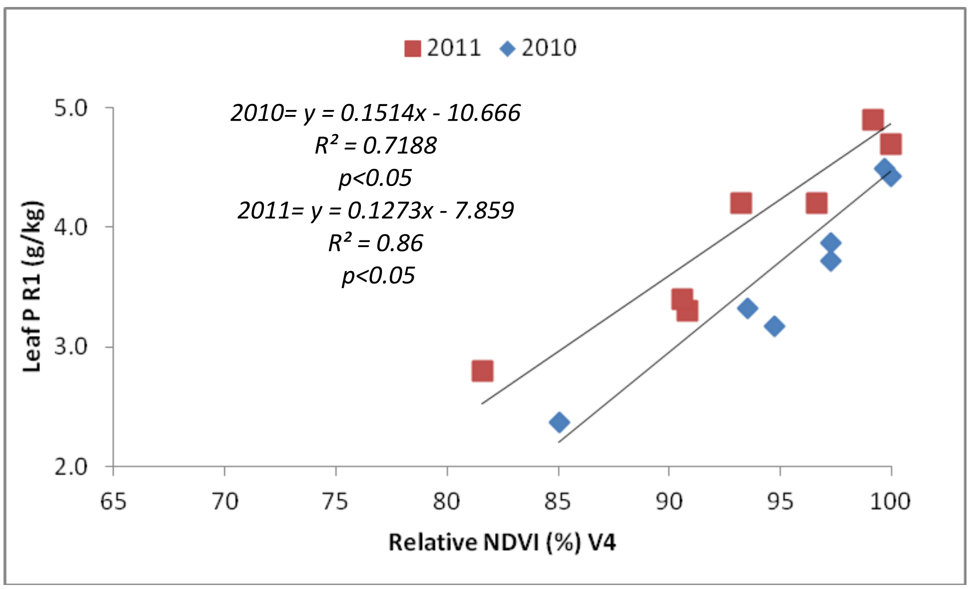

Figure 5.4: *Relationship between relative NDVI at V4 and leaf P concentration at R1.*

In 2010, and 2011, there was a positive and strong linear correlation between NDVI at V7 and leaf P at R1 (Figure 5.6). Correlation coefficients were similar for the two years. However, the differences in relative NDVI and leaf P due to treatment continued to increase as the growing season progressed.

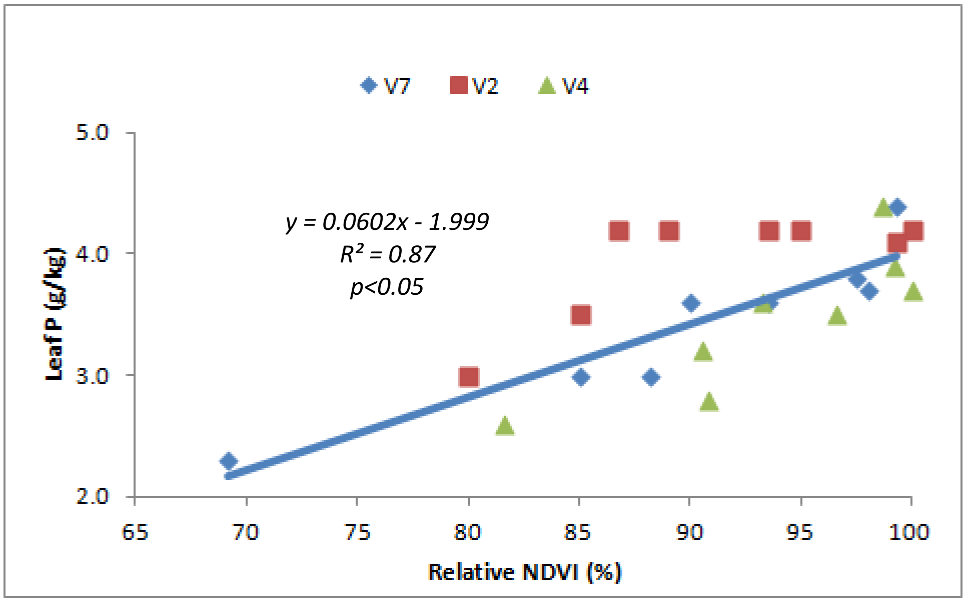

Figure 5.5: *Relationship between relative NDVI and leaf P concentration at V7 in 2011.*

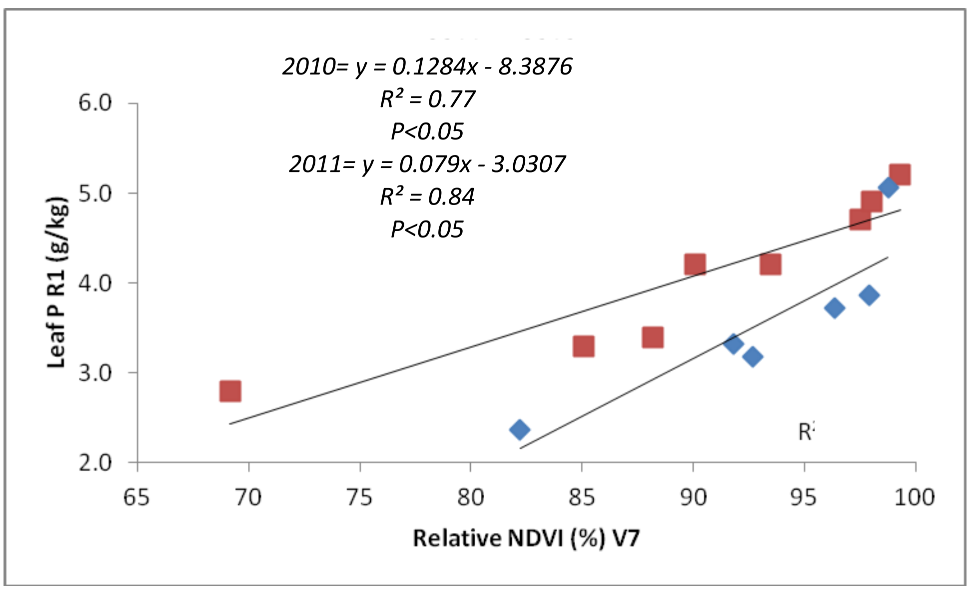

Figure 5.6: *Relationship between relative NDVI at V7 and leaf P concentration at R1.*

At R1, there was still a positive and strong correlation between leaf P concentration and relative NDVI (Fig. 5.7). However, by R1 crop growth was beginning to saturate the NDVI, especially with greater P and moisture availability in 2011. The

NDVI was able to detect differences due to lower P availability, but treatments with higher P rates exhibited similar NDVI values. The correlation between NDVI and leaf P at R1 was stronger for NDVI measured at V2, V4 and V7 than at R1. Due to NDVI saturation at R1, the proximal sensor was not able to detect differences among treatments receiving medium and high P fertilizer rates. The range in NDVI and leaf P concentration values was greater at R1 than at the other growth stages.

In conclusion, there was a strong and positive correlation between NDVI and leaf P at all growth stages. At V2, NDVI was more sensitive, able to detect P deficiency, than leaf tissue analysis. This could be related to the fact that NDVI is sensitive to biomass production and/or LAI. The results suggest that the best moment to use a proximal reflectance sensor to determine early P stress falls between V4 and V7, followed by leaf tissue analysis to confirm a P deficiency. By R1, crop growth resulted in NDVI saturation and no ability to detect differences between moderate P deficiency and P sufficiency.

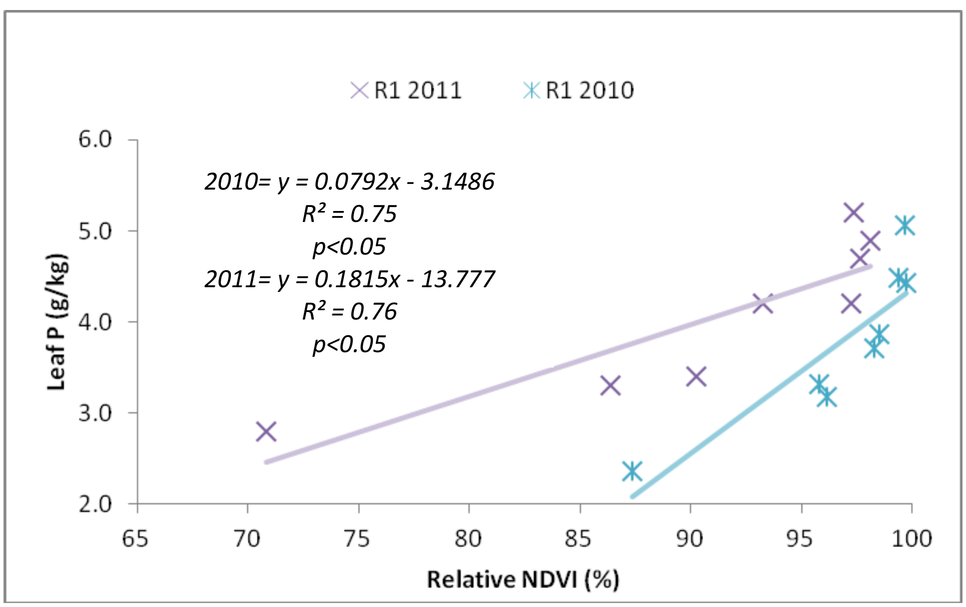

Figure 5.7: *Relationship between relative NDVI and leaf P concentration at R1.*

NDVI – Leaf K – K Stress Relationships

Mandal et al. (2009) attempted to quantify root biomass and density, nodulation, crop biomass and grain yield of soybean in relation to NPK fertilizer and organic manure. Observations were recorded for the no fertilizer, NPK and NPK + manure treatments. Biomass of stem, petiole and leaf were significantly greater in NPK and NPK + manure treatments. Grain yields were increased by 72 and 98 %, and stover yields by 56 and 95 % with NPK and NPK + manure treatments. Again, NDVI detected differences in biomass production and leaf area. Phosphorus and K deficiencies affect these two parameters, allowing a correlation between NDVI and P and K deficiencies.

In 2010, leaf samples were at R1, and in 2011 leaf samples were taken at V2, V4, V7 and R1. In 2011, relative NDVI and leaf K concentration at V2 were moderately and positively correlated (Fig. 5.8). At V2, the range in NDVI values with K stress was smaller than the range in NDVI values due to P stress.

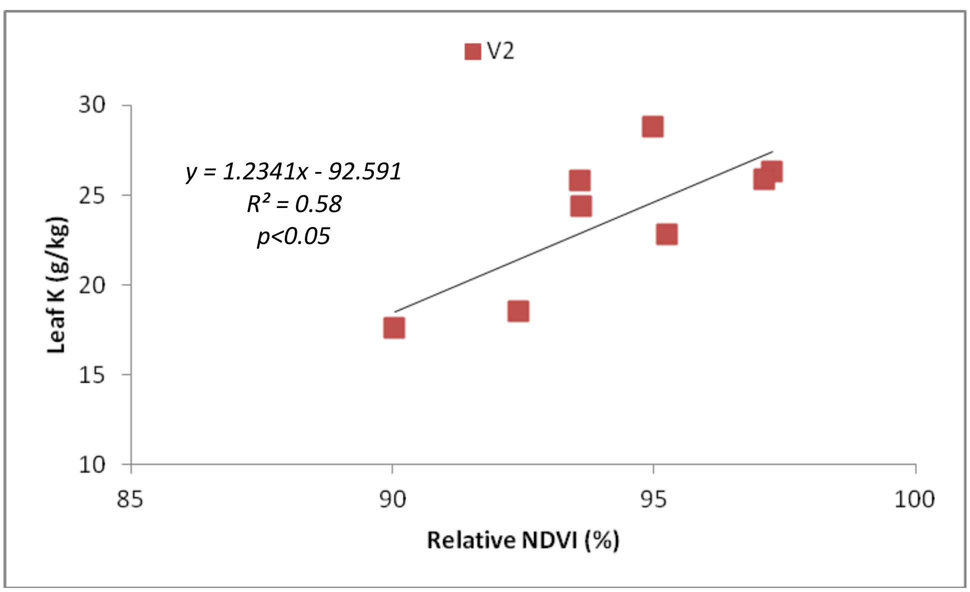

Figure 5.8: *Relationship between relative NDVI and leaf K concentration at V2 in 2011.*

There was a positive and moderate correlation between NDVI measured at V2 and leaf K content at R1 in 2011, but in 2010 the correlation was not significant (Fig. 5.9). The NDVI measurements were a good predictor of leaf K at V2, but not at R1. However, NDVI was a better predictor of leaf P at V2 and R1 than leaf K. The NDVI was not very sensitive to K deficiency at V2. However, with more normal weather, in 2011, conditions caused better results. Another important point is that soybean K deficiency was not as severe as P deficiency, in either year.

