UTILIZING NPKS RICH STRIPS THROUGHOUT OKLAHOMA WINTER WHEAT PRODUCTION

By

LANCE M. SHEPHERD

Bachelor of Science in Agriculture

Northwest Missouri State University

Maryville, MO

2011

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July, 2013

UTILIZING NPKS RICH STRIPS THROUGHOUT
OKLAHOMA WINTER WHEAT PRODUCTION

Thesis Approved:

Daryl Arnall

Thesis Adviser

William Raun

Randal Taylor

ACKNOWLEDGEMENTS

I would like to thank the Department of Plant and Soil Sciences of Oklahoma State University and the Soil Nutrient Management/Soil Fertility projects for their support in assisting me in this chapter of my educational career. I would like to thank my committee members, Dr. Brian Arnall, Dr. Bill Raun and Dr. Randy Taylor who have assisted me with their wisdom, expertise, guidance, leadership and friendship throughout my experiences at Oklahoma State University. Furthermore, I would also like to thank my committee members who have graciously allowed me to be a part of their exceptional state wide extension program, where I gained valuable experiences and wisdom which cannot be gained in another form. I would also like to thank Dr. Art Klatt for his knowledge and expertise as well as his Plant Breeding Team for permitting me to use their equipment and aiding in the wheat threshing process. I would like to extend my appreciation to several colleagues, Scott Fine, Candi Byani, Bruno Figueiredo, Andre Cortinas and the Nutrient Management Crew: Robert Calhoun, Katlynn Weathers, Brandon Burgess, Murilo Campo, Nadia Sousa, Darren Butchee and Mattie Crownover who graciously helped me succeed in completing this state wide multifaceted project as well as the many producers and county educators who were actively involved. I would like to thank my fiancé Victoria Harms for her love and support throughout this period of our lives. Lastly and mostly I would like to thank my sister Ashley Brown, my mother Denise Shepherd and my dad Mitch Shepherd for always believing in me and my abilities, supporting me through trying and tough times, and passing along the power of determination and work ethics I have inherited as well as many other qualities. These qualities have permitted me to achieve many accomplishments thus far.

Name: Lance Shepherd

Date of Degree: JULY, 2013

Title of Study: UTILIZING NPKS RICH STRIPS THROUGHOUT OKLAHOMA
WINTER WHEAT PRODUCTION

Major Field: Plant and Soil Sciences

Abstract:

Both temporal and spatial variation plays a major role in nutrient requirements and availability. This study was conducted to improve nutrient use efficiencies, demonstrate ability to visually identify nutrient needs throughout a cropping season, along with the evaluation of both soil nutrient recommendations across divergent environments and current producer fertilization management schemes. This project is an extension of the N-rich strip concept which is used to identify in season nitrogen deficiencies. Nutrient rich strips of nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) were applied at 59 site years with 236 comparisons across Oklahoma, on multiple soil types with a wide range of environmental conditions and wheat varieties. Nutrient rich strips were applied at a rate of 257.6 kg ha^{-1} of product to a 1.8 by 30.5 meter strip in producer fields. Urea (46-0-0), triple super phosphate (0-20-0$_)$, potash (0-0-52) and gypsum (0-0-0-19) were used for sources of nitrogen, phosphorus, potassium and sulfur respectively. Composite surface (0-15 cm) and subsurface (15-45 cm) soil samples were taken prior to application for soil nutrient recommendations. Normalized difference vegetative index (NDVI) data was collected from the nutrient rich strips and the farmer practice, where the GreenSeeker™ sensor was used to estimate biomass. At maturity three one m^2 subplots were hand harvest from each strip. Samples were threshed, grain weight recorded and grain samples analyzed for N, P, K and S content. Of 59 locations and 236 comparisons 17 responses were documented. Most responses were due to underestimated yield goal, overestimated NUE or identified by soil testing results. In the two years this study was conducted winter wheat grain yield was increased with the addition of N at seven locations, P at seven locations, K at three locations. Over the 59 locations sampled there was no response to additional S fertilizer. Soil testing proved to be an adequate method for nutrient recommendation. At 75% of the locations yield was maximized by the producer with his or her NPKS management system. The study was however unable to identify if the management strategies optimized yield economically.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Over 10.8 million metric tons of nitrogen (N) fertilizer was consumed in the United States of America in 2010 alone, with 1.2 million metric tons of the total N consumed being applied to wheat (FAO, 2009). Raun et al. (2010) have estimated the nitrogen use efficiency (NUE) of cereal crops to be 33%. Implying 0.8 million metric tons of applied N to wheat in 2010 was not utilized. Improvement of current fertilizer application methods would decrease producer expenses and environmental effects. Variation in environment from field to field plays a major role in nutrient availability. Plant sensing systems have the potential to improve profitability and efficiency over traditional fertilizer application methods by taking into account the yearly potential of each field based on individual variability for that year (Zhao et al., 1999). Oklahoma State University currently promotes use of the GreenSeeker^{TM} Sensor and N-Rich strip as its economical practice. With this system producers have the ability to treat their individual field needs separately. Applying nitrogen rich strips throughout a producers field and measuring its response can help producers economically by only applying the right rate of nitrogen where needed for that cropping season. According to Raun et al. (2010) when applications of N based on in-season estimation of yield (INSEY), NUE was improved by greater than 15%. Yet, N is not the only nutrient considered to vary from year to year and effect crop production, phosphorus (P), potassium (K), and sulfur (S) are all significant plant nutrients that impact plant production.

The variability of these nutrients, need to be taken into account to result in the most economical return. One potential method to account for and monitor this variability is nutrient rich strips, previously proven with the use of the nitrogen rich strip. Sulfur and nitrogen should behave similarly in soil systems and allow adequate interpretation of S variability. Unlike N and S, P and K are less mobile in the soil system (Johnston and Syers, 2009) and provide a new challenge for nutrient rich strips. Plant nutrient needs vary over different environments (soils, climate, etc.) and seed varieties. With the use of nutrient rich strips in P, K and S fertilizers as well as N, increase in yields can be made to maximize production across variable conditions found from field to field and across the state.

CHAPTER II

REVIEW OF LITERATURE

Nitrogen

Nitrogen is one of the most abundant nutrients within a plant, second to only carbon. Novoa and Loomis (1981) described N as the "central element" for its many roles and functions throughout a plant. Nitrogen is a vital component of amino acids, proteins, co-enzymes, phytohormones, chlorophyll, cytoplasm, nucleic acids and in the action of energy transformation such as adenosine diphosphate (ADP) and adenosine triphosphate (ATP) (Barker and Pilbeam, 2007; Marschner, 2012; Novoa and Loomis, 1981; Troeh and Thompson, 1993). Nitrogen is used to form amino acids, which are the building blocks of proteins. Proteins can perform as structural components in a cell, be involved in metabolic processes or be basic storage proteins, such as arginine and amides. Dhont et al. (2006) suggests vegetative storage proteins may help with winter hardiness, while Marschner (2012) expresses that seed storage proteins serve as primary amino acids for germination and growth during seed development. In cereal seeds 50-85% of proteins are storage proteins (Shewry, 2007). Proteins contain roughly 85% of the total N in a plant, but amino acids not only construct proteins but also help with the transportation and storage of N (Barker and Pilbeam, 2007). Phytohormones regulate growth, germination, and metabolism processes. An absence of N will cease plant development and reproduction (Troeh and Thompson, 1993). Nitrogen in the chloroplast is known as chlorophyll proteins within the stroma and lamellae, more than 75% of N in the leaves are in this form (Barker and Pilbeam, 2007). Nitrogen is also found in nucleic acids which form deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) that control the creation of new cells. Nucleic acids control the transport, storage, and coding of genetic information (Novoa and Loomis, 1981)

Nitrogen is a mobile nutrient, transported throughout the soil solution by mass flow. The two primary forms of N in the soil are organic and inorganic. Organic N makes up over 90% of the total N in the soil surface (Barker and Pilbeam, 2007) consisting of organic matter in different stages of decay (Barker et al., 2000), yet release of this N occurs at a sluggish rate. On the other hand the soil surface contains less than 2% inorganic N (Barker and Pilbeam, 2007), which is available N that can be used by the plant or moved throughout the soil profile. Pate (1973) indicated that inorganic N in solution is the primary N source obtained within the immediate soil environment. Nitrate (NO_3) and ammonium (NH_4) are the two forms of N in which a plant can uptake through their roots. Nitrogen can go through many transformations within the soil system allowing it to be easily lost through denitrification, immobilization, ammonia volatilization, leaching, and plant loss. No method of N soil testing is widely excepted, except residual NO_3 and NH_4, due to the majority of N within the soil being present as complex organic compounds that depend on microbial activity for the release of available N as well as the possibility of losses (Dahnke and Johnson, 1990). These losses are dependent on different environments: such as temperatures, precipitation, soil characteristics, pH, C:N ratios and microorganism activity. For the above reasons the N cycle has been labeled the “leaky system” (Lu et al., 2011; Troeh and Thompson, 1993).

Since N is a mobile nutrient that can be moved and lost fairly easy throughout the soil it is common to identify deficiency symptoms. It is identified as leaf chlorosis along the mid-rib present on older leaves first and moves toward younger leaves since N is mobile within the plant. Other symptoms are stunted plants, reduced root growth along with all other organs and decrease in protein assembly. Photosynthesis is reduced as chlorophyll starts to diminish from the plant leaves (Troeh and Thompson, 1993). The reduction of roots also affect water and nutrient uptake (Troeh and Thompson, 1993). Reduced N can decrease the number of tillers (Halse et al., 1969) and the development of florets decreasing grain production (Thomas et al., 1978). Leaf senescence in the later part of the growing season should not be mistaken for a N deficiency. Nitrogen is redistributed to grain fill around boot stage causing leaf senescence (Harper et al., 1987). According to Spiertz and De Vos (1983) 65-85% of total nitrogen in grain is trans-located from plant vegetation, while Cox et al. (1986) found in wheat 100% of the nitrogen found in the grain must be derived from nitrogenous compounds remobilized and trans-located from other plant parts. Not only can plants be N deficient, but they can have an excess too. Excessive growth can reduce grain production (Troeh and Thompson, 1993) and generate lodging where the efficiency of translocation of N is negatively affected (Gasser and Iordanou, 1967).

Nitrogen makes up 78% of the atmosphere, although it is a renewable resource the overuse of the nutrient should not be taken lightly. Roughly 105.02 million metric tons of N fertilizer were consumed globally in 2009 (FAO, 2009). High N losses lead to eutrophication and global warming caused by the release of nitrous oxide. Over fertilization along with leaching and erosion are some main factors that lead to eutrophication. With N being a limiting factor in estuaries (Vitousek et al., 1997) an increase from N leaching or erosion can lead to eutrophication causing the same symptoms as seen in P. This can also cause an excess of N in drinking water. The consumption of high NO_3 water by infants results in a medical condition called Blue Baby Syndrome (methemoglobinemia). Troeh and Thompson (1993) state that water with a concentration of 10 ppm of NO_3 or greater is unsafe for infant consumption. The release of nitrous oxide by denitrification and volatilization are known to lead to global climate change. Marschner (2012) indicated global climate change is caused by the discharge of nitrous oxide from an inefficient conversion of fertilizer N in the soil system. The emissions of nitrous oxide convert sunlight energy into heat, warming the atmosphere past its original level (Byrnes, 1990).

Increasing the nitrogen use efficiency (NUE) will help reduce how “leaky” the N cycle is. The use of cover crops will reduce erosion along with leaching during fallow periods and cropping systems allow diverse rooting systems within the soil. Certain crops will exploit nutrients from the shallow soil, while a different crop will exploit the nutrients deeper in the soil (Tilman, 1999). No-till diminishes fallow periods reducing soil loss and runoff (Tilman, 1999). Along with management practices new fertilizer practices can decrease losses and increase NUE. Nitrification inhibitors reduce nitrous oxide emissions (Byrnes, 1990). Timing of N applications, N placement, and soil testing allow for an increase in NUE. Hamid (1972) found that N applied in wheat at tillering had maximum recovery rate and Hunter and Stanford (1973) saw an increase in recovery of N in applications during the spring compared to fall applications. Applying N by banding, injection, and split application allows N to be available at critical periods of maximum plant uptake (Sharpley et al., 1987). Using soil sample maps and precision application also allows you to apply N at limited areas throughout a field. Currently N application rates are based on pre-plant NO_3 soil tests and desired yield goals. Fox et al. (1989) reported NO_3 soil test was accurate in predicting fertilizer N response, but also stated that the NO_3 tests do not make accurate N rate estimates. Looking at crop response to soil test N, García et al. (2007) reported residual effects of N fertilizer were not discovered based on NO_3 soil tests during a long term study started in 2000. In 2001-2004 Laboski et al. (2008) found soil samples analyzed for soil NO_3 and total N did not significantly correlate with yield, crop response, nor N fertilizer requirements in corn. Bundy and

Malone (1988) expressed the importance of how soil characteristics and climate conditions can effect NO_3 soil tests.

Phosphorus

Phosphorus is a critical, limiting nutrient needed by plants. Following N, P is the most extensively used fertilizer in the world (Batten, 1992). Phosphorus is involved in nearly every step throughout a plants life, from germination to reproduction. Once P is taken up by the plant it creates bonds with several other elements to form different particles. Every living cell contains P as a component of DNA and RNA within the cell's nucleus, without P cells will not divide to create new cells (Troeh and Thompson, 1993). Phosphorus has the availability to have variable charges, enabling the storage and transfer of energy needed during photosynthesis, CO_2 fixation, protein synthesis and nutrient transportation throughout the plant by ADP and ATP. Without an adequate amount of phosphoric acid (Pi) within the chloroplast photosynthesis will be reduced, while a high concentration of Pi in the chloroplast will inhibit CO_2 fixation (Marschner, 2012). ATP is the main phosphate required for starch synthesis, in addition ATP is also diffused with other coenzymes needed for sucrose and cellulose synthesis (Marschner, 2012). Up to 90% of P within a wheat plant is transferred from the shoot to grain (Batten, 1992) and stored as phytate to provide P for future germinating seeds (Marschner, 2012).

An insufficient amount of P within the plant will result in sugar buildup causing nutrient deficiencies. This results in the formation of anthocynins, which also forms from frost injury (Troeh and Thompson, 1993). Phosphorus deficiencies are most often expressed by purpling of leaf margins of older leaves or the base of stems, due to the fact that P is mobile inside the plant. Plants may also become dark green, since P is not a factor of chlorophyll, as chlorophyll may increase during P deficiencies when there is still an abundance of available N (Troeh and Thompson, 1993). Other side effects are stunted growth and a delay in or lack of maturity.

Phosphorus is an immobile nutrient in the soil, mainly up taken by the plant through root interception or ion diffusion as $H_2PO_4^-$ and HPO_4^{2-}. Little applied P is lost throughout the soil, besides the amount taken up by the plant, from season to season. Soil applied P infrequently surpasses 25% efficiency (Johnston and Syers, 2009). Soil pH plays a role on the availability of P. Phosphorus fixation is at the lowest when pH are maintained at 6.0-7.0 (Laboski et al., 2008) .Johnston and Society (2001) suggested P occurs in four different pools within the soil system which was further refined by Syers et al. (2008). The four P pools consist of immediately available, readily available, low availability and very low availability: immediately available P is in the soil solution, readily available P is where P can be removed from the soil surface, low availability P is tightly bonded within the soil, and very low availability is the least available P since it has an extremely tight bond within the soil it takes several years to become available. Up to 5% of the soil can be fully engaged by the plant (Wiersum, 1962) causing a high percentage of total P (immobile nutrients) in the soil to be unavailable. Currently plant available P is based on soil test P (STP) using varies extractions (ex. Mehlich 3, Bray 1-P) to simulate plant availability based on regional soil properties (pH, CEC) (García et al., 2007). Bray 1 has a good correlation between P uptake in acidic soils and crop response while Olsen and Mehlich-3 have good correlation in both acidic and alkaline soils (Hammond et al., 1989; Mallarino and Atia, 2005). Cope (1981) showed that throughout 50 years, P fertilization rates corresponded with soil test P. Extractable soil test P is a relatively good prediction of available soil P for plant uptake, therefore indicating previous P applications are not permanently lost but available for future plant consumption (Kamprath, 1967). Jemison et al. (2006) expressed the need on refinement of soil test P critical levels for P fertilization recommendations.

Although very little P is lost from individual fields, a large quantity is lost globally. Major agricultural sources of P losses are from leaching, runoff, and erosion. Simard et al. (1998) stated P has been reported to leach in soils that are course-textured with high organic matter, due to the low level of soil contents that play a role in fixating P. While leaching is very uncommon, 10 kg P ha^{-1} is lost by the process of erosion (Smit et al., 2009). Losses are frequently seen with over fertilization or high applications of animal waste. Commonly in freshwater aquatic ecosystems P is the limiting nutrient and excessive additions of P can result in unstable growth of plants and algae resulting in hypoxia (oxygen depletion) from algae bloom decomposition. Eutrophication's negative effects consist of fish kills, toxin production, unpleasant drinking water, extermination of native species, and the degradation of a bio diverse ecosystem (Bennett et al., 2001; Tilman, 1999).

While P losses need to be decreased, phosphorus use efficiency (PUE) needs to be increased. Bennett et al. (2001) noted two basic solutions to decrease the impact of excessive P causing eutrophication; reduce P applications and increase the amount of active P sinks. Newer farming practices will also decrease P losses as well as increase PUE at the same time. No-till and cover crops will insulate the soil from erosion and reduce compaction, while increasing pore space and improving soil structure for root interception. Increased organic matter through these practices will also produce an increase in readily available P. Crop rotations will deplete soil pathogens and nematodes destroying roots, allowing for an increase in P uptake by rooting systems (Syers et al., 2008). The use of precision agriculture allows the comparison of soil sample maps and yield maps to interpret variable P application rates throughout a field (Sharpley et al., 1987; Syers et al., 2008). The decrease of acidic soils by applying lime will decrease P fixation (Johnston and Syers, 2009). Environmental programs are also available to prevent erosion, such as buffer strips. Syers et al. (2008) suggested several management systems that would improve PUE; application of substances that compete with P for ion absorption sites within the soil, uniform application of manure, the use of slow release P fertilizers, banding P with seed, along with the strong fertilization method of only applying P to the critical level of plant available P in the soil.

Potassium

Potassium is a vital nutrient needed for crop production. There are three forms of K within the soil, unavailable, slowly available, and readily available: unavailable form-where K is existent in primary minerals throughout soil, slowly available form-where K is fixed between clay particles and readily available form-where K is composed within the soil solution. According to Rehm and Schmitt (1997) 90-98% of the estimated 20,000 ppm of K in the soil is in the unavailable form. The most plentiful cation in a plant is K (Pettigrew, 2008). Potassium is essential to plants not because of the construction of any apparatus but for the many roles it has within the plant. Potassium is pulled into guard cells opening the stamatal allowing photosynthesis and respiration. Fischer (1968) found that K uptake was consistent with the increase of that stomatal opening. During times of drought K withdraws from the guard cells to prevent evaporation. It is also known that K promotes cell elongations and retains adequate water levels (Mengel, 1999). Furthermore K is involved with activating enzymes for plant growth, protein synthesis, and the translocation of amino acids and compounds formed during photosynthesis. Potassium triggers a minimum of 60 plant growth enzymes and accumulates in roots to help draw water in and rouse new root hairs (Armstrong and Griffin, 1998).

Potassium is a relatively immobile nutrient in the soil, taken up by the root system as K^+ primarily by diffusion but can also be up taken by mass flow. Losses of K are less likely, compared to mobile nutrients, since there are relatively abundant amounts of K intermittent in the soil. Ashley et al. (2006) stated that the lithosphere contains 2.5% K making it the fourth most sufficient mineral in the soil. However K can still be lost through leaching and fixation. Exchangeable K is present for plant uptake, exchangeable with the soil, fixation, or leaching (Mengel, 1978). Potassium can easily fluctuate back and forth from the slowly available form to readily available form, making it plant available or non-available throughout an individual cropping year. Also K concentration diminishes around plant root systems as most K is taken up by diffusion (Ashley et al., 2006). Potassium availability is dependent on many soil factors such as cation exchange capacity (CEC), temperature, moisture, and cultivation practices. Clay content and organic matter determines the CEC, higher CEC allows for more available cations (K^+) within the soil. Armstrong and Griffin (1998) said as soil temperatures decrease the availability of K to be consumed by the plant decreases. Soil moisture is needed to transport K through the soil by mass flow and to replenish up taken K by diffusion. Cultivation practices are important for many reasons; root respiration requires air for the uptake of K (Rehm and Schmitt, 1997), compaction layers make roots unavailable to penetrate deep K concentrations, incorporated K fertilizer is more readily available than surface applied fertilizer (Armstrong and Griffin, 1998). Leaching is plausible, although K is a relatively immobile nutrient, if the soil is acidic and/or water is moving down at a faster rate than it is being up taken by the plant. Potassium fixation is more apparent in soils that contain high clay content (2:1 clays). Also anaerobic conditions increase the possibility of K fixation due to the limited availability of oxygen (Armstrong and Griffin, 1998). Potassium can also be lost from the plant. Potassium can be lost in the plant roots when in contact with soil since K is a soluble salt within the plant (Gregory et al., 1979).

Potassium deficiencies are more likely in production systems where large quantities of biomass is removed, as this biomass is important in maintaining organic matter which contains high concentrations of K. Potassium deficiencies are usually characterized by stunted growth and chlorosis along the margin of older leaves, hence K is mobile inside the plant. Plant analysis are rarely helpful, they cannot determine future application rates or deficiencies but can show if the plant had luxury consumption of K (Rehm and Schmitt, 1997). Soil tests are the best way to express the amount of available K in the soil solution for application rates. Available K measures the amount of K in the soil solution and the amount of exchangeable K (Rehm and Schmitt, 1997). This test is a good tool for pre plant applications, although it doesn’t help throughout the growing season since K can be leached, lost by the plant and exchanged from readily available form to the slowly available form.

Sulfur

Sulfur fertilization has been readily ignored since few deficiencies have been previously revealed. Additional S fertilizer applications showed no significant yield increases on several crops in Michigan (Christenson, 1998). Attribution to consistent crop inputs; such as fertilizers, manures, atmospheric deposition, irrigation and so forth have supplied plants with needed S. SO_2 can be retrieved from the atmosphere through the stomatal, however the plant cannot acquire the necessary amount to fulfill its needs (Jordan and Ensminger, 1959). Within the last decade S deficiencies have been reported in cereal crops with the reduction of S emissions (Zhao et al., 1999). Therefore, S is mainly taken up as SO_4^{2-} through the plant roots within the soil. According to Droux (2004) the consumption of sulfate is a four step procedure: uptake, assimulation, reduction, and the production of cysteine. Sulfur contributes to the production of: plant growth regulators and amino acids for protein synthesis. Jordan and Ensminger (1959) noted that the amino acid cystine consists of 27% sulfur, while methionine consists of 21%, both plant growth regulators thiamine and biotin and the amino acid cysteine comprise sulfur as well. The majority of S taken up stays within plant biomass instead of being transferred into grain production, unlike other nutrients. Merely 48% of the 10-20 kg of S ha^{-1} needed by wheat is transported into grain (Zhao et al., 1999).

Sulfur is a relatively mobile nutrient which acts like N within the soil solution. Like N, mineralizable S has not been successfully measured within the soil, therefore mineralizable S is not a component of the present S soil test (SO_4-S) (Fox et al., 1989). Sulfur cycles amongst organic and inorganic sulfur. Plant available S, known as inorganic S can be lost through leaching, runoff/erosion, plant removal/plant losses, volatilization and immobilization. Sulfur leaching can be increased by P and calcium (Ca) additions (Jordan and Ensminger, 1959), fallow soils (Garwood and Tyson, 1973), or just where there is an abundant amount of S within the soil. Runoff, leaching, and erosion losses are primarily S losses created by soils that are fallow or removal of previous year's residue. During high amounts of S uptake, hydrogen sulphide (H_2S) and other forms of S can be discharged into the atmosphere by the plant (Scherer, 2001). Anaerobic environments will cause S volatilization, creating H_2S emissions to precipitate (Jordan and Ensminger, 1959).

Sulfur deficiencies are correlated with interveinal chlorosis on newer plant leaves first. Late vegetative S deficiencies cause optimal grain yields to dwindle. Sulfur levels have to remain sufficient throughout the growing season to produce quality grain. Once S deficiencies have been revealed, grain development has already been negatively affected (Zhao et al., 1999). Haneklaus et al. (1995) found that S deficiencies had to be corrected before their appearance to prevent yield degradation. Soil S test only express the amount which was available at the time the soil sample was taken. Therefore $S0_4^{2-}$ can increase or decrease throughout the cropping season since S is a relatively mobile nutrient. As seen in crop response to soil test N, soil test SO_4 also showed no residual effects on S fertilization in Argentina (García et al., 2007). In arid regions SO_4 tests may be suitable, in other regions sulfate is easily lost through leaching resulting in a poor correlation between soil test SO_4 and crop response (Marx et al., 1996). In wheat production, Arnall and García (2012) noted S soil tests predicts little on yield response. Throughout Dick and Castellano (1991) research they saw season variability in soil SO_4 levels where S levels increased during periods favoring evapotranspiration, confirming exchangeable soil test SO_4 alone is not a good prediction of plant available SO_4. Tissue analyses are another way to determine plant S needs. Individual leaves will result in different sulfur needs since S is immobile in the plant. Tissue samples during early vegetative growth give inaccurate nutrient readings and S deficiencies at the end of vegetative growth will not correct symptoms for the present year's crop (Zhao et al., 1999).

N-Rich Strips

N-rich strips are simple, yet practical fertilization practices that can be easily adopted by most. The method of this practice is to apply a strip or strips across a field that will be non N limiting throughout the entire growing season. Identification of N deficiencies will be easily recognizable with the use of this strip, by comparing it to the entire field. When using this practice Raun et al. (2010) recommends only applying half of the expected N needed by the plant during planting and making top dress recommendations based on the N-Rich strip in the middle of the cropping season. By using the N-Rich strip and GreenSeeker^{TM} Sensor, N application rates are no longer guesstimates. With the use of optical sensors, in season yield potential can be predicted from normalized difference vegetative index (NDVI) readings (Raun et al., 2010). Predicting potential yield and top dress rate is done by the Sensor Based Nitrogen Rate Calculator (SBNRC) by using the NDVI readings recorded from the N-Rich strip and the farmer's practice, the area next to the N-Rich Strip which is considered to have the same N rate that was applied to the entire field. NDVI is divided by the number of growing degree days greater than zero (from planting to sensing) calculating INSEY (Lukina et al., 2001). The top dress N fertilizer rate is then calculated by estimating the N uptake for the N-Rich strip and the farmer's practice. According to Stone et al. (1995) savings of up to 57 kg of N ha^{-1} are plausible when using a variable rate application based on a spectral index compared to a fixed top dress rate. As shown in 2009-2010 the SBNRC method routinely outperformed current producer fertilization methods, while producing comparable yields but decreasing N application rates by 22.42 kg ha^{-1} (Butchee et al., 2011). The N-Rich Strips can also be used without the GreenSeeker^{TM} Sensor by using visual effects throughout the field. If there is a difference between the strip and the rest of the field, N is needed while on the other hand if there are no visual differences an addition of N will unlikely increase yields.

CHAPTER III

OBJECTIVE

The objectives of this state wide multifaceted project were to: demonstrate the ability to visually identify nutrient needs throughout a cropping season, determine the relationship between pre-plant soil tests and nutrient response across divergent environments and evaluate if Oklahoma producer’s current fertilization management scheme for N, P, K and S are maximizing yields.

CHAPTER IV

METHODOLOGY

This study was conducted throughout two growing seasons. In 2011-2012 there were 42 locations within Oklahoma and 40 locations in 2012-2013. Prior to application 15 soil samples were taken using a 2.54 cm diameter soil probe from each site at depths of 0-15 and 15-30 cm. Samples were mixed from each depth, allowing two composite samples from each site. The samples were then sent to Oklahoma State University Soil, Water, and Forage Analytical Laboratory to be analyzed for pH, NO_3-N, extractable P, K, S, Ca, and Mg. Samples were dried at 65°C overnight and ground to pass a 2 mm sieve prior to extraction and analysis. The soil pH was measured by using a combination electrode within a 1:1 ratio of soil to water suspension. Nitrate-N was determined using a 1 M KCl extraction solution with 2.0 g of soil to 20 mL of solution with 15 minutes of shaking time. Nitrate-N was then determined by automated colorimetric flow-injection analysis (Lachat Quickchem 8000, Loveland, CO). Mehlich-3 (M-3) was used to find extractable P, K, Ca and Mg, by extracting 2.0 g of soil with 20 mL of M3 solution and shaking for 5 minutes. Exchangeable S was found by mixing 10.0g of soil with 25 mL of 0.008 M calcium phosphate solution and shaking for 30 minutes. Concentration of P, K, Ca, Mg and S extractions were determined by analysis with inductively coupled plasma atomic emission spectroscopy analyzer (ICP-AES).

A plot consisted of four parallel strips roughly 1.8 x 30.5 m (WxL). A tractor with a NPKS applicator (Figure 1), built by engineers at Oklahoma State University, was transported to every site. The applicator applied a dry fertilizer for each of the four treatments. The treatments consisted of urea (46-0-0), triple super phosphorus (0-20-0), potash (0-0-52), and gypsum (23% Ca and 19% S). Although in 2012-2013 the urea treatment was replaced with ammonium nitrate (34-0-0), due to drought conditions and volatilization concerns. The NPKS applicator contained four dry fertilizer boxes, each holding their own individual fertilizer. Each fertilizer box had three polyurethane tubes connected to a 12 m boom where it dispersed its fertilizer evenly throughout a 1.8 m strip, parallel to one another. Each fertilizer box was ground driven individually to control product application rate. The dry fertilizer was then conveyed through polyurethane tubing pneumatically by a PTO driven fan. Each treatment was roughly applied at the rate of 257.6 kg of product ha^{-1} around sowing.