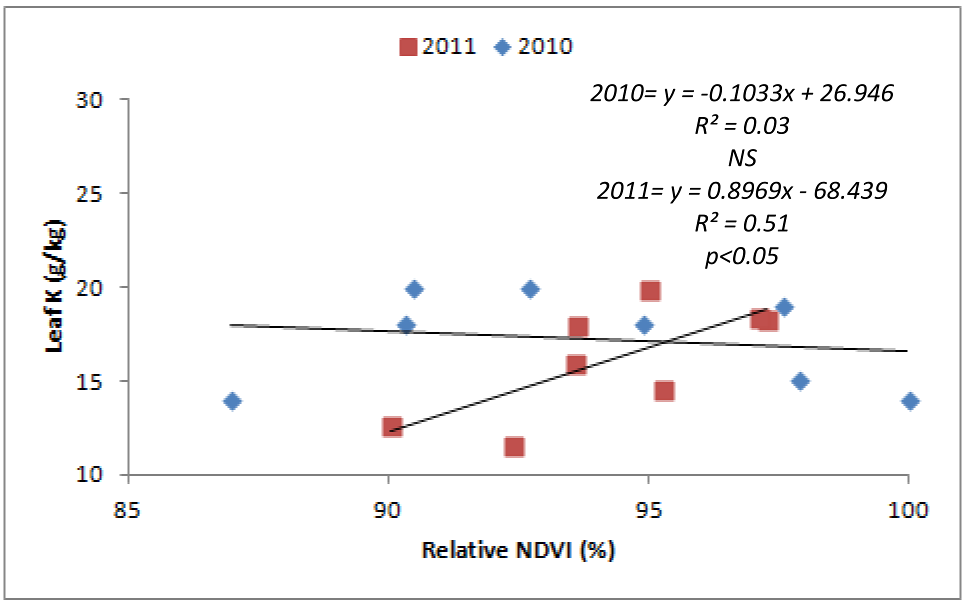

Figure 5.9: *Relationship between relative NDVI at V2 and leaf K concentration at R1.*

In 2011 there was a positive and moderate correlation between NDVI measured at V4 and leaf K concentration at V4 (Fig. 5.10). At this growth stage, there was a general reduction in K concentration as compared with that observed at V2. In contrast, NDVI was more sensitive to leaf P concentration variation at this growth stage.

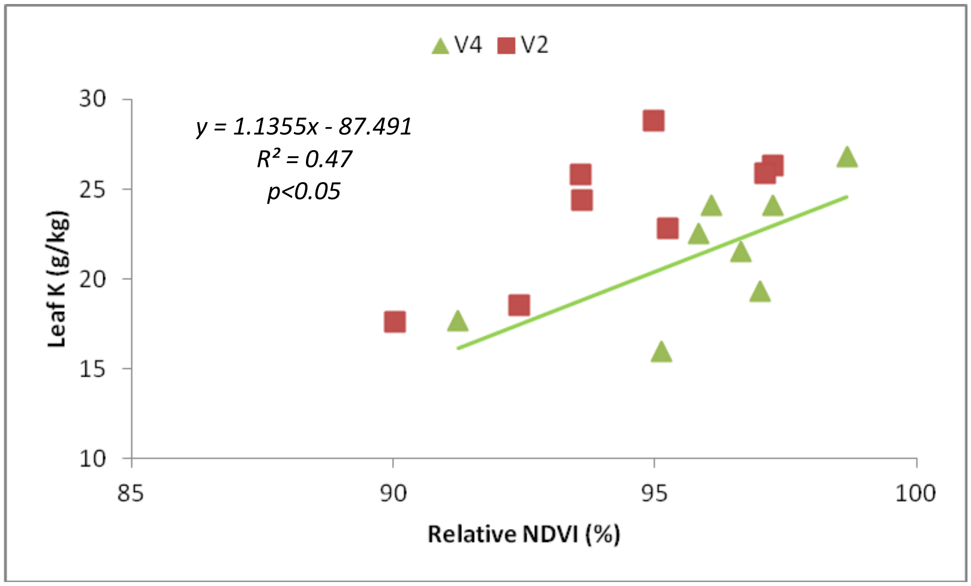

Figure 5.10: *Relationship between relative NDVI and leaf K concentration at V4 in 2011.*

There was a positive and moderately strong correlation between NDVI at V4 and leaf K at R1 in both 2010 and 2011 (Fig 5.11). Though the regression was stronger with leaf K at R1 than at V4, NDVI at V4 was a fair predictor of leaf K at both growth stages.

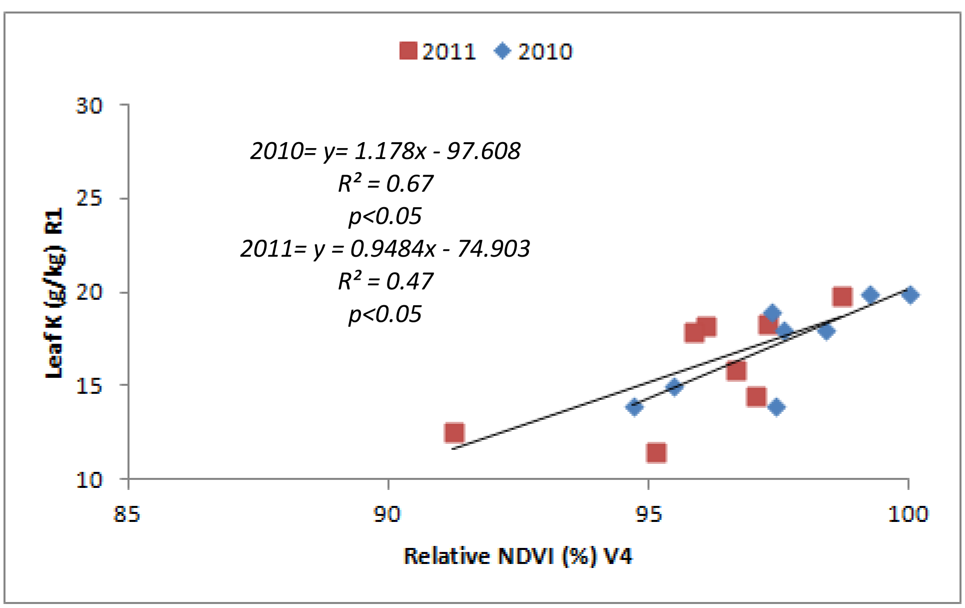

Figure 5.11: *Relationship between relative NDVI at V4 and leaf K concentration at R1.*

At V7, the regression between NDVI and leaf K (Fig. 5.12) was better than that observed at earlier growth stages. Treatment leaf K concentrations at V7 were lower than at V2 and V4. However, the range in NDVI values was similar.

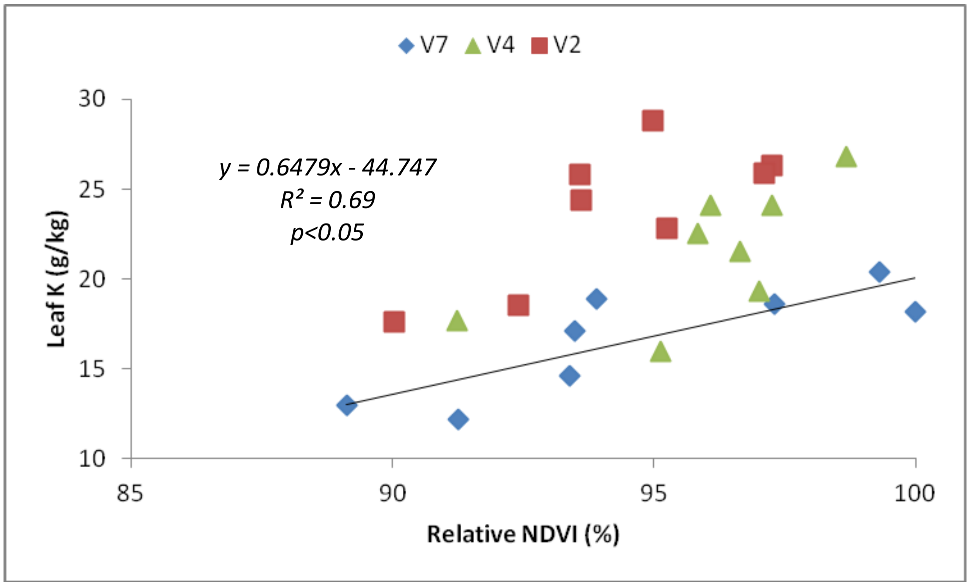

Figure 5.12: *Relationship between relative NDVI and leaf K concentration at V7 in 2011.*

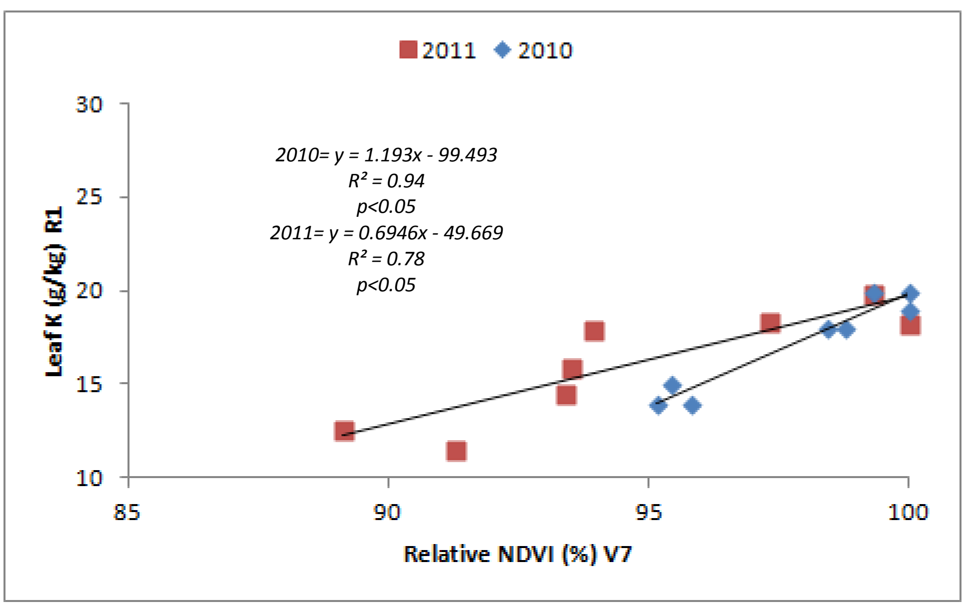

Figure 5.13: *Relationship between relative NDVI at V7 and leaf K concentration at R1.*

In both years there was a strong, positive correlation between NDVI at V7 and leaf K at R1 (Fig. 5.13). In 2011, with normal weather, there was larger variation in leaf K and NDVI due to treatment. However, in 2010 there was a stronger regression than in 2011. The regression between NDVI at V7 and leaf K concentration at V7 or R1 was stronger than when NDVI was measured at earlier growth stages (V2 and V4).

In both years a strong, positive correlation between NDVI and leaf K was observed at R1 (Fig. 5.14). However, 2011 exhibited a greater range in NDVI and leaf K values, and a stronger correlation, than did 2010. In 2010, the range in NDVI values was smaller, due to the dry conditions.

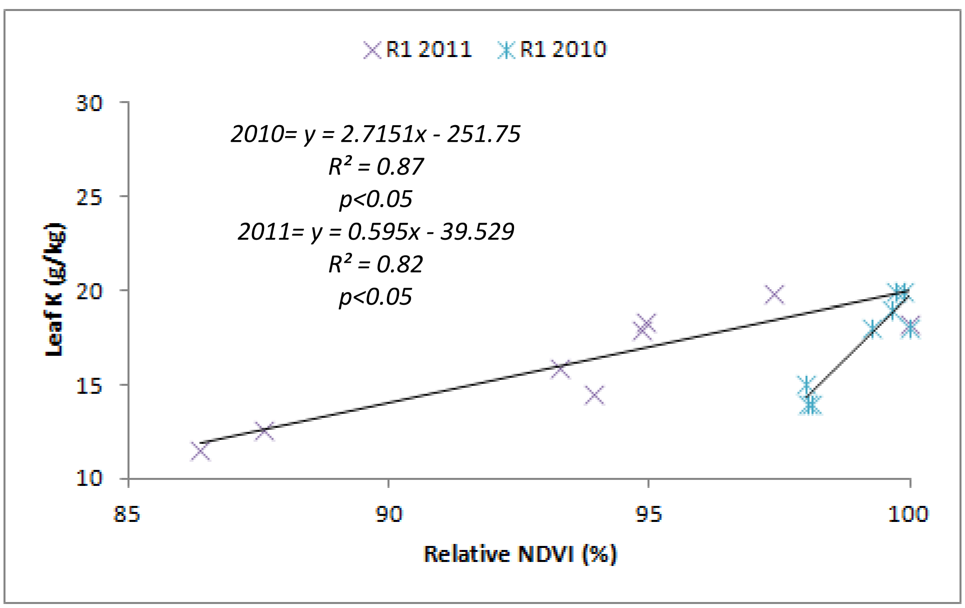

Figure 5.14: *Relationship between relative NDVI and leaf K concentration at R1.*

In conclusion, there was a moderately positive correlation between NDVI and leaf K at V2 and V4. At V7, NDVI was more sensitive to K deficiency, exhibiting stronger regressions between NDVI and leaf K values measured at R1 and V7. Measurements taken at R1 exhibited the strongest correlation, in both years. However, 2011 gave a larger range in NDVI values and a stronger correlation. Dry weather conditions in 2010 may have limited K uptake and plant growth and narrowed the range in observed NDVI values. The best moment to scan soybean to detect early K deficiency and allow for corrective action, lies between V4 and V7. At those growth stages, leaf tissue analysis is needed to confirm any K deficiency.

NDVI – Yield – P Stress Relationships

Soybeans require large amounts of P, especially at pod set, and P is required for normal N fixation. Phosphorus deficient soybean plants are spindly, with small leaflets and stunted growth. Leaves may appear dark or bluish green. In general, early P deficiency detection is difficult. In this study, at V2, there was a positive and moderately strong regression between NDVI and yield (Fig. 5.15). Both years follow a similar linear model. Given less variation in leaf P at this growth stage (Fig. 5.1), the proximal sensor

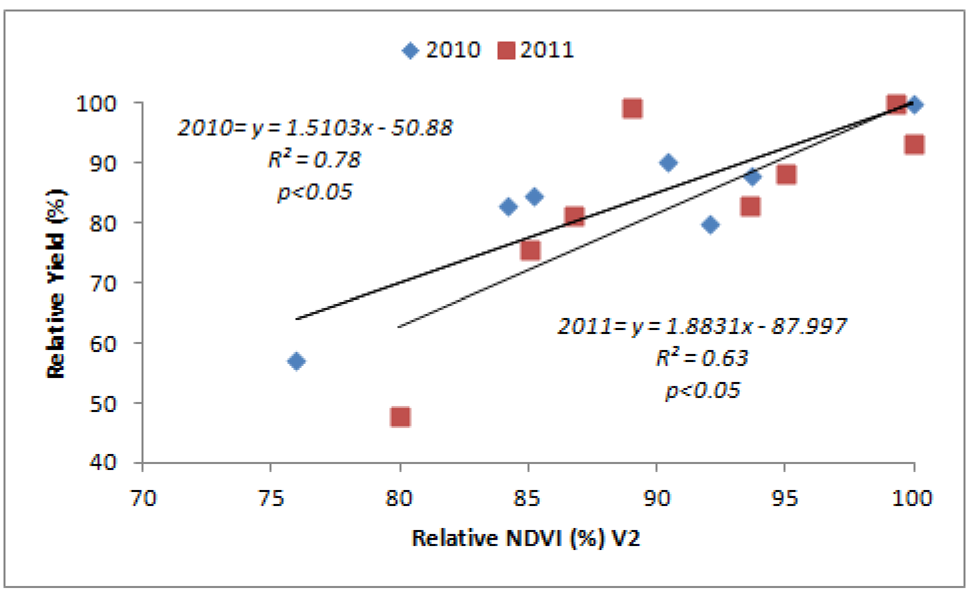

Figure 5.15: *Relationship between relative NDVI at V2 and relative yield due to P.*

detected differences in biomass or leaf area. At this very early growth stage, leaf tissue analysis does not seem to be a good predictor of P nutrition stress (Fig. 5.1). This is a limitation to the use of NDVI at V2, because P deficiency may be confused with another stressor, unless the P deficiency is severe.

A positive and strong correlation between NDVI at V4 and relative yield was observed in both years, following a similar linear model (Fig. 5.16). At this growth stage the range in NDVI values was similar to that observed at V2. At V4, visual observation did not detect any P deficiency.

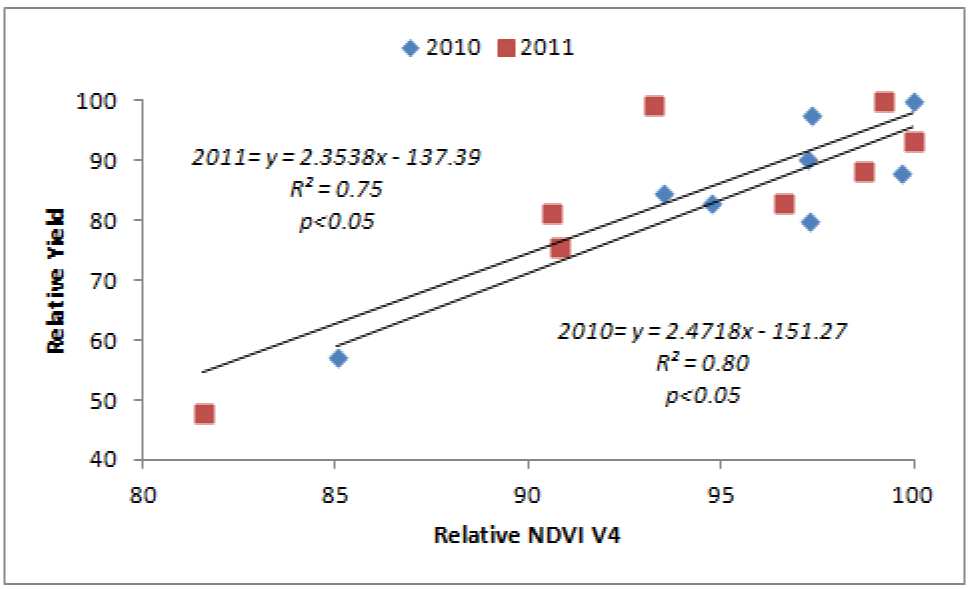

Figure 5.16: *Relationship between relative NDVI at V4 and relative yield due to P.*

The regression between relative NDVI at V7 and relative yield was stronger than at the previous growth stages, with a greater range in NDVI values (Figure 5.17). The greater range in NDVI values followed the greater range in leaf P concentrations discussed previously (Chapter 3). There was leaf P dilution in treatments with lowest P availability. Under P stress, plants were not able to maintain P concentrations after V4.

The range in NDVI values was larger in 2011 than in 2010, due to the water stress during 2010. Water limited yields, reducing the impact of P deficiency.

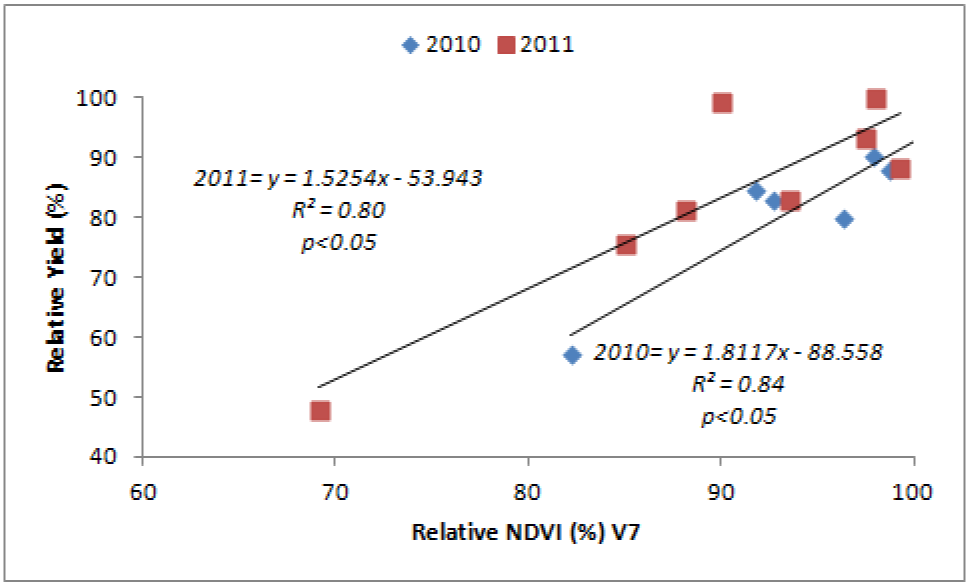

Figure 5.17: *Relationship between relative NDVI at V7 and relative yield due to P.*

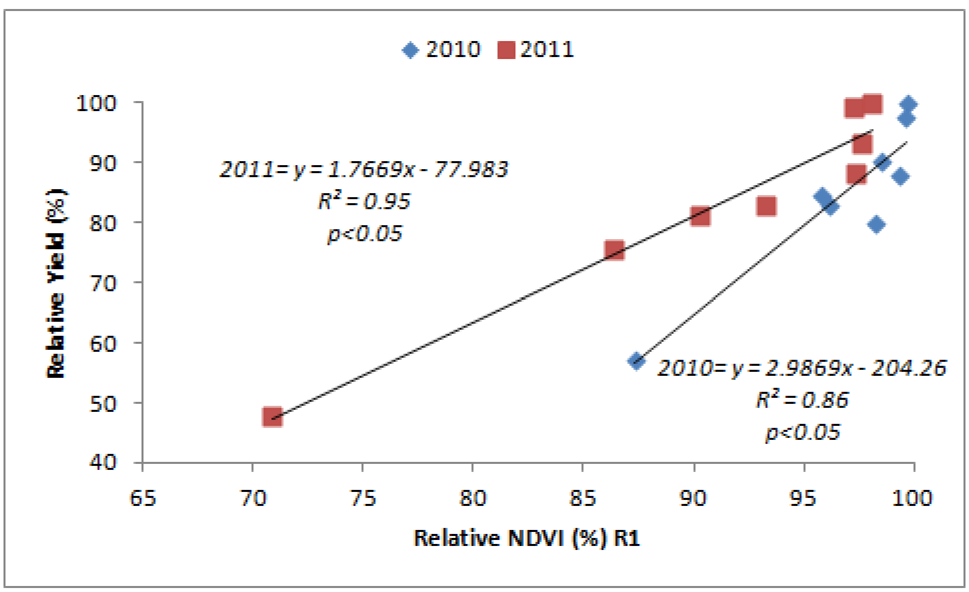

Figure 5.18: *Relationship between relative NDVI at R1 and relative yield due to P.*

At R1, the regression between relative NDVI and relative yield was stronger than at earlier stages (Figure 5.18). The regression was particularly strong in 2011, with normal weather. The greatest range in NDVI values due to P deficiency was observed. In 2010 the range in NDVI values was smaller and related with general water stress.

The NDVI measurements were sensitive to P deficiencies, across all growth stages. The correlation between NDVI and yield became stronger as the growing season progressed, in both years. At V2, NDVI detected something other than differences due to leaf tissue P concentration. Those differences may have been related to biomass production or leaf area. Based on these results, the best time to use NDVI to detect P deficiencies begins at V4, when there is a stronger correlation between NDVI and yield, and plant tissue analysis can determine if P is the growth limiting factor.

NDVI – Yield – K Stress Relationships

Leaf K deficiency symptoms are yellowing of the margins of older leaves, usually beginning at the leaf tip and extending down the margins towards the leaf base. With severe deficiency leaf edges may become necrotic (dead) and affected plants are stunted, although newest leaves may be normal. Symptoms usually appear later in the season.

Among K treatments, the correlation between relative NDVI at V2 and relative yield was positive and strong in 2011, and moderate in 2010 (Fig. 5.19). The NDVI was able to detect early K deficiency in both years. The range in NDVI values and yield, for both years, was smaller than that from the P treatments.

At V4, in both 2010 and 2011, there was a positive and moderate correlation between relative NDVI and relative yield (Fig. 5.20). Similar linear models were fitted in both years. The yield response to K was greater in 2011 than in 2010, due to better environmental conditions during the 2011 crop season.

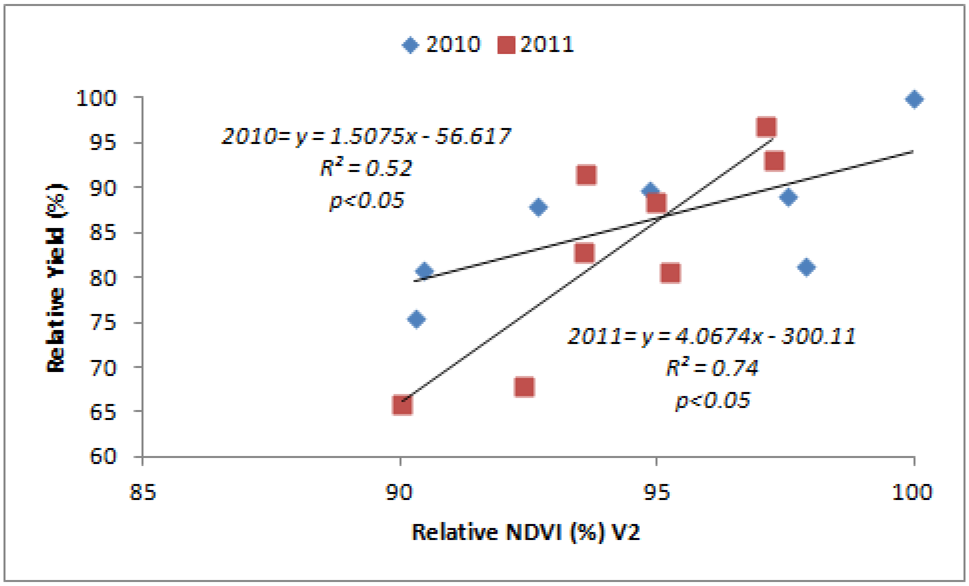

Figure 5.19: *Relationship between relative NDVI at V2 and relative yield due to K.*

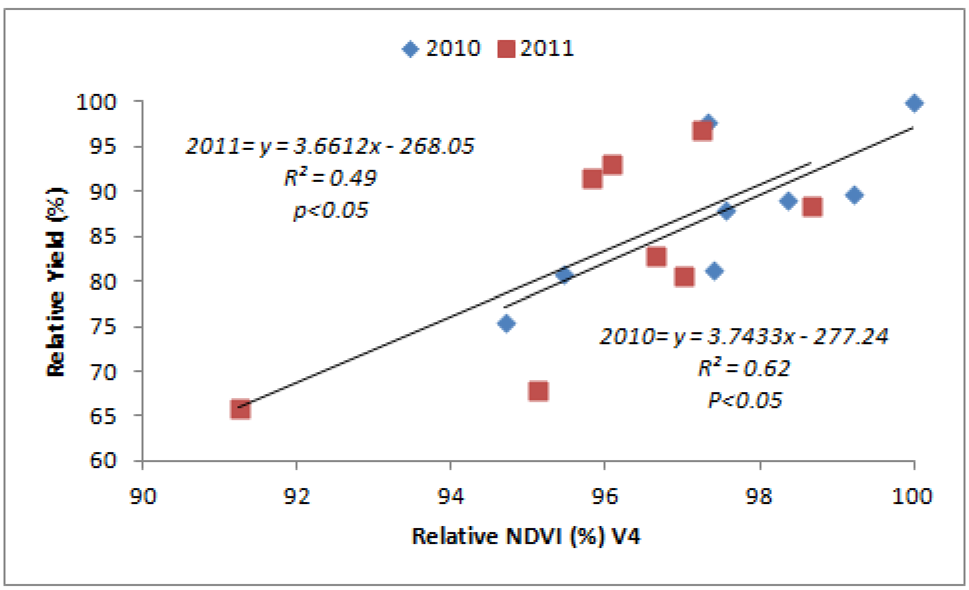

Figure 5.20: *Relationship between relative NDVI at V4 and relative yield due to K.*

In both years, the regression between relative NDVI at V7 and relative yield due to K stress was positive and strong (Figure 5.21). The range in NDVI values at this growth stage was higher in 2011 than in 2010, and the range in NDVI values observed at previous stages was similar. At this growth stage, it was impossible to visually distinguish among K treatments in the field and no clear symptoms were observed. The NDVI was sensitive enough to detect differences between K treatments.