Prior to top dressing, GreenSeeker^{TM} readings were collected for the total length of each treatment, including the farmer practice treatment, to record in-season NDVI values. At maturity three 1 m^2 sections were harvested from each strip at every individual site by hand cutting the total biomass 2.54 cm above the soil surface. Each biomass sample was then placed into its own individual labeled bag, head first, and the bag was tied around the stems with bailing twine. Samples were dried in an air forced oven at roughly 65 °C. Prior to threshing dry weights were taken and recorded. Each sample was then threshed and grain was collected, weighed and recorded. The grain was then ground and rolled in glass bottles with 4 stainless steel pins for 48 hours. Grain samples were then sent to Oklahoma State University Soil, Water, and Forage Analytical Laboratory and analyzed for N, P, K, and S content. Grain samples were first sieved through a 2 mm sieve. Total N was analyzed by the combustion method where 0.145-0.16 g of the grain sample was placed in the LECO TruSpec 628 (St. Joseph, MI) for analysis. Phosphorus, K, and S grain content were determined by the digestible minerals method as follows: 10 mL of nitric acid was added to 0.5 g of the grain sample and left to set for one hour. The samples were then placed into a digestion block for 30 min. at 60 °C with an additional 2.5 hours at 115°C. The samples were then removed and allowed to cool to room temperature. Once cooled the samples were diluted with deionized (DI) water to 50 mL where it was then analyzed by the Spectro Ciros CCD ICP-AES (Mahwah, NJ). Statistical Analysis was performed using SAS 9.3. Individual locations were analyzed separately using Proc GLM and Dunnett’s Test identifying significant variables using alpha=0.05. Grain yield is reported at 12.5% moisture and all recommendations and interpretations are based on the Oklahoma Soil Fertility Handbook (Zhang and Raun, 2006).

CHAPTER V

FINDINGS

Drought conditions in 2011 prevented the sampling of some locations to a depth of 45 cm. Therefore soil sampling depths varied across locations. Due to failed crop or miscommunication with producers, 30 locations (Table 1) of the 42 (Figure 2) applied were harvested in 2011-2012. Many producers reduced nutrient inputs during 2011-2012 due to extreme environment conditions.

Drought conditions in 2012 also prevented the sampling of some locations to a depth of 45 cm. Due to frost injury, rye problems or wheat being completely grazed out, a total of 29 locations (Table 2) of the 40 applied (Figure 3) were harvested in 2012-2013. As seen in 2011-2012 many producers reduced nutrient inputs during 2012-2013 due to extreme environment conditions from previous year. Grain responses to added nutrients are reported separately due to specific responses to each variable.

Nitrogen

Surface and subsurface soil test NO_3-N results for harvested locations in 2011-2012 varied throughout Oklahoma. Surface soil test results ranged from 3 to 56 ppm with an average of 18 ppm, while subsurface samples ranged from 2 to 51.5 ppm with an average of 15.4 ppm (Table 3). Nitrogen recommendations are based on yield goals, where 2.2 kg of N ha^{-1} should be added for every 67.2 kg of wheat ha^{-1} expected. When applying N, soil sample results should be taken into consideration. Producer yield goals were not recorded, thus yield goals were assumed using total N considering pre-plant, with seed, top-dress and residual.

Total N applications (pre-plant, with seed and top-dress) also varied throughout the locations. Total applied N ranged from 0 kg ha^{-1} to 100.8 kg ha^{-1} (Table 4). The N rich strips applied an additional 118.5 kg ha^{-1} of N compared to the farmer practice. Dunnett's test reported five responsive locations, where the N rich strip significantly increased grain yield when compared to the farmer practice (Table 5).

Location 1 had 6 ppm of residual NO_3-N within the surface and 8 ppm within the subsurface. Farmer practice consisted of a N application of 22.4 kg ha^{-1} applied at planting resulting in a grain yield of 3213 kg ha^{-1}. Grain yield was increased by 846 kg ha^{-1} with the N rich strip treatment, where the N rich strip produced a grain yield of 4059 kg ha^{-1}. An estimated yield goal of 1612.8 kg ha^{-1} was expected and adequate for the location. Significant yield increase in the N rich strip can be contributed to the farmer practice applying insufficient N to maximize yield.

Location 8 contained 24 ppm of residual NO_3-N in surface and 15 ppm in the subsurface. The producer applied 12.5 kg ha^{-1} with seed and top-dressed 77.3 kg ha^{-1} by broadcast, resulting in 89.8 kg ha^{-1} of total N applied, producing a grain yield of 2677 kg ha^{-1}. The N rich strip produced a grain yield of 3696 kg ha^{-1}, an increase of 1019 kg ha^{-1}.

The farmer practice applied enough N, accounting for residual, for a yield goal of 5315.5 kg ha^{-1}. Differences in yield goal compared to actual yield could be attributed to ammonia loss with the application of urea on the surface. Meyer et al. (1961) reported broadcasting urea on soil surfaces need significant rainfall or irrigation (12.7 mm) directly following application to prevent ammonia volatilization. Top-dress applications of winter wheat in Oklahoma typically occur from January to late March. According to the Hinton Oklahoma Mesonet Station, near location 8, there were 18 rainfall events during this time period where only three of them accumulated more than 12.7 mm. In addition to the lack of adequate precipitation at N application, Meyer et al. (1961) showed that crop residue and initially moist soil surface can increase the severity of ammonia volatilization. Consequently, at this site we can hypothesize that both the no-till management practice and lack of adequate rainfall at application increased N losses resulting in farmer practice yields below yield goal.

Location 14 had 5.5 ppm in the surface with a subsurface of 3 ppm of residual NO_3-N. A top-dress N application of 51.5 kg ha^{-1} was made generating a grain yield of 2781 kg ha^{-1}. The N rich strip improved yield by 1416 kg ha^{-1} producing 4197 kg ha^{-1}. A yield goal of 2116.8 kg ha^{-1} was estimated using total applied and residual N. The N rich strip indicated yield potential was underestimated. Hence, yields were not maximized due to inadequate N inputs.

Location 24 had 4.5 ppm NO_3-N in the surface and 8 ppm within the subsurface. Prior to planting a N application of 33.6 kg ha^{-1} was applied as well as a top-dress application of 44.8 kg ha^{-1}, resulting in a total application of 78.4 kg ha^{-1}. A farmer practice yield goal of 3192 kg ha^{-1} was estimated by combining applied and residual N.

Farmer practice strip produced a grain yield of 2436 kg ha^{-1}, while the N rich strip produced 3783 kg ha^{-1}. The N rich strip increased grain yield by 1347 kg ha^{-1}. Similar to location 8, urea was also broadcasted as the N top-dress method for this location. As previously mentioned differences in yield goal compared to actual yield may be due to ammonia loss with the application of urea on the surface. According to the Cherokee Oklahoma Mesonet Station, near location 24, 23 rainfall events took place during the top-dress application period where two of the events accumulated more than 12.7 mm. In addition to inadequate precipitation at N application, Meyer et al. (1961) and Ernst and Massey (1960) reported increases in pH increase ammonia volatilization. Subsequently, a near neutral pH level of 6.8 and inadequate precipitation increased N losses giving rise to the significant N rich strip yield increase.

Location 30 had residual soil NO_3-N levels consisting of 4 ppm in the surface and 2 ppm in the subsurface. Nitrogen was not applied during the growing season resulting in a grain yield of 1589 kg ha^{-1}. The N rich strip boosted yield 1347 kg ha^{-1}, concluding a yield of 2936 kg ha^{-1}. A research station was used as location 30, giving rise to why there was a minimum residual soil NO_3-N level as well as no N applied for wheat production. Therefore, maximum yield potential was not reached, due to the lack of additional N throughout the growing season.

Despite the N rich strip increasing grain yield at 5 of the 30 harvested locations during 2011-2012, grain N content was significantly increased at 11 of the locations. The N rich strip also increased S grain content at a total of eight locations. At five of these locations grain content of both N and S was increased, two of which grain yield was also increased.

Nitrogen removal was significantly increased at six locations. There was only one location where N removal increased and grain yield did not increase. However, the addition of N increased grain yield and the removal of: N, P, K and S at locations 1 and 30, N, K and S at location 24 and N and S at location 14. The removal of S was increased by the addition of N at location 16, although grain yield was not improved.

As previously seen in 2011-2012, surface and subsurface soil test NO_3-N results for 2012-2013 harvested locations varied throughout Oklahoma. Surface soil test results ranged from 1.5 to 68.5 ppm with an average of 29.3 ppm, while subsurface samples ranged from 1.5 to 37.5 ppm with an average of 15.9 ppm (Table 6).

Total N applications (pre-plant, with seed and top-dress) also varied throughout the locations. Total applied N ranged from 0 kg ha^{-1} to 151.2 kg ha^{-1} (Table 7). Due to dry conditions ammonium nitrate was used for the N rich strip in 2012-2013, adding 87.6 kg ha^{-1} of N above the farmer practice. Dunnett's test reported two responsive locations, where the N rich strip significantly increased grain yield when compared to the farmer practice (Table 8).

Location 38 had 68.5 ppm of residual NO_3-N within the surface and 8 ppm within the subsurface. Farmer practice consisted of a pre-plant N application of 31.4 kg ha^{-1}, producing a grain yield of 3083 kg ha^{-1}. The farmer practice had enough total N, including residual and applied N, for a yield goal of 6082 kg ha^{-1}. The N rich strip produced a grain yield of 4275 kg ha^{-1}, improving grain production by 1192 kg ha^{-1}.It is hypothesized that residual NO_3-N was decreased due to immobilization or N loss with a soil pH of 6.5. Also with a moist spring in 2013, N leaching may have been plausible.

Location 43 had residual soil NO_3-N levels consisting of 6 ppm in the surface and 9 ppm in the subsurface. The farmer practice was comprised of a top-dress N application of 22.4 kg ha^{-1}, with an estimated yield goal of 1680 kg ha^{-1} considering both applied and residual N. Farmer practice produced a grain yield of 2954 kg ha^{-1}, although the yield goal was exceeded the N rich strip verified the assumed yield goal was under estimated. Figure 4 is an image of location 43 where the difference in height of the N rich strip is visible at maturity. The farmer practice reduced maximum grain yield by 2474 kg ha^{-1}, where the N rich strip generated a grain yield of 5428 kg ha^{-1}.Therefore, inadequate N inputs significantly decreased maximum grain yield.

As seen in 2011-2012 the addition of N increased grain N content at a total of 11 locations in 2012-2013, where six of those locations also increased S grain content. One of these locations consisted of location 38 where grain yield was also improved. At both locations 36 and 43 N, K and S grain content were significantly increased compared to the farmer practice, although grain yield was only improved at location 43.

Nitrogen removal was significantly increased at five locations in 2012-2013 with the addition of N. Nitrogen, P, K and S total uptake was also improved at both locations where grain yield was improved.

Phosphorus

Phosphorus recommendations are based on soil test results, where estimated available soil P is recorded as percent sufficiency. In Oklahoma a soil test resulting in 32.5 ppm is considered 100% sufficient. Soil test P (STP) levels extended from 9.5 ppm to 91.5 ppm with an average across locations being 36.6 ppm in 2011-2012 (Table 3).

While the average was above sufficiency, 16 locations dropped below 32.5 ppm, a level considered insufficient. Phosphorus availability is also controlled by soil pH. Soil pH levels of harvested locations ranged from 4.5 to 8.2, while the average soil pH over locations was 5.8 (Table 3). For winter wheat production in Oklahoma a soil pH level of 5.5 to 7.0 is considered to be optimum, 37% of harvested locations fell outside this optimum soil pH range, while only one location was above 7.0. Similar P and pH levels were found by Zhang et al. (1998) during a soil testing review analyzed across Oklahoma, where approximately 50% of P levels in 1996 were below sufficiency and 30% of sampled locations in 1985. Also 39% of locations in 1996 had soil pH levels below 5.5. Two harvested locations resulted in soil pH levels below critical and STP below sufficiency.

Total P applications (pre-plant and with seed) ranged from 0 kg ha^{-1} to 18.6 kg ha^{-1} (Table 4). Of the 12 locations where P was applied, 11 of them were applied at planting by banding with seed. Several authors reported banding P is more efficient then broadcast, even when fertilizer was worked into the soil, banded P applications could be reduced between 11- 40% (Sanchez et al., 1991; Sanchez et al., 1990; Sander et al., 1990; Sander et al., 1991). Therefore producers could possibly be banding P to be more efficient and economic compared to other P application methods. Sanchez et al. (1991) and Welch et al. (1966) found that efficiency of banding P ceased once STP levels were sufficient. The P rich strip added 51.5 kg ha^{-1} of P in addition to the farmer’s application. Dunnett’s test reported four responsive locations where the P rich strip significantly increased grain yield when compared to the farmer practice (Table 9).

Location 12 had a soil pH of 4.9 with a STP level of 20.5 ppm within the surface. A P application of 10.1 kg ha^{-1} was applied at planting, resulting in a farmer practice grain yield of 3679 kg ha^{-1}. Phosphorus rich strip produced a grain yield of 4681 kg ha^{-1} improving grain yield by 1002 kg ha^{-1}. Soil test P reported 90.4% sufficient and recommended 9.4 kg ha^{-1} of P be added. Although it has been reported that banding P is more efficient, Zhang et al. (2005) found that when banding P on acidic soils applying 14.7 kg ha^{-1} of P was most sufficient in alleviating aluminum toxicity. Although P was applied by an efficient method, according to Oklahoma State University an inadequate rate of P was applied to alleviate aluminum toxicity. In addition, K was also insufficient at this location, therefore according to Baule (1918) percent sufficiency can be reduced to 89%.

Location 13 had a neutral soil pH of 6.9 with a STP level of 19 ppm. Phosphorus was applied prior to planting at 7.3 kg ha^{-1}, producing a grain yield of 2971 kg ha^{-1} for the farmer practice. When compared to the P rich strip, which produced 3990 kg ha^{-1}, the farmer practice grain yield was reduced by 1019 kg ha^{-1} compared to the maximum potential. Although P was applied, soil test reported P levels being 89% sufficient and a recommended 10.7 kg ha^{-1} of P was needed to reach sufficiency. However since the P application was banded with seed the rate should have been sufficient.

Location 20 had a soil pH below the critical level at 4.5, as well as a STP level of 19 ppm which is below 100% sufficiency. At planting a P application of 6.7 kg ha^{-1} was made by the farmer. When banding P on acidic soils Oklahoma State University recommends a rate of 14.7 kg ha^{-1} of P. Phosphorus rich strip increased grain yield by 1468 kg ha^{-1} where the farmer practice produced 2833 kg ha^{-1} and the P rich strip produced 4301 kg ha^{-1}. Figure 5 is an image of location 20 where the difference in height and color of the P rich strip is visible during vegetative growth. Soil P levels were 89% sufficient and 10.7 kg ha^{-1} of P was recommended to bring P levels to sufficiency. Inadequate P was applied based on fertility recommendations, giving rise to grain yield increase from P rich strip application.

Location 24 also had a neutral soil pH of 6.8 with a STP level of 66 ppm. No P was added, due to STP being 100% sufficient. The farmer practice produced a grain yield of 2436 kg ha^{-1}, while the P rich strip improved yield by 1485 kg ha^{-1} with a grain yield of 3921 kg ha^{-1}. Both location13 and 24 soil samples were sent to Kansas State University for additional P analysis using Bray and Olsen extractions. The results of this analysis gave no indication of why P response was recorded, thus results were not included.

As previously mentioned, a high percent of Oklahoma producers have soil pH levels below critical for winter wheat production. To avoid high yield losses 6 of the 10 locations with low pH levels banded P at planting. Toxic metals bind with P making both the toxic metals and P unavailable. This is a short term solution and has to be done annually since as P is removed more aluminum and manganese become available (Zhang et al., 2005). All locations where P was banded to compensate for sub optimum soil pH levels soil will continue to acidify with the additions of N until pH is corrected by the application of lime.

In the 2011-2012 cropping season grain P content was significantly increased at four locations, of which only two were locations that had significant increases in grain yield. It was observed at location 21 that the P rich strip increased both P and K concentration in the grain.

Phosphorus removal from the P rich strip was significantly increased at six locations, three of these locations having significantly increased grain yields as well. The P rich strip also significantly increased nutrient removal of N at one location, K at four locations and S at two locations. At location 24 where the N and P rich strips significantly increased grain yields, the P rich strip significantly increased N, P, K and S removal. Also at location 12 where soil P and K levels were insufficient, P and K removal were increased in the P rich strip. This was not seen in the K rich strip at this location.

Soil test P levels, in 2012-2013, ranged from 12.5 ppm to 150.0 ppm with an average across locations being 43.9 ppm (Table 6). As seen in the previous year the average was above sufficiency and 15 locations fell below 32.5 ppm. Furthermore harvested locations soil pH levels ranged from 4.4 to 8.2, while the average soil pH over locations was 6.0 (Table 6), 57% of harvested locations fell outside this optimum soil pH range of 5.5 to 7.0. Twelve harvest locations had a soil pH below 5.5, while five locations had a pH above 7.0. Similar P and pH levels were recorded in the preceding year, as well in Zhang et al. (1998). However locations with soil pH levels outside of the optimum range increased from 2011-2012 NPKS locations. Six locations had soil pH levels below critical and STP below sufficiency and four locations with soil pH levels above 7.0 and STP below sufficiency.

Total P application (pre-plant and with seed) rates were similar to 2011-2012, ranging from 0 kg ha^{-1} to 18.6 kg ha^{-1} (Table 7). Of the 19 locations where P was applied, 15 of them were applied by banding with seed during planting. Phosphorus application methods were similar to 2011-2012 although locations where P was applied increased. Phosphorus rich strip added 51.5 kg ha^{-1} of P beyond the farmer practice. Dunnett's test reported three responsive locations where the P rich strip significantly increased grain yield when compared to the farmer practice (Table 10).

Location 32 had a calcareous soil pH of 8.0 with a STP level of 12.5 ppm. According to Oklahoma State University STP was 82.5% sufficient and a recommended 17.1 kg ha^{-1} of P should be added. Farmer practice applied a pre-plant of 7.9 kg ha^{-1} of P, producing a grain yield of 1671 kg ha^{-1}. Grain yield was significantly increased by 467 kg ha^{-1}, where the P rich strip improved grain yield to 2138 kg ha^{-1}. The farmer applied 9.2 kg ha^{-1} less than Oklahoma State University recommends, giving rise to grain yield improvement with the addition of P.

Location 55 had an acidic soil pH of 4.6 with a STP level of 17 ppm. Not only did the soil pH level fall below the critical level, but STP was 87% sufficient as well. A rate of 17.6 kg ha^{-1} of P was recommended. The farmer applied P at planting, by banding 11.2 kg ha^{-1}, resulting in a grain yield of 1801 kg ha^{-1}. The P rich strip improved grain yield by 1179 kg ha^{-1} producing a grain yield of 2980 kg ha^{-1}. As seen in the preceding year, when banding P on acidic soils with STP levels below sufficient, Oklahoma State recommends a P application of 14.7 kg ha^{-1}. Therefore the addition of inadequate P fertilizer on an acidic and low STP soil resulted in a grain yield improvement with the application of a P rich strip.

Location 56 also had a soil pH level below critical and STP level below sufficient. Soil test reported a soil pH of 4.4 and a STP level of 26 ppm, being 94.8% sufficient. An application of 5.1 kg ha^{-1} of P was recommended. The farmer applied 11.2 kg ha^{-1} of P at planting, resulting in a grain yield of 2138 kg ha^{-1}. The P rich strip produced a grain yield of 3278 kg ha^{-1}, improving grain yield by 1140 kg ha^{-1}. As previously mentioned in location 55, a rate of 14.7 kg ha^{-1} of P is recommended when banding P in acidic and low STP soils.

In 2012-2013 P grain content was significantly increased at eight locations. Of the three locations where P additions significantly improved grain yield, P grain content was increased at two of these locations. Potassium grain content was also improved at two of these locations and N and K grain content at another one of these locations. Another location increased N and S grain content with the addition of P, although P grain content was not increased.

Of the eight locations where P grain content was improved five of them increased total P removal, two of which (54 and 55) also increased the removal of N, K and S. Location 56 also increased the removal of P and K, although grain content was not increased. All locations where the addition of P increased grain yield also significantly increased P removal.

Potassium

Soil test K (STK) averaged 212.6 ppm over 2011-2012 harvested locations, ranging from 119 ppm to 422 ppm (Table 3). While 11 locations were below average only two locations had K levels lower than 125 ppm, which is considered to be 100%

sufficient according to Oklahoma State University recommendations. In 1985 and 1996 Zhang et al. (1998) reported over 80% of 3,075 locations sampled in Oklahoma had K levels above 125 ppm, comparable to 93% of harvested NPKS locations. This may be due to low K removal by grain and little K losses from semi-arid conditions. Like P, K recommendations are based on estimated available K from soil test results. Only 1 of the 30 harvested locations had a K application in 2011-2012, where the producer added 4.5 kg ha^{-1} (Table 4). The K rich strip added 134 kg ha^{-1} of K and 121.1 kg ha^{-1} of chloride (Cl) compared above the farmer practice. Dunnett's test reported two responsive locations where the K rich strip significantly increased grain yield when compared to the farmer practice (Table 11).

Location 4 had a STK level of 191.5 ppm with no additional K added producing a 2366 kg ha^{-1} grain yield for the farmer practice. Although grain yields would not be expected to increase with the application of additional K, yields did increase by 830 kg ha^{-1} with the K rich strip producing 3196 kg ha^{-1}. Girma et al. (2007) noted K increases drought tolerance in stressful years from the long-term Magruder plots. Applications of K during drought like conditions have been reported to improve: water use efficiency (WUE) during vegetative growth, leaf area, root growth, vegetative growth and rate of growth (Andersen et al., 1992a; Andersen et al., 1992b). The surface composite sample for this location was returned to Oklahoma State University Soil, Water, and Forage Analytical Laboratory to be reanalyzed for Cl levels. Analysis showed a soil Cl concentration of 7.2 ppm. Oklahoma State University recommends a soil test Cl level of 17.5 ppm in the top 45 cm of the soil profile to be adequate (Zhang et al., 2000). Since only the surface composite soil sample was analyzed for Cl, Oklahoma State University recommends multiplying that value by 3 to provide a total surface and subsurface (0-45 cm) Cl level. Therefore, a soil Cl level of 21.6 ppm was estimated at application. It would be assumed Cl levels were adequate, however both Freeman et al. (2006) and LaRuffa et al. (1999) reported Cl response in Oklahoma sandy loam soils. The K rich strip at this location also significantly increased N uptake, similar to Freeman et al. (2006) where an increase in N uptake with a Cl application to the sandy loam soil location was reported. Significant yield increase in K rich strip could be due to the increase of drought tolerance by K or to an increase of Cl and the effect it has on N uptake.

Location 12 had a STK level of 119 ppm, although STK was below sufficiency no additional K was added. This resulted in K rich strip increasing yield by 726 kg ha^{-1}, where the farmer practice produced a grain yield of 3679 kg ha^{-1} and the K rich strip produced 4405 kg ha^{-1}. Soil tests reported K at 98.8% sufficient, therefore 4 kg ha^{-1} of K should have been applied prior to the growing season. As previously mentioned, location 12 also had STP levels below sufficiency.

The K rich strip failed to increase K grain content at any location. Although, N and S grain content was significantly increased at location 22 from the application of the K rich strip. Even though K grain content was not increased at any location, the addition of K significantly increased K removal at location 4 and 24. Location 4 also increased N, P and S removal as well as improved grain yield significantly. Nitrogen and S removal were also increased at location 24 due to the addition of K.

Soil test K levels from 2012-2013 harvested locations averaged 216.2 ppm, ranging from 68.5 ppm to 436 ppm (Table 6). Four of the harvested locations had K levels below 100% sufficient, 125 ppm. Similar to STP levels, STK levels were also comparable to 2011-2012 soil test results and Zhang et al. (1998), where 86% of harvested NPKS locations in 2012-2013 were above 100% sufficient. Three harvested locations received a K application in 2012-2013, where one location applied 1.3 kg ha^{-1} and two locations applied 11.7 kg ha^{-1} of K fertilizer (Table 7).

Surface soil tests reported Cl^{-} levels ranging from 7.0 to 66.7 ppm, averaging 20.3 ppm over harvested locations. Subsurface Cl^{-} levels averaged 17.4 ppm, extending from 6.6 to 72.8 ppm (Table 6). Potassium rich strip added 134 kg ha^{-1} of K and 121.1 kg ha^{-1} of Cl above the farmer practice. Dunnett's test reported one responsive location where the K rich strip significantly increased grain yield when compared to the farmer practice (Table 12).

Location 33 had a surface STK level of 169.5 ppm, well above 100% sufficient. Soil test Cl levels were also taken into consideration, where the surface Cl level consisted of 11.4 ppm and a subsurface of 15.8 ppm. The farmer practice produced a grain yield of 2384 kg ha^{-1}. Although both K and Cl were adequate to produce maximum yields, the K rich strip increased grain yields by 725 kg ha^{-1} generating a grain yield of 3109 kg ha^{-1}. With drought conditions in 2012 it is hypothesized the addition of K boosted vegetative growth compared to the farmer practice, where Andersen et al. (1992a) and (Andersen et al., 1992b) reported K applications improved vegetative production.

The addition of K did not increase K grain content in 2012-2013, as seen in the previous year; however it did increase N grain content at location 54. Total K removal nonetheless was increased at location 35 where N and S removal were also significantly increased with the addition of K. Nitrogen and S removal were also increased at location 3 where the addition of K increased grain yield.

Sulfur

Surface soil tests reported SO_4-S levels fluctuating from 4.4 ppm to 31 ppm, while averaging 13 ppm across 2011-2012 harvested locations. Average subsurface SO_4-S was 11.6 ppm, as S levels were widely variable across locations varying from 5.1 ppm to 47.5 ppm (Table 3). Like N, S recommendations are based on yield goal and soil test results. Sulfur requirements are 10% of the N requirement minus surface and subsurface soil test values (Zhang et al., 2000). Only 1 of the 30 locations had a SO_4 application in 2011-2012, where the producer added 4.5 kg ha^{-1} (Table 4). Sulfur rich strip added 47.9 kg ha^{-1} of S above the farmer practice. Dunnett's test reported no responsive locations where the S rich strip significantly increased grain yield when compared to the farmer practice.

Sulfur, a secondary nutrient, was included in this study due to an increase in reported deficiencies across the world, with reductions in S emissions (Zhao et al., 1999). In the United States S deficiencies have been reported as far south as Kansas (Lamond, 1997). Therefore the application of the S rich strip was intended to document if Oklahoma winter wheat is also suffering from S deficiencies. In the 2011-2012 cropping season S applications did not increase grain yields at any location. In fact soil test results reported average total SO_4-S well above sufficient. Location 3, which had the lowest residual SO_4-S level, had enough S to reach a yield goal of 9889 kg ha^{-1} although the farmer practice only produced 2487 kg ha^{-1}. These high S concentrations may be due to average annual S addition of 9.8 kg ha^{-1} from rainfall (Harper, 1942) or low S removal where roughly half of the S taken up by the plant is removed with grain (Zhao et al., 1999). In addition S is added through impurities in fertilizers (Zhang et al., 2000).

Even though the S rich strip failed to significantly increase grain yields in 2011-2012, S grain content was significantly increased at 4 locations. The S rich strip also increased P and N content at one location each, where N and S were increased at location 4 and P and S were increased at location 9. Sulfur additions failed to significantly increase the removal of N, P, K and S.

Surface soil tests reported SO_4-S levels fluctuating from 3 ppm to 33 ppm, while 2012-2013 harvested locations averaged 13.2 ppm. Subsurface SO_4-S levels varied from 2.5 to 52.5 ppm, averaging 14.2 ppm over harvested locations (Table 6). Sulfur additions comprised of two locations, where both locations applied a split application at planting with seed and as top-dress. Total applications consisted of 19 and 20 kg ha^{-1} of S (Table 7). Sulfur rich strip increased additional S by 47.9 kg ha^{-1} compared to the farmer practice. Dunnett's test reported no responsive locations where the S rich strip significantly increased grain yield when compared to the farmer practice, similar to 2011-2012 NPKS results. Location 35, which had the minimum total SO_4-S level of 2013 harvested locations, had adequate S for a yield goal of 5376 kg ha^{-1} where the farmer practice produced a 3718 kg ha^{-1} grain yield.

Sulfur additions only increased S grain content at one location in 2012-2013. Nitrogen grain content was also increased at another location from the addition of S. The addition of S also increased the removal of K and S at location 5 although neither S grain content nor yield was increased at this site.

Although S deficiencies were not recorded in either year, Girma et al. (2005) found grain yield response to additions of S is possible in fine sandy loam soils in Oklahoma. Even though a grain yield response to S was reported, it was inconsistent and was only significant 6 of 14 site years. This is consistent with Lamond (1997) who stated responses to S additions in Kansas are more suitable in course textured soils with low organic matter.

CHAPTER VI

CONCLUSIONS

In 59 site years, 236 comparisons were made towards Oklahoma producer's current N, P, K and S fertilization management practices. Of these 236 comparisons only 17 were significant, where two sites had two significant comparisons at the same location. The lack of responses suggests overall producers in Oklahoma are properly managing N, P, K and S inputs in a way that maximizes yield.

Seven locations reported a significant response to the addition of N. Responsive locations consisted of under estimated yield potential and N losses, whether it was ammonia losses, immobilization or leaching, due to independent environmental conditions. Although 52 locations received adequate N to produce maximum grain yields, over application of N at these locations could not be calculated and are likely plausible.

Responsive locations to the addition of P were comprised of seven sites. However initial soil tests reported 18 locations with STP below sufficiency, 11 locations with soil pH levels below a critical 5.5, and nine locations where both STP levels were below sufficiency and soil pH levels were below critical. Out of a total of 38 locations expected to have a response to an addition of P only seven locations reported a response, concluding 32 locations applied adequate P to produce maximum grain yields. Four of these responsive locations were identified by initial soil tests and inadequate P applications. However two of these responsive locations added adequate P fertilizer according to Oklahoma State University recommendations to meet sufficiency and one responsive location had a STP level above 100% sufficiency. Concluding, the majority of initial soil tests reported the need for P additions, whether it may be due to low STP, soil pH levels below critical or both low STP and soil pH levels below critical. Further research is needed on STP level recommendations in neutral and calcareous soils for Oklahoma winter wheat production.

Response to the addition of K consisted at three locations, where only one of the locations was identified by initial soil tests. Another responsive location was hypothesized to be due to the addition of Cl. Initial soil test reported adequate soil Cl levels, although Cl losses in sandy loam soils have been reported. Further research is needed on the addition of K in Oklahoma winter wheat to determine if STK levels are appropriate and the effects of added K in drought conditions. Genetic variety by environment interactions also needs further research.