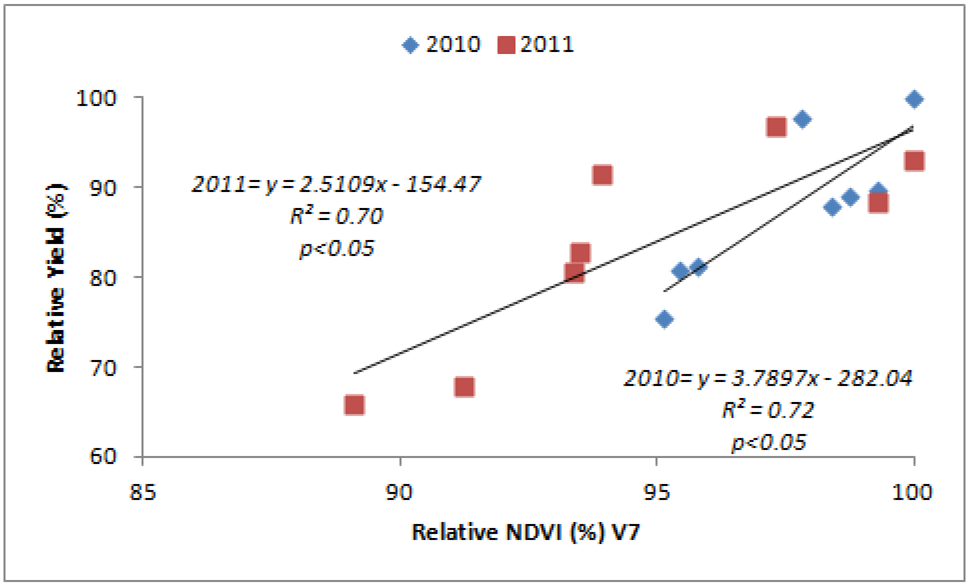

Figure 5.21: *Relationship between relative NDVI at V7 and relative yield due to K.*

The relationship between relative NDVI measured at R1 and relative yield was positive and strong in both years (Fig. 5.22). However, there were some differences between years. In 2011, the regression was a strong linear model, across a wide range of NDVI values. In 2010 the regression was not as strong as in 2011, and the range in relative NDVI values was small (97 to 100 %). The range in NDVI values in 2010 made identifying deficiencies difficult. As was discussed previously, 2010 was a dry year with low yields and 2011 was a normal year, yield-wise. These results indicate that under normal environmental conditions, NDVI was a good predictor of K deficiencies.

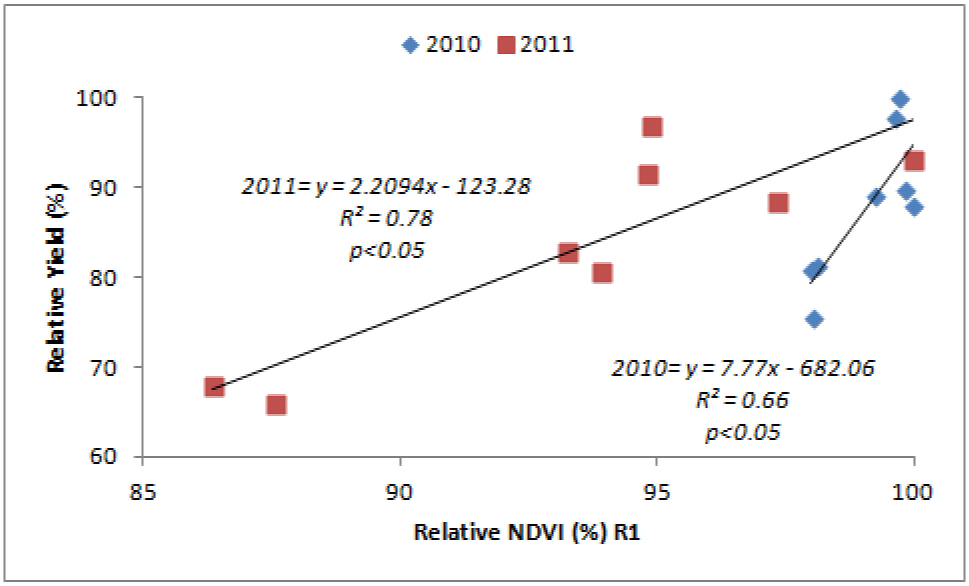

Figure 5.22: *Relationship between relative NDVI at R1 and relative yield due to K.*

The NDVI measurements were sensitive to K deficiencies, across all growth stages. The correlation between relative NDVI and relative yield was moderate at V2 and V4, and strong at V7 and R1. Visual detection of differences between K treatments was impossible before R1. However, NDVI sensed differences between treatments. Maybe those differences were related to small variations in biomass or leaf area, as discussed before. Based on these results, the best time to use NDVI to detect K deficiencies is after V4 when there is a strong correlation between NDVI and yield and plant tissue analysis can assist in the detection of the limiting factor.

SPAD Meter Detection of P and K Nutrition Stress

Chlorophyll measuring equipment such as the Soil-Plant Analyses Development (SPAD, Minolta Camera Co., Osaka, Japan) meter determines chlorophyll concentration of leaves, and is a popular method for estimating leaf N in corn and wheat (Turner and Jund, 1991). As leaf chlorophyll concentration was directly related to N concentration by many investigators (Takebe et al. 1990), the chlorophyll meter can be used to assess plant N status. In this study, SPAD measurements were taken at R1 in 2010, and at V2, V4, V7 and R1 in 2011, on the same days when leaf tissue samples were taken.

There was no significant correlation between SPAD and leaf K at any growth stage, either in 2010 nor 2011 (data not shown). As discussed previously, SPAD values are strongly correlated with chlorophyll. The results obtained in this study suggest that there was no effect of K nutrition on leaf N or chlorophyll. In 2010, there was a strong, positive between SPAD values and R1 leaf N and P concentrations (Fig. 5.23).

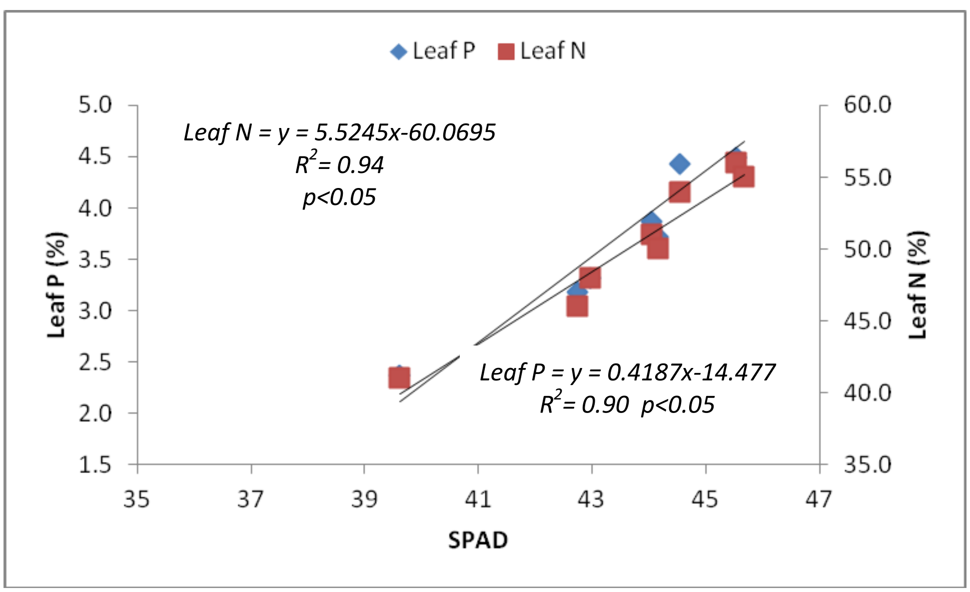

Figure 5.23: *Relationship between SPAD and leaf P and N concentrations at R1 in 2010.*

As discussed previously, there was a strong, positive correlation between leaf P and N at this growth stage. One consequence of N deficiency is a reduction in leaf chlorophyll formation and density (Thomson and Weier, 1962). Legumes require adequate supplies of P and Fe for high BNF rates and growth (Sinclair and Valdez, 2002). The observed responses are due to the high P requirement for energy transfer.

Nitrogen fixation sensitivity to drought stress is well documented (Wilson, 1931). Nitrogenase activity sensitivity to decreasing soil water content constitutes an important constraint to N accumulation and soybean yield. Under 2010's dry conditions, N accumulation was limited by two factors, P and water. Also, there may have been an interaction between the two factors. In 2011, a strong, positive correlation between leaf N and leaf P was observed at R1, similar to 2010 results (chapter 3). However, there was no significant regression between SPAD and leaf N at V7, but there was a strong correlation between SPAD and leaf P (Fig. 5.24).

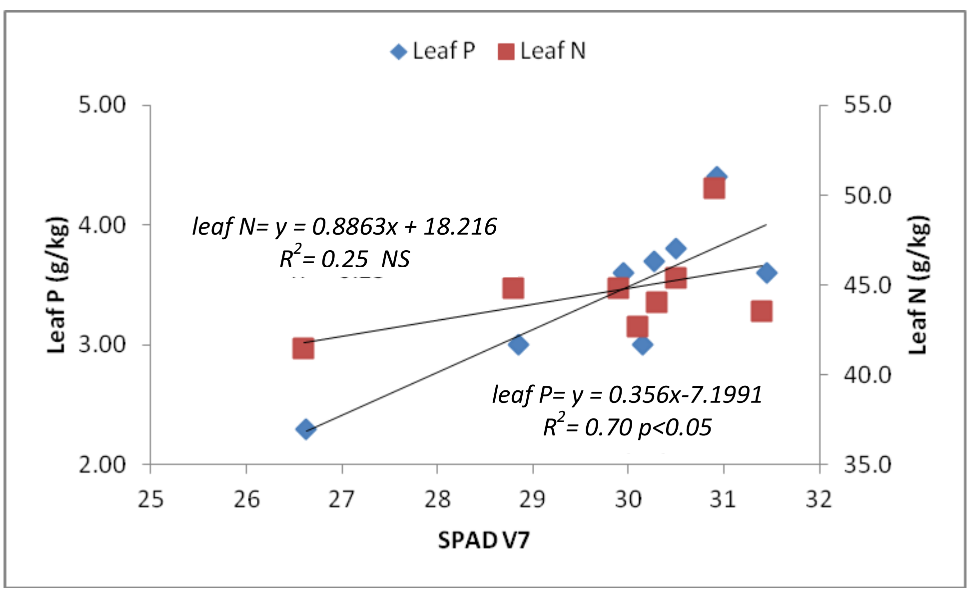

Figure 5.24: *Relationship between SPAD and leaf P and N concentrations at V7 in 2011.*

There was a positive correlation between leaf N and P at V2, but only two of the P treatments exhibited values lower than average. These two treatments were the ones that received the lowest P nutrition. That correlation between P and N may explain why early detection of nutritional deficiency using NDVI was more accurate with P than with K and why the range of NDVI values was greater with the different P rates than with the different K rates. However, there was no correlation between leaf P and N and SPAD values at V2. As opposed to what happened at V2, at V4 there was no relationship between leaf N and leaf P. One possible explanation is the difference in biomass production (detected by NDVI measurements). Treatments with low P nutrition exhibited a medium leaf N concentration and this was associated with lower biomass. There was no relation between leaf K and leaf N.

In conclusion, SPAD readings were strongly related with leaf P and N at R1 in 2010. The dry conditions in 2010 led to low yields. Although there was a moderate to strong correlation between SPAD values and leaf P at V7, there were no significant correlations at other growth stages. One possible explanation for these results is the presence of some kind of interaction between P stress and water deficiency, making SPAD measurements more sensitive at 2010.