The addition of S did not significantly increase grain yields. As initial soil tests reported harvested locations with the minimum soil SO_4-S levels were adequate to produce grain yields above estimated yield goals. However, producers should be conscious of soil SO_4-S levels due to an intensive farming practices and the recognition of S deficiencies throughout the world. Subsoil sampling should also be taken into consideration when soil sampling, where surface soil SO_4-S only contains roughly half of available S when comparing averages across all locations

The majority of producer’s current N, P, K and S fertilization management practices are adequate, where 44 of 59 harvested locations maximized grain yields. Furthermore, non-responsive locations have the potential to maintain maximum grain yields with a decrease in fertilizer inputs. Soil testing proved to be an accurate method of predicting P, K and S response.

REFERENCES

Andersen M.N., Jensen C., Lösch R. (1992a) The interaction effects of potassium and drought in field-grown barley. I. Yield, water-use efficiency and growth. Acta Agriculturae Scandinavica B-Plant Soil Sciences 42:34-44.

Andersen M.N., Jensen C., Lösch R. (1992b) The interaction effects of potassium and drought in field-grown barley. II. Nutrient relations, tissue water content and morphological development. Acta Agriculturae Scandinavica B-Plant Soil Sciences 42:45-56.

Armstrong D.L., Griffin K.P. (1998) Potassium for Agriculture, Better Crops with Plant Food (IPNI).

Arnall B., García F. (2012) Improving Soil Fertility and Wheat Crop Management Through the Long-term Study of Cereal Crop Rotations. Better Crops with Plant Food 3:7-9.

Ashley M., Grant M., Grabov A. (2006) Plant responses to potassium deficiencies: a role for potassium transport proteins. Journal of Experimental Botany 57:425.

Barker A., Stratton M., Rechcigl J., Power J., Dick W., Kashmanian R., Sims J., Wright R., Dawson M., Bezdicek D. (2000) Soil and by-product characteristics that impact the beneficial use of by-products. Land application of agricultural, industrial, and municipal by-products:169-213.

Barker A.V., Pilbeam D.J. (2007) Handbook of plant nutrition CRC press.

Batten G.D. (1992) A review of phosphorus efficiency in wheat. Plant and Soil 146:163-168.

Baule B. (1918) Zu mitscherlichs gesetz der physiologischen beziehungen. Landw. Jahrb 51:363-385.

Bennett E.M., Carpenter S.R., Caraco N.F. (2001) Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience 51:227-234.

Bole J. (1973) Influence of root hairs in supplying soil phosphorus to wheat. Canadian Journal of Soil Science 53:169-175.

Bundy L., Malone E. (1988) Effect of residual profile nitrate on corn response to applied nitrogen. Soil Science Society of America Journal 52:1377-1383.

Andersen M.N., Jensen C., Lösch R. (1992a) The interaction effects of potassium and drought in field-grown barley. I. Yield, water-use efficiency and growth. Acta Agriculturae Scandinavica B-Plant Soil Sciences 42:34-44.

Andersen M.N., Jensen C., Lösch R. (1992b) The interaction effects of potassium and drought in field-grown barley. II. Nutrient relations, tissue water content and morphological development. Acta Agriculturae Scandinavica B-Plant Soil Sciences 42:45-56.

Armstrong D.L., Griffin K.P. (1998) Potassium for Agriculture, Better Crops with Plant Food (IPNI).

Arnall B., García F. (2012) Improving Soil Fertility and Wheat Crop Management Through the Long-term Study of Cereal Crop Rotations. Better Crops with Plant Food 3:7-9.

Ashley M., Grant M., Grabov A. (2006) Plant responses to potassium deficiencies: a role for potassium transport proteins. Journal of Experimental Botany 57:425.

Barker A., Stratton M., Rechcigl J., Power J., Dick W., Kashmanian R., Sims J., Wright R., Dawson M., Bezdicek D. (2000) Soil and by-product characteristics that impact the beneficial use of by-products. Land application of agricultural, industrial, and municipal by-products:169-213.

Barker A.V., Pilbeam D.J. (2007) Handbook of plant nutrition CRC press.

Batten G.D. (1992) A review of phosphorus efficiency in wheat. Plant and Soil 146:163-168.

Baule B. (1918) Zu mitscherlichs gesetz der physiologischen beziehungen. Landw. Jahrb 51:363-385.

Bennett E.M., Carpenter S.R., Caraco N.F. (2001) Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience 51:227-234.

Bundy L., Malone E. (1988) Effect of residual profile nitrate on corn response to applied nitrogen. Soil Science Society of America Journal 52:1377-1383.

Butchee K.B., May J., Arnall D.B., R. T., Raun W.R. (2011) Large Scale Evaluation of the Sensor Based Nitrogen Rate Calculator. J. Crop Prod. doi: 10.1094/CM-2011-0725-01-RS.

Byrnes B. (1990) Environmental effects of N fertilizer use—An overview. Nutrient Cycling in Agroecosystems 26:209-215.

Christenson D.R. (1998) Summary of Sulfur Fertilization studies 1957-1998. Michigan State University. Field Crops Team. Available at http://fieldcrop.msu.edu/uploads/documents/Summary%20of%20sulfur%20studies.pdf (verified 2 Aug. 2012).

Cope J. (1981) Effects of 50 years of fertilization with phosphorus and potassium on soil test levels and yields at six locations. Soil Science Society of America Journal 45:342-347.

Cox M.C., Rains D.W., Qualset C.O. (1986) Genetic variation for nitrogen assimilation and translocation in wheat. III. Nitrogen translocation in relation to grain yield and protein. Crop science 26:737-740.

Dahnke W.C., Johnson G.V. (1990) Testing Soils for Available Nitrogen, in: R. L. Westerman (Ed.), Soil Testing and Plant Analysis, SSSA, Madison, WI. pp. 127-139.

Dhont C., Castonguay Y., Avice J.C., Chalifour F.P. (2006) VSP accumulation and cold-inducible gene expression during autumn hardening and overwintering of alfalfa. Journal of Experimental Botany 57:2325-2337.

Dick R., Castellano S. (1991) Cropping and sulfur fertilization influence on sulfur transformations in soil. Soil Science Society of America Journal 55:114-121.

Droux M. (2004) Sulfur assimilation and the role of sulfur in plant metabolism: a survey. Photosynthesis Research 79:331-348.

Ernst J., Massey H. (1960) The effects of several factors on volatilization of ammonia formed from urea in the soil. Soil Science Society of America Journal 24:87-90.

FAO. (2009) FAOSTAT:Statistics database. [Online.] [Subset Fertilizer within Agriculture database.] Availble at http://apps.fao.org (verified 17 July 2012).

Fischer R. (1968) Stomatal opening: role of potassium uptake by guard cells. Science 160:784-785.

Fox R., Iversen K., Roth G., Piekielek W. (1989) Soil and tissue nitrate tests compared for predicting soil nitrogen availability to corn. Agronomy Journal 81:971-974.

Freeman K., Girma K., Mosali J., Teal R., Martin K., Raun W. (2006) Response of Winter wheat to chloride fertilization in Sandy loam soils. Communications in soil science and plant analysis 37:1947-1955.

García F., Boxler M., Minteguiaga J., Pozzi R., Firpo L., Deza G. (2007) Direct and residual effects of balanced fertilization in field crops of the Pampas. Better Crops:11.

Garwood E., Tyson K. (1973) Losses of nitrogen and other plant nutrients to drainage from soil under grass. The Journal of Agricultural Science 80:303-312.

Gasser J., Iordanou I. (1967) Effects of ammonium sulphate and calcium nitrate on the growth, yield and nitrogen uptake of barley, wheat and oats. J. agric. Sci., Camb 68:307-16.

Girma K., Holtz S.L., Arnall D.B., Tubaña B.S., Raun W.R. (2007) The Magruder Plots. Agronomy Journal 99:1191-1198.

Girma K., Mosali J., Freeman K., Raun W., Martin K., Thomason W. (2005) Forage and grain yield response to applied sulfur in winter wheat as influenced by source and rate. Journal of plant nutrition 28:1541-1553.

Gregory P., Crawford D., McGowan M. (1979) Nutrient relations of winter wheat: 1. Accumulation and distribution of Na, K, Ca, Mg, P, S and N. The Journal of Agricultural Science 93:485-494.

Halse N., Greenwood E., Lapins P., Boundy C. (1969) An analysis of the effects of nitrogen deficiency on the growth and yield of a Western Australian wheat crop. Australian Journal of Agricultural Research 20:987-998.

Hamid A. (1972) Efficiency of N uptake by wheat, as affected by time and rate of application, using N 15-labelled ammonium sulphate and sodium nitrate. Plant and Soil 37:389-394.

Hammond L., Menon R., Sissingh H. (1989) Determination of plant-available phosphorus by the iron hydroxide-impregnated filter paper (Pi) soil test. Soil Science Society of America Journal 53:110-115.

Haneklaus S., Murphy D., Nowak G., Schnug E. (1995) Effects of the timing of sulphur application on grain yield and yield components of wheat. Zeitschrift für Pflanzenernährung und Bodenkunde 158:83-85.

Harper H. (1942) Sulfur content of Oklahoma rainfall. Proc. Okla. Acad. Sci.;(United States) 23.

Harper L.A., Sharpe> R.R., Langdale G.W., Giddens J.E. (1987) Nitrogen Cycling In A Wheat Crop: Soil, Plant, And Aerial Nitrogen Transport. Agron. J. 79:965-973. DOI: 10.2134/agronj1987.00021962007900060004x.

Hunter A.S., Stanford G. (1973) Nitrogen Requirements of Winter Wheat (Triticum aestivum, L.) Varieties 'Blueboy'and 'Redcoat'. Agronomy Journal 65:442-447.

Jemison J., Beegle D., Morris T., Griffin T., Jokela W., Estes G., Sullivan W., Hoskins B., Bhumbla D., Coale F. (2006) Soil test calibration for predicting corn response to phosphorus in the northeast USA. Agronomy Journal 98:280-288.

Johnston A., Society I.F. (2001) Principles of crop nutrition for sustainable food production, International Fertiliser Society.

Johnston A.E.J., Syers J.K. (2009) A new approach to assessing phosphorus use efficiency in agriculture. Better Crops with Plant Food (IPNI) 93:14-16.

Jordan H.V., Ensminger L. (1959) The role of sulfur in soil fertility. Advances in Agronomy 10:407-434.

Kamprath E. (1967) Residual effect of large applications of phosphorus on high phosphorus fixing soils. Agronomy Journal 59:25-27.

Laboski C., Randall G., Sawyer J., Hoeft R., Andraski T., Bundy L., Walters D. (2008) Evaluation of the Illinois soil nitrogen test in the north central region of the United States. Agronomy Journal 100:1070-1076.

Lamond R.E. (1997) Sulphur in Kansas: Plant, Soil, and Fertilizer Considerations. MF-2264 Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Kansas State University.

LaRuffa J., Johnson G., Phillips S., Raun W. (1999) Sulfur and chloride response in Oklahoma winter wheat. Better Crops 32:28-30.

Lu M., Yang Y., Luo Y., Fang C., Zhou X., Chen J., Yang X., Li B. (2011) Responses of ecosystem nitrogen cycle to nitrogen addition: a meta-analysis. New Phytologist 189:1040-1050.

Lukina E., Freeman K., Wynn K., Thomason W., Mullen R., Stone M., Solie J., Klatt A., Johnson G., Elliott R. (2001) Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. Journal of plant nutrition 24:885-898.

Mallarino A.P., Atia A.M. (2005) Correlation of a resin membrane soil phosphorus test with corn yield and routine soil tests. Soil Science Society of America Journal 69:266-272.

Marschner P. (2012) Marschner's Mineral Nutrition of Higher Plants. third ed. Academic press.

Marx E., Hart J.M., Stevens R.G., Service O.S.U.E. (1996) Soil test interpretation guide Oregon State University Extension Service.

Mengel K. (1999) Integration of functions and involvement of potassium metabolism

at the whole plant level. Frontiers in potassium nutrition: new perspectives on the effects of potassium on physiology of plants. Canada: Potash & Phosphate Institute of Canada:1-11.

Mengel K., and E.A. Kirkby. (1978) Principles of Plant Nutrition Switzerland International Potash Institute.

Meyer R., Olson R., Rhoades H. (1961) Ammonia losses from fertilized Nebraska soils. Agronomy Journal 53:241-244.

Novoa R., Loomis R. (1981) Nitrogen and plant production. Plant and Soil 58:177-204.

Pate J. (1973) Uptake, assimilation and transport of nitrogen compounds by plants. Soil Biology and Biochemistry 5:109-119.

Pettigrew W.T. (2008) Potassium influences on yield and quality production for maize, wheat, soybean and cotton. Physiologia plantarum 133:670-681.

Raun B., Solie J., May J., Zhang H., Kelly J., Taylor R., Arnall B., Ortiz-Monasterio I. (2010) Nitrogen Rich Strips for wheat, corn, and other crops., in: Oklahoma State University (Ed.), E-1022, Stillwater, OK.

Rehm G.W., Schmitt M.A. (1997) Potassium for crop production, Minnesota Extension Service, University of Minnesota, College of Agricultural, Food, and Environmental Sciences.

Sanchez C., Porter P., Ulloa M. (1991) Relative efficiency of broadcast and banded phosphorus for sweet corn produced on Histosols. Soil Science Society of America Journal 55:871-875.

Sanchez C., Swanson S., Porter P. (1990) Banding P to improve fertilizer use efficiency of lettuce. Journal of the American Society for Horticultural Science 115:581-584.

Sander D., Penas E., Eghball B. (1990) Residual effects of various phosphorus application methods on winter wheat and grain sorghum. Soil Science Society of America Journal 54:1473-1478.

Sander D., Penas E., Walters D. (1991) Winter wheat phosphorus fertilization as influenced by glacial till and loess soils. Soil Science Society of America Journal 55:1474-1479.

Scherer H. (2001) Sulphur in crop production--invited paper. European Journal of agronomy 14:81-111.

Sharpley A.N., Smith S., Naney J. (1987) Environmental impact of agricultural nitrogen and phosphorus use. Journal of Agricultural and Food Chemistry 35:812-817.

Shewry P.R. (2007) Improving the protein content and composition of cereal grain. Journal of Cereal Science 46:239-250.

Simard R., Joern B., Sims J. (1998) Phosphorus loss in agricultural drainage: Historical perspective and current research. Journal of Environmental Quality 27:277-293.

Smit A.L., Bindraban P.S., Schröder J., Conijn J., Van der Meer H. (2009) Phosphorus in agriculture: global resources, trends and developments. Report to the Steering Committee Technology Assessment of the Ministry of Agriculture, The Neetherlands, Wageningen.

Spiertz J.H.J., De Vos N. (1983) Agronomical and physiological aspects of the role of

nitrogen in yield formation of cereals. Plant and Soil 75:379-391.

Stone M.L., Solie J.B., Raun W.R., Whitney R.W., Taylor S.L., Ringer J.D. (1995) Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Paper No. AETC 95133. Presented at the Agricultural Equipment Technology Conference, November 1-4, 1995. ASAE. St. Joseph, MI.

Syers J., Johnston A., Curtin D. (2008) Efficiency of soil and fertilizer phosphorus use. FAO Fertilizer and Plant Nutrition Bulletin 18.

Thomas S., Thorne G., Pearman I. (1978) Effect of nitrogen on growth, yield and photorespiratory activity in spring wheat. Annals of Botany 42:827-837.

Tilman D. (1999) Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proceedings of the National Academy of Sciences 96:5995.

Troeh F.R., Thompson L.M. (1993) Soils and Soil Fertility fifth ed. Oxford University Press, Inc., New York City, New York.

Vitousek P.M., Aber J.D., Howarth R.W., Likens G.E., Matson P.A., Schindler D.W., Schlesinger W.H., Tilman D.G. (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecological applications 7:737-750.

Welch L., Mulvaney D., Boone L., McKibben G., Pendleton J. (1966) Relative efficiency of broadcast versus banded phosphorus for corn. Agronomy Journal 58:283-287.

Wiersum L. (1962) Uptake of nitrogen and phosphorus in relation to soil structure and nutrient mobility. Plant and Soil 16:62-70.

Zhang H., Edwards J., Carver B., Raun B. (2005) Managing Acid Soils for Wheat Production. PSS-2240., Division of Agricultural Sciences and Natural Resources, Oklahoma State University.

Zhang H., Johnson G., Krenzer G., Gribble R. (1998) Soil testing for an economically and environmentally sound wheat production. Communications in Soil Science & Plant Analysis 29:1707-1717.

Zhang H., Raun B. (2006) Oklahoma Soil Fertility Handbook, 6th edition Okla. Agric. Exp. Sta. Stillwater, OK.

Zhang H., Raun B., Arnall B. (2000) OSU Soil Test Interpretations. PSS-2225., Oklahoma Cooperative Extension Service, Oklahoma State University.

Zhao F., Hawkesford M., McGrath S. (1999) Sulphur assimilation and effects on yield and quality of wheat. Journal of Cereal Science 30:1-17.

TABLES

Table 1. Soil characteristics and classification for 2011-2012 NPKS rich strip locations with site responses

Location	County	Soil Series	Soil Description	Tillage Practice	Response			
					N	P	K	S
1	Cotton	Tillman	Fine, mixed, superactive, thermic Vertic Paleustolls	Conventional	*			
2	Tillman	Hollister	Fine, smectitic, thermic Typic Haplusterts					
3	Tillman	Grandfield	Fine-loamy, mixed, superactive, thermic Typic Haplustalfs					
4	Jackson	Grandfield	Fine-loamy, mixed, superactive, thermic Typic Haplustalfs				*	
5	Jackson	Tillman	Fine, mixed, superactive, thermic Vertic Paleustolls					
6	Washita	Carey	Fine-silty, mixed, superactive, thermic Typic Argiustolls					
7	Grady	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	Conventional				
8	Caddo	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till	*			
9	Custer	St. Paul	Fine-silty, mixed, superactive, thermic Pachic Argiustolls					
10	Noble	Kirkland	Fine, mixed, superactive, thermic Udertic Paleustolls	No-till				
11	Noble	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	Conventional				
12	Noble	Milan	Fine-loamy, mixed, superactive, thermic Udic Argiustolls	No-till		*	*	
13	Kingfisher	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	Conventional		*		
14	Noble	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	No-till	*			
15	Noble	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	No-till				
16	Noble	Kirkland	Fine, mixed, superactive, thermic Udertic Paleustolls	No-till				
17	Garfield	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till				
18	Garfield	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till				
19	Garfield	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	No-till				
20	Grant	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till		*		
21	Grant	Kirkland	Fine, mixed, superactive, thermic Udertic Paleustolls	No-till				
22	Grant	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till				
23	Grant	McLain	Fine, mixed, superactive, thermic Pachic Argiustolls	No-till				
24	Alfalfa	Devol	Coarse-loamy, mixed, superactive, thermic Typic Haplustalfs		*	*		
25	Major	McLain	Fine, mixed, superactive, thermic Pachic Argiustolls					
26	Major	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls					
27	Major	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls					
28	Major	McLain	Fine, mixed, superactive, thermic Pachic Argiustolls	No-till				
29	Major	McLain	Fine, mixed, superactive, thermic Pachic Argiustolls					
30	Payne	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	Conventional	*			

* indicates grain yield significance at 0.05 significance level, respectivel

Table 2. Soil characteristics and classification for 2012-2013 NPKS rich strip locations with site responses

Location	County	Soil Series	Soil Description	Tillage Practice	Response			
					N	P	K	S
31	Tillman	Hollister	Fine, smectitic, thermic Typic Haplusterts					
32	Washita	Obaro	Fine-silty, mixed, superactive, thermic Typic Haplustepts	Conventional		*		
33	Custer	St. Paul	Fine-silty, mixed, superactive, thermic Pachic Argiustolls				*	
34	Grady	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	Conventional				
35	McLain	Keokuk	Course-silty, mixed, superactive, thermic Fluventic Haplustolls	Conventional				
36	Kingfisher	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	Conventional				
37	Noble	Kirkland	Fine, mixed, superactive, thermic Udertic Paleustolls	Conventional				
38	Noble	Port	Fine-silty, mixed, superactive, thermic Cumulic Haplustolls	Conventional	*			
39	Noble	Norge	Fine-silty, mixed, active, thermic Udic Paleustolls	No-till				
40	Garfield	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till				
41	Garfield	Grant	Fine-silty, mixed superactive, thermic Udic Argiustolls	No-till				
42	Garfield	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	No-till				
43	Woods	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	Conventional	*			
44	Woods	Burford	Fine-silty, mixed, superactive, thermic Typic Haplustepts	Conventional				
45	Woods	Bethany	Fine, mixed superactive, thermic Pachic Paleustolls	No-till				
46	Alfalfa	Devol	Course-loamy, mixed, superactive, thermic Typic Haplustalfs	No-till				
47	Alfalfa	Grant	Fine-silty, mixed, superactive, thermic Udic Argiustolls	No-till				
48	Major	Canadian	Course-loamy, mixed, superactive, thermic Udic Haplustolls	No-till				
49	Major	Reinach	Course-silty, mixed, superactive, thermic Pachic Haplustolls	No-till				
50	Major	Eda	Mixed, thermic Lamellic Ustipsamments	No-till				
51	Osage	Braman	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till				
52	Pawnee	Renfrow	Fine, mixed, superactive, thermic Udertic Paleustolls	Conventional				
53	Grant	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	Conventional				
54	Grant	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	No-till				
55	Grant	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till		*		
56	Grant	Pond Creek	Fine-silty, mixed, superactive, thermic Pachic Argiustolls	No-till		*		
57	Noble	Bethany	Fine, mixed, superactive, thermic Pachic Paleustolls	Conventional				
58	Pottawatomie	Asher	Fine-silty, mixed, superactive, thermic Fluventic Haplustolls	Conventional				
59	Pottawatomie	Keokuk	Course-silty, mixed, superactive, thermic Fluventic Haplustolls	conventional				

Table 3. Initial soil test ranges across all 2011-2012 harvested locations

	pH	NO_3^- 0-15 cm ppm	NO_3^- 15-45 cm ppm	STP 0-15 cm ppm	STK 0-15 cm ppm	SO_4^- 0-15 cm ppm	SO_4^- 15-45 cm ppm
Average	5.8	18.0	15.4	36.6	212.6	13.0	11.6
Maximum	8.2	56.0	51.5	91.5	422.0	31.0	47.5
Minimum	4.5	3.0	2.0	9.5	119.0	4.4	5.1

Table 4. Producer application timing and rates (kg ha^{-1}) for 2011-2012 harvested locations

Location	Pre-Plant				With Seed		Top-Dress	Total Applied			
	N	P	K	S	N	P	N	N	P	K	S
1	0.0	0.0	0.0	0.0	22.4	4.9	0.0	22.4	4.9	0.0	0.0
2	-	-	-	-	-	-	-	-	-	-	-
3	0.0	0.0	0.0	0.0	0.0	0.0	44.8	44.8	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	44.8	44.8	0.0	0.0	0.0
5	44.8	0.0	0.0	0.0	0.0	0.0	0.0	44.8	0.0	0.0	0.0
6	55.1	0.0	0.0	0.0	12.1	13.5	0.0	67.2	13.5	0.0	0.0
7	51.5	0.0	0.0	0.0	0.0	0.0	31.4	82.9	0	0.0	0.0
8	0.0	0.0	0.0	0.0	12.5	18.6	77.3	89.8	18.6	0.0	0.0
9	-	-	-	-	-	-	-	-	-	-	-
10	0.0	0.0	0.0	0.0	0.0	0.0	56.0	56.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	56.0	56.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	9.1	10.1	31.4	40.5	10.1	0.0	0.0
13	28.0	7.3	4.5	4.5	0.0	0.0	0.0	28.0	7.3	4.5	4.5
14	0.0	0.0	0.0	0.0	0.0	0.0	51.5	51.5	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	51.5	51.5	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	9.1	10.1	31.4	40.5	10.1	0.0	0.0
17	0.0	0.0	0.0	0.0	8.1	9.0	67.2	75.3	9.0	0.0	0.0
18	0.0	0.0	0.0	0.0	8.1	9.0	67.2	75.3	9.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	67.2	67.2	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	21.5	6.7	33.6	55.1	6.7	0.0	0.0
21	0.0	0.0	0.0	0.0	21.5	6.7	33.6	55.1	6.7	0.0	0.0
22	0.0	0.0	0.0	0.0	53.8	16.8	33.6	87.4	16.8	0.0	0.0
23	110.2	0.0	0.0	0.0	0.0	0.0	0.0	110.2	0.0	0.0	0.0
24	33.6	0.0	0.0	0.0	0.0	0.0	44.8	78.4	0.0	0.0	0.0
25	-	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-	-
27	-	-	-	-	-	-	-	-	-	-	-
28	0.0	0.0	0.0	0.0	10.0	14.9	90.7	100.7	14.9	0.0	0.0
29	33.6	0.0	0.0	0.0	0.0	0.0	33.6	67.2	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 5. Soil test results, application rates and grain yield for responsive locations to the addition of N in 2011-2012

Location	Soil Test NO_3^-	Soil Test NO_3^-	Farmer Applied N	N Strip Applied N	Farmer Practice	N Rich Strip
	0-15 cm	15-45 cm			Grain Yield	
	ppm	ppm	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	6.0	8.0	22.4	140.9	3213	4059
8	24.0	15.0	89.8	208.3	2677	3696
14	5.5	3.0	51.5	170.0	2781	4197
24	4.5	8.0	78.4	196.9	2436	3783
30	4.0	2.0	0.0	118.5	1589	2936

Table 6. Initial soil test ranges across all 2012-2013 harvested locations

	pH	NO_3^- 0-15 cm ppm	NO_3^- 15-45 cm ppm	STP 0-15 cm ppm	STK 0-15 cm ppm	SO_4^- 0-15 cm ppm	SO_4^- 15-45 cm ppm	Cl^- 0-15 cm ppm	Cl^- 15-45 cm ppm
Average	6.0	29.3	15.9	43.9	216.2	13.2	14.2	20.3	17.4
Maximum	8.2	68.5	37.5	150.0	436.0	33.0	52.5	66.7	72.8
Minimum	4.4	1.5	1.5	12.5	68.5	3.0	2.5	7.0	6.6

Table 7. Producer application timing and rates (kg ha-1) for 2012-2013 harvested locations

Location	Pre-Plant				With Seed				Top-Dress		Total Applied			
	N	P	K	S	N	P	K	S	N	S	N	P	K	S
31	-	-	-	-	-	-	-	-	-	-	-	-	-	-
32	25.1	7.9	0.0	0.0	0.0	0.0	0.0	0.0	15.7	0.0	40.8	7.9	0.0	0.0
33	-	-	-	-	-	-	-	-	-	-	-	-	-	-
34	35.8	11.2	0.0	0.0	0.0	0.0	0.0	0.0	31.4	0.0	67.2	11.2	0.0	0.0
35	12.5	18.6	0.0	0.0	0.0	0.0	0.0	0.0	72.0	0.0	84.5	18.6	0.0	0.0
36	67.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	67.2	0.0	0.0	0.0
37	14.1	15.7	0.0	0.0	0.0	0.0	0.0	0.0	66.2	0.0	80.3	15.7	0.0	0.0
38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.4	0.0	31.4	0.0	0.0	0.0
39	4.7	5.5	1.3	0.0	0.0	0.0	0.0	0.0	66.9	0.0	71.6	5.5	1.3	0.0
40	64.3	0.0	0.0	0.0	10.1	11.2	0.0	0.0	33.6	0.0	108.0	11.2	0.0	0.0
41	64.3	0.0	0.0	0.0	10.1	11.2	0.0	0.0	33.6	0.0	108.0	11.2	0.0	0.0
42	64.3	0.0	0.0	0.0	5.6	8.3	0.0	0.0	33.6	0.0	103.5	8.3	0.0	0.0
43	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.4	0.0	22.4	0.0	0.0	0.0
44	50.4	0.0	0.0	0.0	6.3	9.3	0.0	0.0	33.6	0.0	90.3	9.3	0.0	0.0
45	32.5	14.2	0.0	0.0	0.0	0.0	0.0	0.0	43.8	0.0	76.3	14.2	0.0	0.0
46	50.4	0.0	0.0	0.0	6.3	9.3	0.0	0.0	56.0	0.0	112.7	9.3	0.0	0.0
47	50.4	0.0	0.0	0.0	6.3	9.3	0.0	0.0	56.0	0.0	112.7	9.3	0.0	0.0
48	0.0	0.0	0.0	0.0	15.1	16.9	0.0	0.0	56.9	0.0	72.0	16.9	0.0	0.0
49	0.0	0.0	0.0	0.0	15.1	16.9	0.0	0.0	56.9	0.0	72.0	16.9	0.0	0.0
50	10.3	0.0	0.0	0.0	12.1	13.5	0.0	0.0	128.8	0.0	151.2	13.5	0.0	0.0
51	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	89.6	0.0	89.6	0.0	0.0	0.0
52	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	79.6	0.0	79.6	0.0	0.0	0.0
53	55.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	55.6	0.0	0.0	0.0
54	0.0	0.0	0.0	0.0	28.0	11.2	0.0	0.0	56.0	0.0	84.0	11.2	0.0	0.0
55	0.0	0.0	0.0	0.0	28.0	11.2	0.0	0.0	56.0	0.0	84.0	11.2	0.0	0.0
56	0.0	0.0	0.0	0.0	28.0	11.2	0.0	0.0	56.0	0.0	84.0	11.2	0.0	0.0
57	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
58	0.0	0.0	0.0	0.0	1.5	4.8	11.7	2.2	94.1	16.8	95.6	4.8	11.7	19.0
59	0.0	0.0	0.0	0.0	1.5	4.8	11.7	2.2	100.8	18.0	102.3	4.8	11.7	20.2

Table 8. Soil test results, application rates and grain yield of responsive locations to the addition of N in 2012-2013

Location	Soil Test NO_3^-	Soil Test NO_3^-	Farmer Applied N	N Strip Applied N	Farmer Practice	N Rich Strip
	0-15 cm	15-45 cm			Grain Yield	
	ppm	ppm	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
38	68.5	8.0	31.4	119.0	3083	4275
43	6.0	9.0	22.4	110.0	2954	5428

Table 9. Soil test results, applications rates and grain yield of responsive locations to the addition of P in 2011-2012

Location	pH	STP	Farmer Applied P	P Strip Applied P	Farmer Practice	P Rich Strip
		0-15 cm			Grain Yield	
		ppm	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
12	4.9	20.5	10.1	61.6	3679	4681
13	6.9	19.0	7.3	58.8	2971	3990
20	4.5	19.0	6.7	58.2	2833	4301
24	6.8	66.0	0.0	51.5	2436	3921

Table 10. Soil test results, application rates and grain yield of responsive locations to the addition of P in 2012-2013

Location	pH	STP	Farmer Applied P	P Strip Applied P	Farmer Practice	P Rich Strip
		0-15 cm			Grain Yield	
		ppm	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
32	8.0	12.5	7.9	59.4	1671	2138
55	4.6	17.0	11.2	62.7	2980	1801
56	4.4	26.0	11.2	62.7	2138	3278

Table 11. Soil test results, application rates and grain yield of responsive locations to the addition of K in 2011-2012

Location	Soil Test Cl^- 0-15 cm	STK 0-15 cm	Farmer Applied K	K Strip Applied K	Farmer Practice Grain Yield	K Rich Strip Grain Yield
	ppm	ppm	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
4	7.2	191.5	0.0	134	2366	3196
12	-	119	0.0	134	3679	4405

Table 12. Soil test results, application rate and grain yield for responsive location to the addition of K in 2012-2013

Location	Soil Test Cl^-	Soil Test Cl^-	STK	Farmer Applied K	K Strip Applied K	Farmer Practice	K Rich Strip
	0-15 cm	15-45 cm	0-15 cm			Grain Yield	
	ppm	ppm	ppm			kg ha^{-1}	kg ha^{-1}
33	11.4	15.8	169.5	0.0	134	2384	3109

FIGURES

Figure 1. Application of NPKS rich strips with an applicator built by engineers at Oklahoma State University, containing four dry fertilizer boxes that held individual fertilizer connected to three polyvinyl chloride tubes attached to a 12 m boom. Fertilizer boxes were fed by two drive wheels as a PTO controlled fan forced fertilizer through the polyvinyl tubing to a reflection plate where it was evenly dispersed throughout a 1.8 m strip parallel to one another.