CHAPTER SIX

Final Analysis and Conclusions

Sensor NDVI measurements accurately predicted leaf P and K concentrations, and yield, across different levels of K and P nutrition in 2010 and 2011. Results were similar between years, under completely different weather conditions and yield levels. Figure 6.1 shows the relationship between relative NDVI measured at R1 and relative yield, combining all treatments and both years, which exhibited a positive and strong correlation, a singular linear model. Similar models were observed at V4 and V7, with regression coefficients of 0.64 and 0.68, respectively.

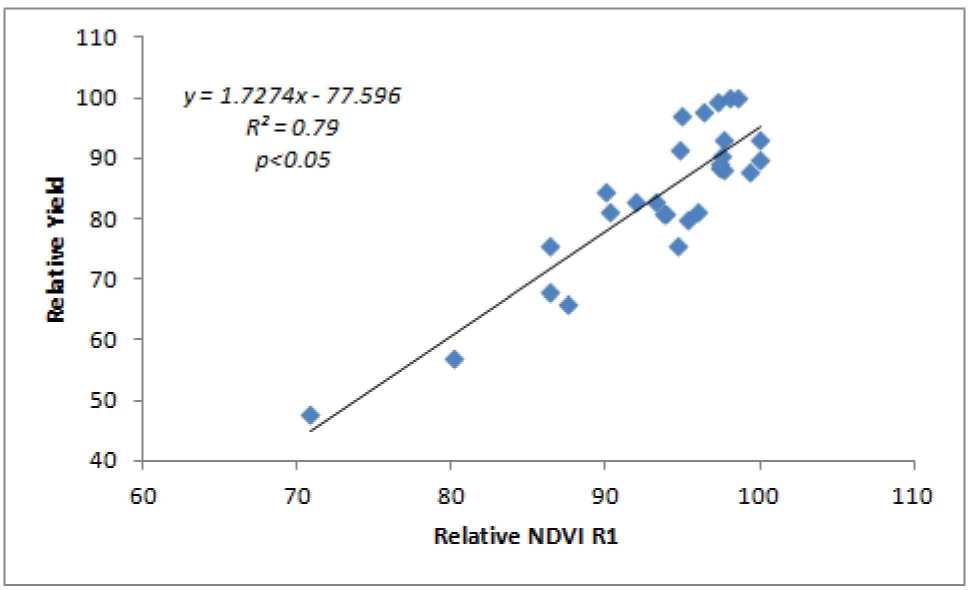

Figure 6.1: *Relationthip between relative NDVI at R1 and relative yields, across all treatments, and combined across the 2010 and 2011production seasons.*

The sensor detected K or P deficiencies. However, it was not possible to distinguish between the two deficiencies measuring only NDVI. So, though NDVI detected that there was a crop growth limitation, the tool was not able to distinguish among the different causes of growth problems. Early leaf tissue analysis could be a tool to determine nutritional limitations. Soybean P deficiencies were first detected at V4 using leaf tissue analysis. Leaf tissue analysis was able to detect K deficiencies after V2.

The NDVI was as accurate as plant tissue analysis in detecting P deficiencies and predicting grain yield at R1 (Figs. 5.18 and 3.16). At V2, NDVI better predicted P deficiency and grain yield, compared to plant tissue analysis (Figs. 5.2 and 5.15). At this growth stage only two treatments exhibited lower leaf P concentrations. However, NDVI measurement detected differences between treatments related with something other than leaf P concentration. Those differences in NDVI values among the P treatments may be related with differences in biomass or leaf area. Board et. al. (2007) used NDVI to detect differences in LAI and light interception among different soybean varieties. In 2004, differences in LAI and light interception were created by manual defoliation, whereas in 2005 LAI/light interception differences occurred because of different cultivars and planting dates. Results indicated that across canopies ranging from very low LAI to canopy closure (95 % light interception), NDVI accurately predicted LAI and light interception ($r^2 = 0.93$ to 0.97). Light interception and LAI were linked to NDVI by strong linear regression models. However, NDVI was measured around R1.

The NDVI, at any growth stage and over both years, better predicted P deficiency and grain yield than soil test analysis (Figs. 3.1 and 3.2). Post-harvest soil analysis in 2012 did not reflect the addition of P and K to manure treatments (Fig. 3.2). However, NDVI well reflected plant P status, both years, at any growth stage (Figs. 5.1, 5.3 and 5.5).

Plant tissue analysis, at any growth stage, was more accurate than NDVI in detecting soybean K deficiency and predicting grain yield response to K nutrition (Fig. 3.13). However, NDVI was accurate enough to be used as a diagnostic tool. The NDVI was more accurate than soil analysis in detecting K deficiency and grain yield loss.

Remote sensed data are capable of capturing changes in plant growth throughout the growing season, whether related to changes in chlorophyll concentration or canopy structure (Shih, 1994). The NDVI provides the opportunity to create field maps that can help one to understand spatial and temporal variability across the field. There are multiple ways to collect data for the maps: equipment-mounted sensors, images taken from airplanes and satellites. The NDVI maps could give an idea of crop status when management practices can be executed. When both yield and NDVI maps are collected, the NDVI map can be an in-season progress report and the yield map the final report.

The NDVI measurements could be used to detect early nutritional deficiencies in soybean. Based on these results, the best time to scan the crop would be between V4 and V7. Another measurement, like leaf tissue analysis, should be used to accurately determine which nutritional factor is limiting plant growth. These results suggest an opportunity for the use of NDVI for the diagnosis of P and K deficiencies. However, this opportunity presents a potential challenge in fields where NDVI is used to detect N deficiencies, because N deficiencies may be confounded with P or K deficiencies.

APPENDIX

Table A1: *Soil information-2010.*

Plot	Treatment	Soil P	Soil K	Soil pH	OM
Number	Number	PPM	PPM		%
5	1	10	178	4.83	2.13
21	1	12	151	4.13	2.22
34	1	9	153	4.74	2.10
47	1	8	129	4.91	2.00
10	2	14	158	5.28	2.20
26	2	14	169	4.87	2.27
33	2	15	121	5.13	2.46
43	2	9	169	5.68	2.39
2	3	10	130	4.94	1.77
25	3	13	137	4.89	2.00
37	3	12	128	4.91	2.46
53	3	11	131	5.06	2.29
7	4	21	181	5.05	2.37
22	4	16	151	5.40	2.44
40	4	24	146	5.09	2.58
44	4	14	155	5.16	2.30
8	5	21	168	5.28	2.37
17	5	26	119	4.99	3.16
35	5	17	121	4.55	2.22
50	5	12	133	5.11	2.53
6	6	28	135	5.03	2.41
15	6	40	160	5.22	2.70
30	6	35	149	5.19	2.94
52	6	26	136	5.14	2.56
1	7	16	120	4.84	1.93
19	7	27	118	4.78	2.65
41	7	18	106	4.68	2.24
45	7	17	136	5.04	2.17
14	8	49	154	5.02	2.24
27	8	36	131	4.59	2.37
31	8	61	127	5.27	2.63
55	8	36	154	5.09	2.43
4	9	17	88	4.96	2.01
18	9	35	126	5.03	2.92
42	9	25	105	4.53	2.18
46	9	22	108	4.94	2.29
9	10	55	109	5.37	2.25
20	10	65	124	4.61	2.84
32	10	47	111	5.19	2.87
51	10	34	122	5.22	2.77
11	11	30	105	4.81	2.30

28	11	37	86	4.39	2.34
36	11	18	131	4.98	2.27
56	11	28	98	4.57	2.17
13	12	52	121	5.08	2.36
24	12	33	108	4.94	2.03
38	12	42	156	5.01	2.44
49	12	35	92	4.83	2.18
12	13	39	81	4.72	2.48
23	13	24	100	4.97	2.25
39	13	34	90	4.92	2.10
48	13	32	77	4.86	1.77
3	14	19	94	4.99	1.77
16	14	82	102	5.21	2.68
29	14	48	138	5.28	2.80
54	14	45	80	5.12	2.10

Table A2: *Leaf nutrient concentrations and NDVI and SPAD readings at R1 in 2010.*

Plot Number	Treatment Number	N Conc. %	P Conc. %	K Conc. %	SPAD reading	NDVI reading
5	1	4.16	0.234	2.20	0.6645	38.9
21	1	4.28	0.260	2.19	0.68671	39.4
34	1	3.82	0.197	2.24	0.63564	40.4
47	1	3.99	0.258	2.01	0.74452	39.75
10	2	4.54	0.318	2.27	0.74747	42.4
26	2	4.86	0.333	2.17	0.74569	43.1
33	2	4.77	0.326	2.01	0.72452	43.4
43	2	4.41	0.293	2.09	0.77515	42.1
2	3	4.55	0.286	1.88	0.69785	41.8
25	3	4.86	0.356	1.95	0.7092	44.4
37	3	4.90	0.363	2.15	0.76744	43.4
53	3	4.72	0.324	2.01	0.76764	42.3
7	4	5.03	0.384	2.30	0.77356	43.6
22	4	5.26	0.394	2.08	0.77275	42.4
40	4	5.19	0.407	2.11	0.77601	42.9
44	4	4.92	0.363	2.28	0.79887	47.3
8	5	5.08	0.398	1.77	0.77792	44.2
17	5	5.01	0.379	1.79	0.77227	43
35	5	4.94	0.360	1.69	0.74616	44.4
50	5	4.93	0.351	1.73	0.77473	45
6	6	5.26	0.457	2.27	0.78398	45.1
15	6	5.46	0.408	2.15	0.78417	44.3
30	6	5.77	0.458	1.99	0.79135	47.4
52	6	5.81	0.472	2.18	0.79208	45.3
1	7	5.50	0.442	1.99	0.75876	43.6
19	7	5.22	0.437	1.94	0.803	44.4
41	7	5.31	0.449	1.93	0.78827	44.5

45	7	5.48	0.445	2.05	0.79853	45.7
14	8	5.07	0.496	2.04	0.75732	47.5
27	8	5.40	0.504	2.09	0.7903	46
31	8	5.76	0.516	1.71	0.77417	43.7
55	8	5.84	0.508	1.93	0.80127	45.5
4	9	5.18	0.399	1.45	0.75671	43.2
18	9	5.20	0.438	2.01	0.79135	45.3
42	9	5.38	0.480	1.68	0.78137	45.2
46	9	5.82	0.488	1.94	0.79193	45.4
9	10	5.55	0.532	1.99	0.79007	43.9
20	10	5.77	0.521	2.09	0.79151	45.9
32	10	5.63	0.532	1.80	0.79024	45.3
51	10	5.53	0.521	1.97	0.79905	44.7
11	11	5.49	0.499	1.64	0.76202	43.4
28	11	5.33	0.490	1.43	0.75266	44
36	11	5.50	0.431	1.80	0.78714	44.6
56	11	5.37	0.474	1.21	0.78816	43.5
13	12	5.52	0.499	1.94	0.77545	46.8
24	12	5.52	0.515	1.69	0.76117	45.6
38	12	5.65	0.522	1.85	0.78148	46.3
49	12	5.67	0.492	1.64	0.79697	46
12	13	5.39	0.508	1.53	0.74075	45.1
23	13	5.35	0.487	1.60	0.76614	45.1
39	13	5.49	0.506	1.52	0.76942	43.7
48	13	5.30	0.511	1.13	0.76722	42.4
3	14	5.17	0.461	1.34	0.7481	45.3
16	14	5.83	0.525	1.55	0.78137	44.5
29	14	5.91	0.455	1.47	0.78438	42.6
54	14	5.90	0.565	1.30	0.78648	43.25

Table A3: *NDVI readings at V2, V4, and V7 in 2010.*

Plot Number	Treatment Number	NDVI V2 Reading	NDVI V4 Reading	NDVI V7 Reading
5	1	0.55786	0.651	0.64826
21	1	0.49846	0.63703	0.65908
34	1	0.56546	0.63659	0.58737
47	1	0.61075	0.71079	0.71696
10	2	0.51469	0.71686	0.72857
26	2	0.58455	0.73362	0.71542
33	2	0.64963	0.71671	0.72471
43	2	0.72494	0.76865	0.7766
2	3	0.59028	0.67415	0.70712
25	3	0.55178	0.69852	0.69971
37	3	0.67005	0.75709	0.7708
53	3	0.69289	0.76811	0.73875
7	4	0.54703	0.72127	0.75507

22	4	0.61772	0.73302	0.76672
40	4	0.74675	0.7723	0.78562
44	4	0.7459	0.78671	0.80396
8	5	0.52603	0.73643	0.75622
17	5	0.6975	0.7562	0.76698
35	5	0.68851	0.74237	0.76151
50	5	0.7931	0.77933	0.77603
6	6	0.55713	0.73084	0.76271
15	6	0.73675	0.77748	0.78335
30	6	0.69104	0.76645	0.79805
52	6	0.7674	0.81441	0.79358
1	7	0.71386	0.75639	0.7835
19	7	0.76385	0.77926	0.79595
41	7	0.70633	0.77719	0.79603
45	7	0.75467	0.78594	0.80179
14	8	0.57687	0.72483	0.76152
27	8	0.68979	0.75745	0.78615
31	8	0.62458	0.74534	0.77902
55	8	0.66439	0.78823	0.78068
4	9	0.64758	0.7318	0.76578
18	9	0.74011	0.76844	0.78516
42	9	0.72893	0.76444	0.78256
46	9	0.75029	0.80988	0.80458
9	10	0.57638	0.75639	0.77949
20	10	0.71517	0.77926	0.77114
32	10	0.68955	0.77719	0.78971
51	10	0.80706	0.78594	0.81419
11	11	0.65143	0.73267	0.75383
28	11	0.56511	0.68844	0.7223
36	11	0.68737	0.76467	0.78364
56	11	0.75456	0.77195	0.77219
13	12	0.67861	0.75284	0.77901
24	12	0.58905	0.71812	0.76003
38	12	0.67416	0.77027	0.7893
49	12	0.78152	0.78193	0.79841
12	13	0.64514	0.73596	0.74186
23	13	0.59771	0.72418	0.76711
39	13	0.68287	0.74343	0.77004
48	13	0.72785	0.73077	0.74394
3	14	0.65959	0.71435	0.71242
16	14	0.71905	0.7611	0.77936
29	14	0.72317	0.76051	0.79293
54	14	0.77478	0.78257	0.7588

Table A4: *Grain yield and nutrient concentrations in 2010.*

Plot Number	Treatment Number	Grain Yield kg/ha	Grain N %	Grain P %	Grain K %
5	1	949.7297	6.45	0.3	1.6
21	1	771.6843	6.5	0.342	1.61
34	1	553.6	6.505	0.328	1.68
47	1	1055.122	6.61	0.369	1.76
10	2	1203.797	6.67	0.423	1.66
26	2	1263.116	6.8	0.399	1.74
33	2	1212.869	6.79	0.398	1.73
43	2	1156.555	6.84	0.417	1.66
2	3	1438.955	6.61	0.385	1.61
25	3	1147.22	6.5	0.387	1.64
37	3	1231.719	6.715	0.429	1.70
53	3	1122.556	6.84	0.379	1.59
7	4	1474.435	6.54	0.459	1.62
22	4	1165.358	6.71	0.493	1.71
40	4	1434.579	6.8	0.48	1.63
44	4	1207.588	6.74	0.452	1.73
8	5	1253.705	7.08	0.504	1.64
17	5	1151.618	7.03	0.452	1.62
35	5	1010.372	6.81	0.461	1.58
50	5	1245.923	6.93	0.427	1.56
6	6	1556.395	6.18	0.512	1.66
15	6	1109.671	6.98	0.561	1.71
30	6	1127.888	7.15	0.583	1.73
52	6	1344.407	6.86	0.54	1.66
1	7	1275.52	6.7	0.524	1.62
19	7	1540.74	6.95	0.486	1.59
41	7	1410.464	6.83	0.494	1.52
45	7	1614.905	6.9	0.522	1.63
14	8	1438.9	7.06	0.613	1.65
27	8	1657.109	6.71	0.597	1.66
31	8	1136.51	7	0.604	1.66
55	8	1475.021	6.98	0.605	1.61
4	9	1319.67	7.04	0.546	1.52
18	9	1459.06	6.85	0.545	1.66
42	9	1196.643	6.93	0.561	1.53
46	9	1231.215	6.985	0.544	1.64
9	10	1370.1	6.84	0.605	1.62
20	10	1374.52	6.74	0.579	1.61
32	10	1276.242	7.04	0.611	1.68
51	10	1223.089	6.95	0.614	1.65
11	11	1267.277	7	0.594	1.44
28	11	1036.847	6.95	0.593	1.54
36	11	1091.85	7.1	0.523	1.54
56	11	1324.161	6.93	0.608	1.41

13	12	1490.581	6.94	0.601	1.56
24	12	1152.065	6.925	0.597	1.59
38	12	1259.588	7.12	0.588	1.59
49	12	1228.515	7.08	0.614	1.51
12	13	1244.372	7.09	0.6	1.43
23	13	1050.075	7.16	0.608	1.58
39	13	1155.574	6.95	0.583	1.43
48	13	961.6944	7.1	0.619	1.32
3	14	1388.691	6.69	0.57	1.49
16	14	1104.639	6.93	0.603	1.45
29	14	989.6729	7.2	0.602	1.54
54	14	1255.728	6.93	0.611	1.41

Table A5: *Soil information 2011.*

Plot	Treatment	Soil P	Soil K	Soil ph	OM
Number	Number	PPM	PPM		%
5	1	14	253	4.89	2.27
21	1	13	153	4.55	2.06
34	1	11	205	4.93	2.25
47	1	15	206	5.01	2.67
10	2	14	125	5.27	2.25
26	2	21	149	4.63	2.49
33	2	18	166	5.39	2.61
43	2	16	240	5.41	2.91
2	3	14	159	4.99	2.34
25	3	17	123	4.62	2.51
37	3	16	149	5.03	2.32
53	3	13	117	4.86	2.30
7	4	32	190	5.33	2.99
22	4	18	127	4.81	2.61
40	4	23	140	4.93	2.36
44	4	22	229	5.06	2.99
8	5	20	125	5.08	2.29
17	5	14	112	4.86	2.27
35	5	20	159	4.79	3.01
50	5	12	136	4.81	2.44
6	6	43	181	5.26	3.04
15	6	25	119	4.90	2.39
30	6	36	179	5.05	2.68
52	6	21	137	4.99	2.43
1	7	34	171	4.87	2.94
19	7	25	107	4.52	2.30
41	7	21	103	4.35	2.17
45	7	29	177	5.02	2.96
14	8	42	128	4.64	2.27
27	8	66	131	4.61	2.86

31	8	41	150	4.85	2.39
55	8	36	121	4.91	2.34
4	9	29	102	4.83	2.82
18	9	23	104	4.78	2.63
42	9	35	94	4.38	2.22
46	9	33	153	5.02	3.18
9	10	53	116	4.99	2.51
20	10	49	110	4.50	2.37
32	10	42	128	4.97	2.77
51	10	29	124	4.78	2.67
11	11	30	76	4.68	2.24
28	11	39	87	4.13	2.48
36	11	24	123	4.72	2.58
56	11	42	111	4.34	2.70
13	12	41	103	4.97	2.22
24	12	38	91	4.77	2.17
38	12	32	99	4.90	2.27
49	12	82	120	5.02	2.73
12	13	30	81	4.58	2.10
23	13	22	97	4.89	2.10
39	13	29	73	4.61	2.22
48	13	52	93	4.65	2.20
3	14	46	115	4.93	2.41
16	14	48	97	4.77	2.30
29	14	45	144	4.99	3.01
54	14	35	84	5.07	2.30

Table A6: *Leaf nutrient concentrations, and NDVI and SPAD readings at V2 in 2011*.

Plot Number	Treatment Number	N Conc. %	P Conc. %	K Conc. %	SPAD reading	NDVI reading
5	1	4.22	0.284	2.59	30.0	0.4031
21	1	4.27	0.240	2.79	26.8	0.3978
34	1	4.20	0.320	2.39	32.1	0.3211
47	1	4.43	0.362	2.76	30.5	0.3844
10	2	4.52	0.441	2.68	26.9	0.4197
26	2	4.41	0.440	3.19	24.8	0.4522
33	2	4.33	0.406	2.63	26.6	0.3862
43	2	4.36	0.391	2.81	25.9	0.4183
2	3	4.32	0.333	2.39	29.3	0.3674
25	3	4.38	0.363	2.57	28.1	0.3989
37	3	4.51	0.386	2.90	26.3	0.4291
53	3	4.66	0.324	2.86	27.4	0.4066
7	4	4.63	0.421	2.80	26.9	0.4993
22	4	4.56	0.417	2.72	27.1	0.4445
40	4	4.60	0.443	2.99	26.9	0.4747
44	4	4.64	0.409	3.20	25.0	0.4653
8	5	4.63	0.428	2.08	29.5	0.4010
17	5	4.71	0.435	2.54	27.5	0.4518

35	5	4.73	0.401	2.01	32.3	0.3496
50	5	4.56	0.402	2.17	27.0	0.4313
6	6	4.50	0.441	2.82	28.4	0.4693
15	6	4.35	0.357	2.81	25.8	0.4953
30	6	4.48	0.439	2.92	26.7	0.3964
52	6	4.58	0.399	3.07	24.7	0.5096
1	7	4.59	0.422	2.38	28.2	0.4476
19	7	4.79	0.430	2.59	29.6	0.4179
41	7	4.82	0.385	2.58	27.3	0.4582
45	7	4.91	0.436	2.78	26.3	0.4391
14	8	4.53	0.437	3.04	27.3	0.5072
27	8	4.52	0.402	2.86	27.3	0.4427
31	8	4.56	0.415	2.85	26.7	0.3745
55	8	4.68	0.441	2.77	26.1	0.4650
4	9	4.82	0.440	1.68	32.1	0.4262
18	9	4.71	0.399	2.53	26.4	0.4371
42	9	5.10	0.455	2.42	28.2	0.4764
46	9	4.83	0.418	2.49	26.7	0.4547
9	10	4.59	0.467	2.44	28.1	0.4682
20	10	4.55	0.426	2.62	26.9	0.4360
32	10	4.60	0.427	2.67	28.3	0.4093
51	10	4.82	0.460	2.80	26.1	0.5187
11	11	4.94	0.465	1.90	30.4	0.4146
28	11	4.78	0.412	1.61	31.7	0.4402
36	11	4.89	0.430	2.36	28.7	0.4407
56	11	4.98	0.428	1.51	30.0	0.4453
13	12	4.48	0.423	2.51	29.4	0.4391
24	12	4.57	0.435	2.68	28.3	0.4352
38	12	4.57	0.418	2.66	27.2	0.4689
49	12	4.81	0.443	2.50	26.8	0.4863
12	13	4.87	0.452	1.66	29.9	0.4271
23	13	4.87	0.439	1.98	28.3	0.4128
39	13	4.95	0.425	1.92	29.2	0.4327
48	13	4.88	0.457	1.47	29.7	0.4236
3	14	4.34	0.408	2.25	28.2	0.4382
16	14	4.40	0.419	2.70	28.0	0.4578
29	14	4.61	0.417	2.43	26.1	0.4114
54	14	4.64	0.419	2.36	26.2	0.4561

Table A7: *Leaf nutrient concentrations, and NDVI and SPAD readings at V4 in 2011*

Plot Number	Treatment Number	N Conc. %	P Conc. %	K Conc. %	SPAD reading	NDVI reading
5	1	4.51	0.280	2.75	25.9	0.6383
21	1	4.22	0.208	2.68	25.5	0.6058
34	1	4.63	0.270	2.47	22.7	0.5476
47	1	4.50	0.271	2.32	26.0	0.6634
10	2	4.45	0.350	2.61	24.8	0.6917
26	2	4.03	0.378	2.69	27.3	0.7345
33	2	4.31	0.369	2.45	25.9	0.6546

43	2	4.47	0.347	2.66	25.6	0.7253
2	3	4.63	0.258	1.87	23.2	0.6242
25	3	4.23	0.284	2.45	28.0	0.6802
37	3	4.51	0.307	2.40	28.4	0.7278
53	3	4.55	0.279	2.23	28.1	0.7015
7	4	4.21	0.368	2.68	30.7	0.7815
22	4	4.63	0.345	2.45	27.5	0.7128
40	4	4.49	0.379	2.49	29.5	0.7527
44	4	4.65	0.373	2.62	28.9	0.7625
8	5	4.25	0.325	2.22	27.0	0.6694
17	5	4.42	0.316	2.07	28.1	0.7290
35	5	4.74	0.337	1.93	28.0	0.6204
50	5	4.92	0.299	2.09	28.8	0.7077
6	6	4.17	0.390	2.42	26.5	0.7542
15	6	4.53	0.401	2.52	28.3	0.7508
30	6	4.50	0.397	2.49	28.4	0.6922
52	6	4.46	0.385	2.65	31.9	0.7881
1	7	4.35	0.349	2.14	26.8	0.7198
19	7	4.61	0.354	2.15	26.3	0.6746
41	7	4.46	0.348	2.07	32.8	0.7546
45	7	4.58	0.340	2.23	30.6	0.7595
14	8	4.39	0.459	2.74	28.3	0.7775
27	8	4.61	0.391	2.61	26.9	0.7571
31	8	4.51	0.460	2.65	24.6	0.6521
55	8	4.04	0.436	2.70	32.9	0.7828
4	9	4.58	0.391	1.75	27.7	0.6678
18	9	4.47	0.367	2.02	27.6	0.7329
42	9	4.52	0.396	1.87	31.2	0.7738
46	9	4.62	0.379	2.09	30.7	0.7454
9	10	4.58	0.426	2.51	25.3	0.7176
20	10	4.68	0.397	2.28	26.9	0.7093
32	10	4.68	0.392	2.44	24.9	0.6809
51	10	4.25	0.381	2.42	29.5	0.7838
11	11	4.93	0.399	1.56	26.6	0.6767
28	11	4.43	0.391	1.43	29.6	0.7195
36	11	4.53	0.359	2.02	29.3	0.7439
56	11	4.87	0.382	1.38	32.7	0.7227
13	12	4.52	0.412	2.33	28.4	0.6886
24	12	4.58	0.442	2.50	27.8	0.7004
38	12	4.66	0.412	2.46	28.1	0.7588
49	12	4.75	0.438	2.34	31.9	0.7788
12	13	4.63	0.430	1.76	28.0	0.6761
23	13	4.58	0.396	1.85	29.5	0.6871
39	13	4.61	0.427	1.94	25.7	0.7065
48	13	4.50	0.423	1.53	27.8	0.6763
3	14	4.43	0.368	2.02	26.6	0.7024
16	14	4.79	0.419	2.39	27.0	0.7295
29	14	4.73	0.335	2.18	29.4	0.6959