Figure 2. 42 locations where NPKS rich strips were applied throughout Oklahoma during winter wheat production in 2011-2012. Yellow pins represent a single location.

Figure 3. 40 locations where NPKS rich strips were applied throughout Oklahoma during winter wheat production in 2012-2013. Yellow pins represent a single location.

Figure 4. Visual height difference at maturity to the addition of N at site 43, located in Woods Co. west of Alva, OK in 2012-2013

Figure 5. Visual height and color difference during vegetative growth to the addition of P at site 20, located in Grant Co. north of Lamont, OK in 2011-2012

APPENDICES

Table 13. Geographic locations for 2011-2012 harvested NPKS sites

Location	Latitude	Longitude
1	34°17’30.64”N	98°27’7.82”W
2	34°23’32.44”N	98°59’57.72”W
3	34°29’59.86”N	99°7’55.29”W
4	34°41’47.31”N	99°10’29.89”W
5	34°38’16.66”N	99°28’2.12”W
6	35°9’35.38”N	99°14’43.34”W
7	35°19’33.38”N	97°56’24.33”W
8	35°29’8.27”N	98°27’55.21”W
9	35°33’58.37”N	98°46’42.92”W
10	36°15’39.44”N	97°26’6.11”W
11	36°16’9.12”N	97°25’33.87”W
12	36°22’37.83”N	97°18’44.68”W
13	35°51’17.64”N	97°42’38.21”W
14	36°27’52.99”N	97°4’59.61”W
15	36°27’52.86”N	97°4’40.45”W
16	36°24’22.72”N	97°17’36.64”W
17	36°23’34.59”N	97°57’16.84”W
18	36°23’34.63”N	97°57’21.23”W
19	36°17’27.65”N	97°53’53.90”W
20	36°45’59.74”N	97°33’32.26”W
21	36°44’26.61”N	97°33’5.27”W
22	36°44’16.33”N	97°33’29.74”W
23	36°41’17.25”N	97°38’37.86”W
24	36°34’46.76”N	98°31’55.56”W
25	36°18’18.94”N	98°30’37.74”W
26	36°13’54.78”N	98°24’33.38”W
27	36°13’54.37”N	98°24’48.03”W
28	36°11’19.60”N	98°26’55.16”W
29	36°34’11.24”N	98°35’8.78”W
30	36°8’44.11”N	97°17’42.32”W

Table 14. Initial surface (0-15 cm) and subsurface (15-45 cm) soil analysis for 2011-2012 harvested locations, pH - 1:1 soil: deionized water, NO_3^- - 2 M KCl extract, STP and STK – Mehilich-3 extraction, SO_4^- - 0.008 M Calcium Phosphate

Location	depth	pH	NO_3^-	STP	STK	SO_4^-
	cm		ppm	ppm	ppm	ppm
1	0-15	6.2	6.0	9.5	176.0	10.7
	15-45	4.8	8.0	147.5	168.5	8.1
2	0-15	8.2	9.5	14.5	359.0	6.1
	15-45	8.0	9.0	6.0	264.5	6.9
3	0-15	6.5	3.0	29.0	235.5	4.4
	15-45	6.5	3.0	13.5	204.0	5.1
4	0-15	5.1	8.5	91.5	191.5	5.9
	15-45	4.9	6.0	60.5	199.5	17.3
6	0-15	6.5	7.0	25.5	161.0	6.2
	15-45	7.3	32.5	8.0	170.5	8.6
7	0-15	5.2	12.5	35.5	122.0	10.6
	15-45	5.3	16.5	14.5	109.5	13.3
8	0-15	4.8	24.0	39.5	235.5	11.9
	15-45	5.2	15.0	14.5	165.0	11.4
9	0-15	6.2	9.0	27.0	187.0	10.0
	15-45	6.7	51.5	16.0	162.0	10.6
10	0-15	5.7	20.5	36.5	165.0	13.5
	15-45	7.4	12.0	6.0	184.5	8.0
11	0-15	5.9	13.5	28.5	185.5	11.0
	15-45	6.5	15.5	7.5	171.0	11.5
12	0-15	4.9	38.0	20.5	119.0	14.5
	15-45	5.7	16.5	7.5	132.0	11.0
13	0-15	6.9	16.0	19.0	259.0	8.5
	15-45	7.4	11.5	11.5	194.5	7.0
14	0-15	6.9	5.5	16.0	142.5	14.0
	15-45	8.0	3.0	3.0	168.5	47.5
15	0-15	5.5	22.0	21.0	135.5	21.5
	15-45	7.0	11.5	7.0	144.0	21.0
16	0-15	6.1	29.0	38.5	190.5	10.0
	15-45	7.2	23.0	12.5	175.0	8.0
17	0-15	6.2	7.5	30.5	312.5	8.5
	15-45	6.8	7.5	9.5	213.0	8.0
18	0-15	4.8	14.0	50.0	219.0	14.5
	15-45	6.0	18.0	10.5	186.5	8.5
19	0-15	5.5	6.0	25.5	157.0	22.0
	15-45	6.7	7.0	7.5	153.0	10.0
20	0-15	4.5	40.5	19.0	141.0	14.5
	15-45	5.2	32.0	9.0	126.5	9.5
21	0-15	4.7	30.0	17.0	161.0	10.3
	15-45	5.7	19.5	7.0	119.5	10.0
22	0-15	4.8	23.0	57.5	221.0	13.2
	15-45	5.1	19.0	20.0	169.5	11.1
23	0-15	6.2	36.5	29.0	231.5	10.0
	15-45	6.8	21.0	12.5	207.0	8.4
24	0-15	6.8	4.5	66.0	151.0	31.0
	15-45	6.8	8.0	20.0	119.0	19.0
25	0-15	5.8	56.0	72.0	300.0	15.5
	15-45	6.3	31.5	20.5	235.5	10.7
26	0-15	5.8	39.5	84.0	293.0	13.0
	15-45	6.2	11.0	20.0	278.0	10.7
27	0-15	5.8	28.0	52.0	256.5	10.4
	15-45	6.0	9.0	26.0	205.0	8.3
28	0-15	6.7	11.0	13.0	422.0	19.9
	15-45					
29	0-15	5.4	24.5	33.0	290.5	8.7
	15-45	6.0	10.0	19.0	225.5	7.3
30	0-15	5.3	4.0	60.0	145.0	27.5
	15-45	6.3	2.0	15.0	132.0	9.0

Table 15. Grain yield (kg ha^{-1}) for all treatments throughout 2011-2012 harvested location

Location	N Rich Strip Yield	P Rich Strip Yield	K Rich Strip Yield	S Rich Strip Yield	Farmer Practice Yield
1	4059*	3334	3126	3869	3213
2	2574	2971	2867	3299	2246
3	2626	2591	2902	2349	2487
4	2591	2539	3196*	2297	2366
5	1416	1693	1555	1382	1365
6	2487	2902	3196	2522	2729
7	1520	2988	2643	2228	2366
8	3696*	3506	3075	3023	2677
9	2004	2263	2505	2159	2418
10	2867	3057	3489	3144	2919
11	2988	2902	2729	2850	2556
12	4094	4681*	4405*	3904	3679
13	2712	3990*	2816	2712	2971
14	4197*	2885	2366	3040	2781
15	4042	2936	3956	4042	3265
16	5251	4698	5406	4336	5320
17	2436	3489	2988	2919	3299
18	3800	3731	3109	3696	3472
19	4819	3610	3610	3506	3973
20	2988	4301*	2176	2729	2833
21	2816	3731	2885	3109	3161
22	3265	3956	1710	1727	3731
23	4543	4923	4733	3593	3990
24	3783*	3921*	3455	3437	2436
25	4474	5009	5666	4526	4664
26	3144	3092	4128	3800	3990
27	2850	3541	3714	3334	3230
28	3886	4405	3973	4284	4042
29	1745	1624	1779	1969	1641
30	2936*	1900	2090	1555	1589

* indicates significance at 0.05 significance level, respectively

Table 16. Straw biomass weight (kg ha^{-1}) for all treatments and harvested locations in 2011-2012

Location	N Rich Strip	P Rich Strip	K Rich Strip	S Rich Strip	Farmer Practice
1	6091	4519	4716	5879	4489
2	5033	4368	3839	4942	2993
3	5124	4852	4534	4156	4353
4	5547	4368	5381	4640	4398
5	3008	3083	2524	2811	2418
6	5758	6665	5758	7678*	5365
7	9325*	7104	6937	6862	7209
8	8343	8328	6937	7617	7119
9	5622	5622	6348	6363	6182
10	6091	5743	6242	6439	5668
11	6136	6091	6015	6151	6076
12	7013	7013	6847	6529	6182
13	5456	6680	4716	5003	4549
14	5592*	4081	3537	3930	3899
15	5547	4141	5577	5622	4095
16	6711	6182	6302	5245	5924
17	6423	5411	5229	6076	6559
18	6378	6212	5124	6212	5425
19	6015	3884	4035	3824	4700
20	4821	6318*	3506	3930	4035
21	4610	5864	4171	4519	4322
22	5804	5879	3522	3733	5849
23	6454	6635	6076	4972	5667
24	5637*	5381*	4519*	4761*	3219
25	8071	7693	9114	8736	8554
26	6514	7481	8554	7104	7587
27	6560	8192	7693	7481	6967
28	6862	5985	5517	5940	6302
29	3899	3068	3612	3597	3370
30	4852*	2947	3008	2040	2282

* indicates significance at 0.05 significance level, respectively

Table 17. Grain nutrient concentration for all treatments and harvested locations in 2011-2012

	N Rich Strip				P Rich Strip				K Rich Strip				S Rich Strip				Farmer Practice			
Location	%N	%P	%K	%S	%N	%P	%K	%S	%N	%P	%K	%S	%N	%P	%K	%S	%N	%P	%K	%S
1	2.1*	0.45	0.63	0.14*	1.7	0.39	0.47	0.12	1.7	0.38	0.48	0.12	1.7	0.40	0.50	0.12	1.8	0.43	0.53	0.13
2	2.5*	0.36	0.58	0.14	1.9	0.41	0.58	0.13	1.9	0.43	0.61	0.14	1.9	0.41	0.57	0.13	1.8	0.36	0.54	0.13
3	3.0*	0.47	0.74	0.18	2.5	0.47	0.61	0.17	2.6	0.46	0.61	0.16	2.4	0.42	0.58	0.17	2.6	0.45	0.66	0.17
4	2.8	0.46	0.65	0.16	2.7	0.47	0.68	0.16	2.8	0.48	0.75	0.16	2.9*	0.44	0.65	0.19*	2.5	0.46	0.62	0.16
5	3.3	0.36	0.51	0.19	3.0	0.43	0.64	0.18	2.8	0.34	0.56	0.18	3.1	0.35	0.60	0.19	3.2	0.40	0.66	0.19
6	3.0	0.51	0.66	0.19	2.5	0.48	0.61	0.17	2.4	0.49	0.69	0.15	2.4	0.43	0.58	0.17	2.6	0.47	0.63	0.17
7	2.3	0.39	0.57	0.16	2.2	0.47	0.70	0.15	2.3	0.44	0.75	0.16	2.3	0.41	0.69	0.17*	2.4	0.44	0.75	0.16
8	2.4	0.37	0.67	0.16	2.3	0.40	0.59	0.16	2.3	0.43	0.75	0.15	2.2	0.36	0.60	0.14	2.3	0.38	0.62	0.17
9	3.4*	0.45	0.68	0.20	3.0	0.43	0.58	0.19	3.1	0.43	0.62	0.20	3.3	0.48*	0.67	0.23*	3.0	0.40	0.56	0.20
10	2.1	0.37	0.56	0.14	1.8	0.38	0.54	0.13	1.9	0.37	0.55	0.13	2.1	0.33	0.54	0.15	2.0	0.34	0.53	0.13
11	2.1	0.41	0.61	0.14	2.1	0.40	0.58	0.14	2.1	0.42	0.61	0.14	2.0	0.42	0.63	0.15	2.1	0.42	0.60	0.14
12	2.0	0.39	0.55	0.14	1.9	0.46*	0.61	0.13	1.9	0.37	0.50	0.13	1.8	0.36	0.52	0.12	2.0	0.36	0.49	0.13
13	2.3	0.36	0.63	0.16	2.3	0.45	0.74	0.16	2.2	0.35	0.60	0.16	2.4	0.36	0.72	0.17	2.1	0.38	0.62	0.16
14	2.3	0.34	0.43	0.16*	1.8	0.44	0.54	0.14	1.8	0.43	0.52	0.13	1.8	0.45	0.55	0.14	1.9	0.41	0.51	0.14
15	2.1	0.33	0.47	0.17	1.8	0.37	0.47	0.12	1.8	0.36	0.49	0.13	1.9	0.36	0.49	0.14	2.3	0.37	0.51	0.16
16	1.9	0.45	0.68	0.14*	1.8	0.38	0.56	0.12	1.7	0.40	0.63	0.11	1.6	0.40	0.60	0.11	1.7	0.41	0.58	0.11
17	2.6*	0.42	0.57	0.15	2.1	0.44	0.51	0.13	2.2	0.44	0.53	0.14	2.2	0.42	0.54	0.15	2.2	0.46	0.57	0.15
18	2.2	0.36	0.53	0.16	2.1	0.43	0.53	0.15	2.3	0.33	0.47	0.15	2.1	0.36	0.48	0.15	2.3	0.39	0.56	0.16
19	2.0	0.39	0.59	0.15	1.7	0.44*	0.55	0.12	1.6	0.40	0.54	0.12	1.8	0.39	0.55	0.13	1.9	0.36	0.53	0.13
20	2.6	0.26	0.36	0.15	2.2	0.33*	0.44	0.14	2.7	0.26	0.37	0.17	2.6	0.26	0.36	0.17	2.7	0.23	0.33	0.16
21	2.5	0.26	0.39	0.16*	2.1	0.39*	0.51*	0.13	2.3	0.28	0.40	0.14	2.2	0.27	0.39	0.14	2.2	0.28	0.40	0.14
22	2.5*	0.33	0.44	0.16	2.1	0.40	0.49	0.15	2.5*	0.37	0.45	0.17*	2.5	0.37	0.46	0.18*	2.2	0.39	0.48	0.15
23	2.2*	0.45	0.50	0.14*	1.8	0.47	0.53	0.12	1.7	0.39	0.48	0.12	1.9	0.42	0.49	0.13	1.7	0.41	0.48	0.12
24	2.2*	0.35	0.54	0.17*	1.6	0.38	0.57	0.14	1.6	0.35	0.53	0.12	1.7	0.31	0.49	0.14	1.6	0.36	0.48	0.13
25	2.7*	0.48	0.56	0.17*	2.4	0.53	0.61	0.16	2.5	0.49	0.58	0.17	2.4	0.43	0.48	0.16	2.4	0.48	0.55	0.16
26	2.5	0.45	0.63	0.18	2.1	0.47	0.63	0.15	2.1	0.44	0.62	0.15	2.3	0.48	0.69	0.17	2.2	0.45	0.62	0.17
27	2.5	0.42	0.65	0.17	2.2	0.47	0.64	0.15	2.3	0.44	0.64	0.16	2.3	0.40	0.62	0.16	2.4	0.41	0.63	0.17
28	2.8*	0.45	0.61	0.19*	1.8	0.48	0.55	0.14	2.0	0.46	0.60	0.15	1.7	0.39	0.48	0.13	2.1	0.51	0.61	0.15
29	2.4*	0.36	0.57	0.16	1.9	0.41	0.57	0.14	2.0	0.37	0.54	0.14	1.9	0.36	0.50	0.14	2.1	0.38	0.58	0.15
30	1.9	0.42	0.52	0.13	2.0	0.40	0.48	0.14	2.0	0.43	0.50	0.13	2.0	0.45	0.53	0.15	2.0	0.40	0.48	0.14