54	14	4.68	0.434	2.43	30.0	0.7564

Table A8: *Leaf nutrient concentrations, and NDVI and SPAD readings at V7 in 2011.*

Plot Number	Treatment Number	N Conc. %	P Conc. %	K Conc. %	SPAD reading	NDVI reading
5	1	3.93	0.201	2.077419	25.7	0.48881
21	1	4.01	0.211	2.420194	26	0.45912
34	1	4.44	0.228	2.399419	27	0.40705
47	1	4.23	0.276	2.061727	27.8	0.53036
10	2	4.69	0.364	2.202065	30	0.62527
26	2	4.45	0.375	2.337097	30.4	0.64773
33	2	4.35	0.349	2.077419	28.7	0.56798
43	2	4.42	0.343	2.046258	30.7	0.61403
2	3	4.41	0.29	1.656331	27.5	0.51337
25	3	4.38	0.308	1.983935	29.1	0.55056
37	3	4.67	0.308	1.952774	30.2	0.6437
53	3	4.44	0.287	1.765806	28.6	0.61134
7	4	4.41	0.372	2.108581	30.3	0.69076
22	4	4.5	0.37	1.899568	30.6	0.61867
40	4	4.63	0.411	2.077419	30	0.67216
44	4	4.6	0.361	2.077419	31.1	0.67672
8	5	4.32	0.305	1.848903	31.3	0.58839
17	5	4.28	0.275	1.599613	30	0.64651
35	5	4.28	0.317	1.366763	28.9	0.50757
50	5	4.19	0.3	1.672323	30.4	0.66109
6	6	4.29	0.363	1.983935	29.3	0.6454
15	6	4.32	0.358	1.983935	31	0.68282
30	6	4.45	0.37	1.890452	30.8	0.58735
52	6	4.52	0.382	2.170903	30	0.757
1	7	4.25	0.353	1.703484	30.3	0.60978
19	7	4.21	0.353	1.807355	31.6	0.62536
41	7	4.55	0.365	1.630774	32.6	0.65641
45	7	4.38	0.377	1.68271	31.3	0.65711
14	8	4.93	0.425	2.108581	30.2	0.69879
27	8	4.84	0.443	2.191677	30.4	0.67608
31	8	5.42	0.409	1.806906	31.2	0.57154
55	8	4.97	0.464	2.035871	31.9	0.76038
4	9	4.4	0.394	1.402258	32	0.57513
18	9	4.92	0.396	1.599613	32	0.65317
42	9	5.07	0.396	1.319161	33.2	0.65456
46	9	5.2	0.433	1.526903	32.3	0.6626
9	10	4.795	0.412	1.963161	31	0.68836
20	10	4.73	0.425	1.776194	30.4	0.67752
32	10	4.73	0.433	1.68271	30.9	0.61156
51	10	5.03	0.435	1.838516	32.2	0.7485
11	11	4.74	0.397	1.132194	32.7	0.57095

28	11	4.67	0.395	1.026245	33.3	0.58955
36	11	4.72	0.384	1.691079	31.3	0.64516
56	11	4.51	0.39	1.03318	31.6	0.682
13	12	4.71	0.445	2.00471	31.5	0.64106
24	12	4.82	0.412	1.911226	30.7	0.63445
38	12	4.73	0.403	1.817742	31.3	0.67453
49	12	5.29	0.41	1.691079	32.9	0.70266
12	13	4.95	0.429	1.339935	31.6	0.57853
23	13	4.86	0.42	1.423032	32	0.62191
39	13	4.73	0.384	1.329548	31.1	0.62051
48	13	5.09	0.444	1.095727	29	0.6084
3	14	4.59	0.38	1.932	31.5	0.58102
16	14	4.75	0.38	1.890452	31.4	0.65833
29	14	4.69	0.3875	1.86482	29.8	0.58174
54	14	5.23	0.435	1.890452	32.3	0.73894

Table A9: *Leaf nutrient concentrations, and NDVI and SPAD readings at R1 in 2011.*

Plot Number	Treatment Number	N Conc. %	P Conc. %	K Conc. %	SPAD reading	NDVI reading
5	1	4.52	0.255	2.403662	32.2	0.60091
21	1	4.31	0.247	2.324296	29.6	0.45086
34	1	4.81	0.297	2.562394	31.3	0.43738
47	1	4.84	0.307	2.3	34	0.6163
10	2	5.94	0.424	2.108873	34.9	0.75454
26	2	5.73	0.441	2.324296	34.4	0.74749
33	2	5.91	0.424	2.097535	33.3	0.69489
43	2	5.44	0.399	2.346972	35	0.69312
2	3	4.69	0.326	1.948947	32.1	0.62742
25	3	5.51	0.355	2.074859	34.9	0.68738
37	3	5.77	0.346	2.097535	35.8	0.65086
53	3	4.7	0.303	2.029507	33.5	0.60118
7	4	5.3	0.403	2.154225	32.9	0.76119
22	4	5.98	0.493	2.006831	33.8	0.71357
40	4	6.28	0.502	2.029507	34.5	0.69191
44	4	6.01	0.479	2.188239	35.7	0.73465
8	5	5.13	0.375	1.916127	36	0.72374
17	5	4.92	0.344	1.78007	36.1	0.69321
35	5	5.2	0.353	1.573684	34.6	0.64178
50	5	4.92	0.3	1.72338	35.2	0.62286
6	6	5.95	0.486	2.086197	33.5	0.75794
15	6	5.87	0.495	1.972817	34.1	0.71394
30	6	6.34	0.513	1.961479	35.2	0.71531
52	6	5.85	0.462	2.131549	35.6	0.72739
1	7	5.04	0.439	1.451268	34.8	0.71012
19	7	5.77	0.429	1.66669	34.5	0.69982
41	7	5.85	0.366	1.485282	35.3	0.65515

45	7	6.25	0.443	1.768732	36.2	0.70644
14	8	5.2	0.477	2.120211	33.2	0.7253
27	8	6.15	0.537	1.972817	35.7	0.75969
31	8	5.78	0.524	1.938803	35.4	0.71749
55	8	6.28	0.542	1.927465	34.7	0.69038
4	9	5.32	0.457	1.337887	35.1	0.68336
18	9	5.7	0.473	1.632676	34.2	0.72718
42	9	6.1	0.447	1.247183	34.8	0.66179
46	9	5.95	0.413	1.564648	36.2	0.71782
9	10	6.06	0.519	1.927465	34.5	0.76529
20	10	6.13	0.534	1.791408	34.2	0.7378
32	10	6.25	0.527	1.757394	36.2	0.72092
51	10	5.96	0.491	1.825423	34.3	0.74715
11	11	5.86	0.496	1.085049	33	0.67607
28	11	5.94	0.522	0.876421	32.5	0.64496
36	11	5.97	0.416	1.632676	33.9	0.63641
56	11	6	0.464	1.000014	35	0.60855
13	12	5.72	0.52	2.029507	34.3	0.68278
24	12	5.85	0.508	1.768732	34.9	0.73293
38	12	6.3	0.52	1.950141	34.8	0.72614
49	12	6.17	0.52	1.622105	35.8	0.67796
12	13	5.84	0.538	1.201831	32.5	0.65076
23	13	6.3	0.487	1.349225	34.2	0.69708
39	13	5.79	0.478	1.371901	35	0.63602
48	13	6.06	0.539	1.118526	34	0.61823
3	14	5.79	0.494	1.66669	34.8	0.72512
16	14	6.13	0.548	1.938803	33.3	0.70441
29	14	6.1	0.491	1.734718	35.8	0.71168
54	14	6.27	0.554	1.836761	35.4	0.67635

Table A10: *Grain yield and nutrient concentrations in 2011.*

Plot	Treatment	Grain Yield	Grain N	Grain P	Grain K
Number	Number	kg/ha	%	%	%
5	1	1534.506	6.47	0.295	1.655352
21	1	1346.788	6.09	0.296	1.734718
34	1	947.3047	6.24	0.313	1.791408
47	1	2116.226	6.38	0.316	1.72338
10	2	3501.162	6.64	0.401	1.655352
26	2	2924.881	6.53	0.43	1.700704
33	2	2560.396	6.54	0.42	1.700704
43	2	3400.251	6.55	0.393	1.734718
2	3	1967.593	6.33	0.331	1.632676
25	3	2308.906	6.22	0.346	1.61
37	3	2861.119	6.32	0.367	1.700704
53	3	2290.757	6.38	0.324	1.598662
7	4	2687.729	6.66	0.447	1.621338

22	4	2645.999	6.57	0.468	1.621338
40	4	3169.976	6.59	0.498	1.66669
44	4	3124.099	6.49	0.459	1.700704
8	5	2968.708	6.58	0.364	1.61
17	5	2658.116	6.32	0.364	1.575986
35	5	1813.605	6.24	0.388	1.564648
50	5	2695.22	6.5	0.348	1.61
6	6	2809.165	6.75	0.493	1.712042
15	6	3328.286	6.77	0.5125	1.700704
30	6	2627.307	6.6	0.527	1.791408
52	6	3713.922	6.55	0.534	1.757394
1	7	2597.019	6.43	0.43	1.49662
19	7	2601.02	6.55	0.457	1.541972
41	7	2228.484	6.66	0.41	1.473944
45	7	2904.281	6.8	0.439	1.507958
14	8	2996.524	6.745	0.578	1.700704
27	8	2415.975	6.72	0.583	1.700704
31	8	2594.157	6.58	0.594	1.757394
55	8	3020.492	6.86	0.591	1.712042
4	9	2264.517	6.66	0.457	1.360563
18	9	2767.175	6.48	0.476	1.497197
42	9	2167.471	6.58	0.472	1.383239
46	9	2864.628	6.54	0.473	1.43993
9	10	3555.556	6.58	0.566	1.689366
20	10	2460.888	6.91	0.606	1.644014
32	10	2563.812	6.84	0.607	1.644014
51	10	3032.135	6.65	0.562	1.712042
11	11	2130.209	6.87	0.558	1.383239
28	11	1409.85	6.61	0.528	1.405915
36	11	2932.457	6.72	0.489	1.445924
56	11	1988.066	6.72	0.536	1.371901
13	12	2969.665	7.23	0.597	1.632676
24	12	2935.701	6.92	0.572	1.632676
38	12	3526.471	6.75	0.59	1.598662
49	12	2656.835	7.2	0.62	1.530634
12	13	2059.217	6.98	0.563	1.360563
23	13	2328.176	6.62	0.526	1.39465
39	13	2341.721	7	0.549	1.383239
48	13	1503.904	6.84	0.592	1.281197
3	14	2714.337	6.58	0.565	1.485282
16	14	3274.154	6.69	0.601	1.712042
29	14	2490.196	6.82	0.591	1.632676
54	14	2927.299	6.9	0.606	1.55331

References

Bailey, J.S., J.A. Beattie, and D.J. Kilpatrick. 1997. The Diagnosis and Recommendation Integrated System (DRIS) for diagnosing the nutrient status of grassland swards: I. Model establishment. Plant Soil 197:127-135.

Beaufils, E.R. 1973. Diagnosis and Recommendation Integrated System (DRIS). Soil Sci. Bull. 1, Univ. of Natal, Pietermaritzburg, Republic of South Africa.

Beaufils, E.R., and M.E. Sumner. 1976. Application of the DRIS approach for calibrating soil and plant factors in their effects on yield of sugarcane. Proc. South Africa Sugar Tech. Assoc. 50:118–124.

Beegle, D.B., and T.C. Oravec. 1990. Comparison of field calibrations for Mehlich 3 P and K with Bray-Kurtz P1 and ammonium acetate K for corn. Commun. Soil Sci. Plant Anal. 21:1025-1036.

Beverly R. B., M.E. Sumner, W.S. Letzsch, and C.O. Plank. 1986. Foliar diagnosis of soybean by DRIS. Commun. Soil Sci. Plant Anal. 17:237-256.

Black, C.A. 1993. Soil Fertility Evaluation and Control. Lewis Publishers, Boca Raton, Florida.

Blackmer, T.M., and J.S. Schepers. 1995. Use of a chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. J. Prod. Agric. 8:56-60.

Board, J., V. Maka, R. Price, D. Knight, and M. Baur. 2007. Development of vegetation indices for identifying insect infestations in soybean. Agron. J. 99:650–656.

Bronson, K.F., J.D. Booker, J.W. Keeling, R.K. Boman, T.A. Wheeler, R. Lascano, and R. Nichols. 2005. Cotton canopy reflectance at landscape scale as affected by nitrogen fertilization. Agron. J. 97:654–660.

Bronson, K.F., T.T. Chua, J.D. Booker, J.W. Keeling, and R.J. Lascano. 2003. In-season nitrogen status sensing in irrigated cotton: II. Leaf nitrogen and biomass. Soil Sci. Soc. Am. J. 67:1439–1448.

Carter, G. A. 1993. Responses of leaf spectral reflectance to plant stress. Am. J. Bot. 80:239-243.

Chien, S.H., G. Carmona, R.G. Menon, and D.T. Hellums. 1993. Effect of phosphate rock sources on biological nitrogen fixation by soybean. Fert. Res. 34:153–159.

Dahnke, W.C., and R.A. Olson. 1990. Soil test correlation, calibration, and recommendation. pp. 45-71. Soil Testing and Plant Analysis, 3rd ed. SSSA Book Series No. 3. Madison, WI, USA.

Desta B., B. Arnall, and B. Raun. 2011. The Evolution of Reference Strips in Oklahoma. Oklahoma Cooperative Extension Service. http://nue.okstate.edu/Brian/PSS-2258web.pdf.

Eaglesham, A.R., A. Ayanaba, V. Ranga Rao, and D.L. Eskew. 1982. Mineral N effects on cowpea and soybean crops in a Nigerian soil. II. Amounts of N fixed and accrual to the soil. Plant Soil 68:184–192.

Ess, D., M. Morgan, and S. Parson. 2001. Implementing site-specific management: Map versus sensor-based variable-rate application. Technical Report. Available at http://www.ces.purdue.edu/extmedia/AE/SSM-2-W.pdf.

Fehr, W.R., and C.E. Caviness. 1977. Stages of soybean development. Iowa Cooperative Extension Service Special Report 80. Iowa State University, Ames, Iowa, USA.

Fiske, C.H., and W. Subbarow. 1925. The colorimetric determination of phosphorus. J. Biol. Chem. 66:375-400.

Freeman, K., K. Girma, D. Arnall, R. Mullen, K. Martin, R. Teal, and W. Raun. 2007. By-plant prediction of corn forage biomass and nitrogen uptake at various growth stages using remote sensing and plant height. Agron. J. 99:530–536.

Flannery, R. 2002. Mid-Atlantic Grain and Forage Journal. Rutgers Cooperative Research and Extension. Piscataway, NJ, USA.

Flynn, E., Dougherty, C., and Wendroth, O. 2008. Assessment of pasture biomass with the normalized difference vegetation index from active ground-based sensors. Agron. J. 100:114–121.

Gunawardena, S.F., S.K. Danso, and F. Zapata. 1992. Phosphorus requirements and N accumulation by three mungbean (Vigna radiata L.,Wewlzek) cultivars. Plant Soil 147:267–274.

Ham, G.E. 1978. Interactions of Glycine max and Rhizobium japonicum. p. 289–296. In R.J. Summerfield and A.H. Bunting (ed.) Advances in Legume Science. Royal Botanic Gardens, Kew, United Kingdom.

Hanway, J.J., and C.R. Weber. 1971. Accumulation of N, P and K by soybeans (Glycine max (L.) Merrill) plants. Agron. J. 63:406-408.

Henderson, J.B., and E.J. Kamprath. 1970. Nutrient and dry matter accumulation by soybeans. Tech. Bull. 197. NC Agric. Exp. Stn., Raleigh, NC, USA.

Herbert, S.J., and G.V. Litchfield. 1984. Growth response of short-season soybean to variations in row spacing and density. Field Crops Res. 9:163-171.

Hoque, E., and P.J.S. Hutzler. 1992. Spectral blue-shift of red edge monitors damage class of beech trees. Remote Sens. Environ. 39:81-84.

Huang, Z.W., T.J. Zhao, and J.Y. Gai, 2009. Dynamic analysis of biomass accumulation and partition in different yield level soybeans. Acta Agro. Sin. 35:1483-1490.

Isermann, K. 1990. Stickstoff- und Phosphor-Bilanzierung der Landwirtschaft im Vergleich westeuropäischer Länder.- 102. VDLUFA-Kongreß Berlin Landwirtschaft im Spannungsfeld von Belastungsfaktoren und gesellschaftlichen Ansprüchen. 17.-22. September 1990.

Jiang, H., and D.B. Egli. 1995. Soybean seed number and crop growth rate during flowering. Agron. J. 87:264-267.

Jones, G.D., J.A. Lutz, Jr., and T.J. Smith. 1977. Effects of phosphorus and potassium on soybean nodules and seed yield. Agron. J. 69:1003–1006.

Katsvairo, T.W., W.J. Cox, and H.M. Van Es. 2003. Spatial growth and nitrogen uptake variability of corn at two nitrogen levels. Agron. J. 95:1000–1011.

Liebhardt, W.C., and M.R. Teel. 1977. Fluctuations in soil test values for potassium as influenced by time of sampling. Commun. Soil Sci. Plant Anal. 8:591-597.

Lillesand, T.M., and R.W. Kiefer. 1994. Remote Sensing and Image Interpretation, 3rd. Ed., John Wiley and Sons, Inc. Toronto, Canada.

Lough, J.L., and J.J. Varco. 2001. Effects of varying N and K nutrition on the spectral reflectance properties of cotton. In P.C. Robert et al. (ed.) Precision agriculture [CD-ROM]. Proc. Int. Conf., 5th, Minneapolis, MN. 16–19 July 2000. ASA, CSSA, and SSSA, Madison, WI, USA.

Lukina, E.V., K.W. Freeman, K.J. Wynn, W.E. Thomason, R.W. Mullen, M.L. Stone, J.B. Solie, A.R. Klatt, G.Y. Johnson, R.L. Elliot, and W.R. Raun. 2001. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. J. Plant Nutr. 24:885–898.

Ma, B.L., M.J. Morrison, and L.M. Dwyer. 1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. Agron. J. 88:915–920.

Ma, B., L. Dwyer, C. Costa, E. Cober, and M. Morrison. 2001. Early prediction of soybean yield from canopy reflectance measurements. Agron. J. 93:1227–1234.

Maine, N., W. Nell, J. Lowenberg, and Z. Alemu. 2007. Economic analysis of phosphorus applications under variable and single-rate applications in the Bothaville District. Agrekon. 46:532-547.

Maleki, M., A. Mouazen, and H. Ramona. 2008. On-the-go variable-rate phosphorus fertilization based on a visible and near-infrared soil sensor. Bios. Eng. 100:160-166.

Mallarino, A.P., and A.M. Blackmer. 1992. Comparison methods for determining critical concentrations of soil test phosphorus for corn. Agron. J. 84:850–856.

Mallarino, A. 2006. Variable-rate application for phosphorus and potassium: Impacts on yield and nutrient management. Int. Crop Manag. Conf. - Iowa State University. 1:219-224.

Mandal, K., K. Hati, and A. Misra. 2009. Biomass yield and energy analysis of soybean production in relation to fertilizer-NPK and organic manure. Biomass and Bioenergy 33:1670–1679.

Martin, K.L., K. Girma, K.W. Freeman, R.K. Teal, B. Tuban, D.B. Arnall, B. Chung, O. Walsh, J.B. Solie, M.L. Stone, and W.R. Raun. 2006. Expression of variability in corn as influenced by growth stage using optical sensor measurements. Agron. J. 99:384–389.

Mehlich, A. 1984. Mehlich 3 soil test extraction: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Messiga, A., N. Ziadi, C. Morel, C. Grant, G. Tremblay, G. Lamarre, and L. Parent. 2012. Long term impact of tillage practices and biennial P and N fertilization on maize and soybean yields and soil P status. Field Crop Res. 133:10-22.

Mkhabela, M.S., P. Bullock, S. Wang, and Y. Yang. 2011. Crop yield forecasting on the Canadian Prairies using MODIS NDVI data. Agric. Forest Meteor.. 151:385-393.

Moges, S.M. 2004. Evaluation of green, red, and near infrared bands for predicting winter wheat biomass, nitrogen uptake, and final grain yield. J. Plant Nutr. 27:1431-1441.

Nelson, K., P. Motavalli, and M. Nathan. 2005. Response of no-till soybean [Glycine max (L.) Merr.] to timing of preplant and foliar potassium applications in a claypan soil. Agron. J. 97:832–838.

Norton, E., L. Clark, and H. Borrego. 2004. Evaluation of variable rate fertilizer applications in an Arizona cotton production system. Ark. Cotton Res. 142:145-151.

O'Hara, G.W., N. Boonkerd, and M.J. Dilworth. 1988. Mineral constraints to nitrogen fixation. Plant Soil 108:93–110.

Onema, J.M, and A. Taigbenu. 2009. NDVI-rainfall relationship in the Semliki watershed of the equatorial Nile. Phys. Chem. Earth 34:711-721.

Plank, O.C. 1979. Plant analysis handbook for Georgia. Univ. of Georgia Ext. Serv. Bull. 735. University of Georgia, Athens, GA, USA.

Peterson, T.A., T.M. Blackmer, D.D. Francis, and J.S. Schepers. 1993. Using a chlorophyll meter to improve N management. NebGuide G93-1171-A. Cooperative Extension, Institute of Agriculture and Natural Resources, Univ. of Nebraska, Lincoln, NE, USA.

Ponzoni, F.J., and J.L. Goncalves 1999. Spectral features associated with nitrogen, phosphorus, and potassium deficiencies in Eucalyptus saligna seedling leaves. Int. J. Remote Sens. 20:2249–2264.

Potash & Phosphate Institute. 2005. Soil test levels in North America, 2005: Summary update. PPI/PPIC/FAR Technical Bulletin 2005-1. Norcross, GA.

Rotaru, V., and T.R. Sinclair. 2009. Interactive influence of phosphorus and iron on nitrogen fixation by soybean. Env. and Exp. Botany 66:94–99.

Sartain, J.B., R.B. Forbes, and N.R. Usherwood. 1979. Yield response of soybeans to P and K fertilization as correlated with soil extractable and tissue nutrient levels. Commun. Soil Sci. Plant Anal. 10:1219–1232.

SAS Institute Inc. 1993. SAS/ETS User's guide, Version 6, Second Edition, SAS Institute Inc. Cary, NC, USA.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Commun. Soil Sci. Plant Anal. 23:2173-2187.

Schwab, G.J., C.D. Lee, and R. Pearce. 2007. AGR-92: Sampling plant tissue for nutrient analysis. Cooperative Extension Service, University of Kentucky, College of Agriculture, Lexington, KY, USA.

Sinclair, T.R., and V. Vadez. 2002. Physiological traits for crop yield improvement in low N and P environments. Plant Soil 245: 1–15.

Shih, S.F. 1994. NOAA Polar-Orbiting satellite HRPT data and GIS in vegetation index estimation for the Everglades agricultural area. Soil Crop Sci. Soc. Florida Proc., 53:19-24.

Slaton, N., B. Golden, R. DeLong, and M. Mozaffari. 2010. Correlation and calibration of soil potassium availability with soybean yield and trifoliolate potassium. Soil Sci. Soc. Am. J. 74:1642–1651.

Small, H.G., Jr., and A.J. Ohlrogge. 1973. Plant analysis as an aid in fertilizing soybeans and peanuts. p. 315–327. In L.M. Walsh and J.D. Beaton (ed.) Soil Testing and Plant Analysis. Rev. ed. SSSA, Madison, WI.

Sparks, D.L. (ed.). 1996. Methods of Soil Analysis (Part 3). Chemical Methods. Soil Sci. Soc. Amer. Book Series #5. Madison, WI, USA.

Stone, M.L., J.B. Solie, W.R. Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE 39:1623–1631.

Takebe, M., T. Yoneyama, K. Inada, and T. Murakami. 1990. Spectral reflectance ratio of rice canopy for estimating crop nitrogen status. Plant Soil 122:295–297.

Teal, R., B. Tubana, K. Girma, K. Freeman, D. Arnall, O. Walsh, and W. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488–1494.

Thomson, W.W., and T.E. Weier. 1962. The fine structure of chloroplasts from mineral-deficient leaves of Phaseolus vulgarism. Am. J. Bot. 49:1047–1055.

Tucker, C.J. and P.J. Sellers. 1986. Satellite remote sensing of primary production. Int. J. Remote Sens. 7:1133-1135.

Turner, F.T., and M.F. Jund. 1991. Chlorophyll meter to predict nitrogen topdress requirement for semi-dwarf rice. Aus. J. Exp. Agric.. 34:1001–1005.

United States Department of Agriculture (USDA). Web soil survey. Available at http://websoilsurvey.nrcs.usda.gov.

United States Department of Agriculture (USDA). Agricultural Statistics. Available at http://www.usda.gov/wps/portal/usda/usdahome?navid=DATA_STATISTICS.

University of Kentucky. 2010. 2010-2011 Lime and nutrient recommendations. AGR-1. University of Kentucky, College of Agriculture, Cooperative Extension Service, Lexington, KY, USA.

Varvel, G.E., J.S. Schepers, and D.D. Francis. 1997. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. Soil Sci. Soc. Am. J. 61:1233-1239.

Walworth, J.L., and M.E. Sumner. 1986. Foliar diagnosis – a review. In: Adv. Plant Nutr., vol III. Ed. B P Tinker. pp 193–241. Elsevier, New York, NY, USA.

Wilson, J.K., 1931. The shedding of nodules by beans. Agron. J. 23: 670-674.

Wolfe, D.W., D.W. Henderson, T.C. Hsiao, and A. Alvino. 1988. Interactive water and nitrogen effects on senescence of maize: II. Photosynthetic decline and longevity of individual leaves. Agron. J. 80:865-870.

Yin, X., and T. Vyn. 2004. Residual effects of potassium placement for conservation-till corn on subsequent no-till soybean. Soil Tillage Res. 75:151-159.

Vita

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