* indicates significance at 0.05 significance level, respectively

Table 18. Grain nutrient removal (kg ha^{-1}) from the addition of N, P, K and S at all harvested locations in 2011-2012

	N Rich Strip				P Rich Strip				K Rich Strip				S Rich Strip				Farmer Practice			
Location	N	P	K	S	N	P	K	S	N	P	K	S	N	P	K	S	N	P	K	S
1	74.5*	16*	22.2*	5.1*	48.3	11.4	13.6	3.5	46.1	10.3	13.0	3.2	56.3	13.5	17.0	4.1	50.9	12.1	14.8	3.5
2	56.6	8.1	13.1	3.0	50.3	10.8	14.9	3.5	47.6	10.7	15.4	3.4	53.5	11.7	16.5	3.8	35.1	7.1	10.5	2.5
3	69.8	10.9	17.0	4.2	55.6	10.7	13.8	3.8	64.8	11.6	15.6	4.1	50.0	8.5	12.0	3.5	56.8	9.7	14.3	3.7
4	63.2	10.5	14.7	3.6	59.6	10.4	15.0	3.6	77.9*	13.5*	21.0*	4.5*	58.7	8.8	13.1	3.7	52	9.6	12.9	3.2
5	41.2	4.4	6.4	2.4	43.9	6.4	9.5	2.6	38.5	4.6	7.6	2.4	37.5	4.2	7.2	2.2	38.0	4.8	7.9	2.3
6	64.3	11.1	14.3	4.1	64.7	12.2	15.5	4.2	68.3	13.6	19.2	4.3	52.2	9.6	12.8	3.7	62.0	11.2	15.1	4.1
7	31.1	5.1	7.6	2.1	56.2	12.4*	18.3	4.0	53.7	10.2	17.3	3.6	45.4	8.0	13.4	3.2	49.5	9.0	15.5	3.2
8	77.1*	12.0	21.7	5.2	71.0	12.4	18.2	4.8	61.2	11.6	20.1	4.2	58.7	9.6	15.8	3.8	53.9	9.0	14.6	4.0
9	60.2	7.9	11.9	3.6	59.8	8.6	11.5	3.8	67.5	9.5	13.7	4.3	62.7	9.0	12.7	4.3	63.3	8.5	11.8	4.3
10	51.6	9.2	13.9	3.5	48.2	10.2	14.3	3.4	59.2	11.3	16.7	3.9	59.1	9.1	14.8	4.0	51.5	8.8	13.4	3.4
11	55.2	10.6	15.9	3.7	52.1	10.3	14.8	3.6	50.0	10.0	14.6	3.3	50.7	10.4	15.6	3.7	46.7	9.4	13.5	3.2
12	72.7	14.0	19.8	4.9	77.5	18.9*	24.9*	5.4	73.0	14.2	19.2	4.8	60.3	12.4	17.7	4.2	62.9	11.5	15.9	4.1
13	54.4	8.4	15.0	3.8	79.1	15.6	25.7	5.5	53.6	8.7	14.8	3.8	55.9	8.4	17.1	4.0	53.5	10.0	16.0	4.0
14	82.7*	12.4	15.7	6.0*	44.7	11.1	13.7	3.4	37.7	8.9	10.8	2.8	47.6	11.9	14.7	3.7	47.2	10.1	12.3	3.3
15	73.8	11.8	16.6	6.1	46.8	9.6	12.1	3.1	62.2	12.5	17.1	4.3	67.3	12.6	17.3	5.0	64.5	10.5	14.6	4.6
16	89.4	20.6	31.3	6.2*	74.5	15.8	23.1	5.0	79.7	18.9	29.7	5.1	62.5	15.1	22.6	4.2	79.2	19.1	27.1	5.2
17	55.8	9.0	12.2	3.3	63.2	13.5	15.5	4.1	57.7	11.4	13.8	3.6	55.5	10.6	13.9	3.7	62.6	13.3	16.4	4.3
18	73.1	11.9	17.8	5.2	68.5	14.1	17.2	4.9	63.8	8.9	12.8	4.2	68.1	11.6	15.7	4.9	70.2	11.9	17.0	4.8
19	85.9	16.4	24.9	6.1	52.6	13.9	17.3	3.8	52.0	12.5	16.9	3.7	54.2	11.9	17.0	4.0	64.5	12.3	18.4	4.5
20	67.2	6.8	9.4	4.0	82.4	12.3*	16.6*	5.3*	51.8	5.0	7.1	3.2	61.1	6.2	8.6	4.0	66.6	5.7	8.2	4.0
21	61.6	6.4	9.6	3.9	68.3	12.6*	16.8*	4.2	58.6	7.0	10.1	3.6	59.3	7.4	10.6	3.7	61.6	7.8	10.9	3.8
22	71.6	9.6	12.5	4.5	71.3	13.9	16.8	5.1	37.3	5.5	6.7	2.5	37.1	5.6	6.9	2.7	73.3	12.8	15.6	5.0
23	86.2*	17.9	19.8	5.7	76.2	20.0*	22.7	5.2	72.0	16.3	19.6	4.8	59.1	13.1	15.4	4.0	60.6	14.4	16.8	4.1
24	73.2*	11.4	18.0*	5.7*	56.4*	13.0*	19.7*	4.9*	49.8	10.5	16.0*	3.7	49.7	9.3	14.8	4.2	34.7	7.7	10.1	2.8
25	105.7	18.8	22.0	6.8	106.3	23.1	26.7	6.9	125.9*	24.3	28.6	8.2*	97.0	16.8	19.0	6.4	99.0	19.6	22.3	6.5
26	67.7	12.3	17.3	4.9	58.2	12.7	17.1	4.1	75.8	15.9	22.4	5.3	77.0	15.9	22.9	5.5	76.0	15.9	21.6	5.8
27	62.6	10.6	16.2	4.2	68.2	14.7	19.9	4.7	74.0	14.4	20.8	5.0	67.4	11.7	18.0	4.8	68.3	11.7	17.8	4.7
28	94.7	15.2	20.8	6.4	71.3	18.3	21.3	5.2	71.3	16.1	20.8	5.1	64.6	14.6	18.1	4.7	74.2	18.0	21.4	5.4
29	36.6	5.6	8.7	2.5	26.7	5.7	8.0	2.0	31.9	5.7	8.3	2.1	32.8	6.1	8.6	2.4	30.3	5.4	7.9	2.1
30	49.8	10.7	13.3	3.4	34.0	6.7	8.0	2.2	36.1	7.9	9.1	2.4	27.7	6.1	7.2	1.8	27.6	5.6	6.6	1.9

* indicates significance at 0.05 significance level, respectively

Table 19. Geographic locations for 2012-2013 harvested NPKS sites

Location	Latitude	Longitude
31	34°15’29.92”N	98°40’42.97”W
32	35°23’37.54”N	98°58’34.55”W
33	35°33’58.62”N	98°46’47.72”W
34	35°19’33.24”N	97°56’26.45”W
35	35°3’50.77”N	97°28’33.54”W
36	35°51’23.56”N	97°46’4.24”W
37	36°18’15.46”N	97°4’11.94”W
38	36°19’5.97”N	97°23’8.62”W
39	36°20’21.99”N	97°24’30.00”W
40	36°18’30.77”N	97°56’39.14”W
41	36°19’4.76”N	97°54’8.22”W
42	36°17’22.67”N	97°53’52.29”W
43	36°47’52.39”N	98°44’54.10”W
44	36°41’58.24”N	98°40’0.60”W
45	36°42’34.06”N	98°33’32.83”W
46	36°37’24.19”N	98°31’23.28”W
47	36°37’21.14”n	98°29’24.05”W
48	36°21’54.12”N	98°37’36.26”W
49	36°21’44.52”N	98°38’54.35”W
50	36°12’18.99”N	98°39’19.48”W
51	36°32’10.53”N	96°56’28.10”W
52	36°19’6.90”N	96°52’58.45”W
53	36°43’3.68”N	97°27’43.16”W
54	36°42’31.18’N	97°34’11.12”W
55	36°45’58.91”N	97°33’35.36”W
56	36°45’59.18”N	97°33’26.73”W
57	36°31’46.94”N	97°23’22.65”W
58	35°27’27.72”N	97°5’10.39”W
59	35°25’11.65”N	97°3’36.46”W

Table 20. **Initial surface (0-15 cm) and subsurface (15-45 cm) soil analysis for 2012-2013 harvested locations, pH - 1:1 soil: deionized water, NO_3^- - 2 M KCl extract, STP and STK – Mehilich-3 extraction, SO_4^- - 0.008 M Calcium Phosphate**

Location	depth	pH	NO_3^-	STP	STK	SO_4^-	Cl^-
	cm		ppm	ppm	ppm	ppm	ppm
31	0-15	5.4	24.0	29.5	157.5	8.5	24.2
	15-45						
32	0-15	8.0	8.5	12.5	224.5	7.0	18.2
	15-45	8.1	8.5	3.5	221.5	7.5	16.4
33	0-15	7.6	12.0	18.0	169.5	6.0	11.4
	15-45	7.9	19.5	4.5	132.5	28.5	15.8
34	0-15	6.2	5.5.	23.5	145.5	11.5	11.8
	15-45	5.6	12.0	15.0	109.5	11.5	33.9
35	0-15	7.6	1.5	19.5	93.5	3.0	6.6
	15-45	8.1	1.5	7.0	79.5	2.5	13.6
36	0-15	6.0	34.5	30.5	344.0	11.0	14.8
	15-45	7.2	4.0	7.0	293.0	7.0	10.1
37	0-15	6.6	53.5	33.5	138.5	14.5	45.7
	15-45	6.8	20.5	8.5	146.5	52.5	20.7
38	0-15	6.5	68.5	136.5	136.5	33.0	24.0
	15-30	6.5	8.0	35.0	100.0	10.0	17.5
39	0-15	5.3	47.0	68.0	236.5	21.5	13.9
	15-30	6.0	13.5	16.5	211.0	27.0	10.5
40	0-15	5.7	43.0	58.5	213.5	12.5	11.4
	15-30	5.6	17.0	10.5	136.5	12.0	15.7
41	0-15	4.5	43.0	34.0	153.0	17.0	22.7
	15-30	5.5	18.0	22.0	143.5	11.5	10.7
42	0-15	5.2	67.0	27.0	178.5	13.0	19.2
	15-45						
43	0-15	6.3	6.0	23.5	309.5	8.5	12.9
	15-45	6.8	9.0	8.5	298.5	8.5	15.6
44	0-15	6.3	67.0	34.0	252.5	10.0	10.4
	15-45	6.6	37.5	11.5	177.5	7.0	10.1
45	0-15	5.4	48.5	78.5	301.5	19.0	24.2
	15-45	6.3	26.0	23.5	231.0	13.5	17.6
46	0-15	5.0	46.0	64.0	359.5	11.0	12.8
	15-45	4.9	33.0	67.0	259.5	11.0	10.6
47	0-15	5.4	24.0	68.0	434.5	10.5	17.5
	15-45	5.6	33.5	55.5	342.0	14.5	24.0
48	0-15	5.3	40.0	37.5	184.5	12.5	11.3
	15-45	6.3	29.5	11.0	119.5	6.5	10.0
49	0-15	6.2	45.5	56.0	272.5	21.5	17.5
	15-45	7.1	26.5	11.0	184.0	17.0	31.9
50	0-15	7.6	25.0	24.5	102.0	19.0	59.9
	15-45	6.6	7.5	20.0	67.5	16.0	21.5
51	0-15	8.2	2.0	63.0	68.5	8.0	66.7
	15-45	7.5	2.0	22.5	54.0	9.5	72.8
52	0-15	5.7	22.0	17.0	159.5	12.0	22.0
	15-45						
53	0-15	5.1	21.5	26.0	99.5	9.5	21.2
	15-30	6.1	9.0	10.5	138.0	7.5	13.8
54	0-15	4.9	15.0	20.0	193.0	12.0	11.2
	15-30	6.0	8.0	9.5	169.0	25.0	14.7
55	0-15	4.6	21.5	17.0	159.5	16.5	9.5
	15-30	6.6	9.5	3.5	205.5	8.5	10.0
56	0-15	4.4	16.0	26.0	168.5	16.0	8.6
	15-30	5.3	12.5	11.5	152.5	16.5	10.3
57	0-15	6.2	16.0	13.5	203.0	17.0	21.0
	15-30	6.5	10.5	5.0	182.5	17.0	19.9
58	0-15	6.5	7.0	62.5	436.0	13.0	13.9
	15-45	7.4	13.5	12.5	414.0	10.0	15.2
59	0-15	6.3	19.0	150.0	374.0	9.0	13.4
	15-45	6.7	24.5	149.5	283.0	10.0	17.7

Table 21. Grain yield (kg ha^{-1}) for all treatments throughout 2012-2013 harvested location

Location	N Rich Strip Yield	P Rich Strip Yield	K Rich Strip Yield	S Rich Strip Yield	Farmer Practice Yield
31	285	324	415	453	389
32	1710	2138*	1827	2099	1671
33	2358	2772	3109*	2332	2384
34	4055	3861	4158	3886	3912
35	3679	4120	4262	4392	3718
36	1904	2021	2280	1606	2060
37	4171	3938	4405	4223	3977
38	4275*	2941	2785	3018	3083
39	4573	5428	4120	4456	4314
40	4677	4521	4534	4936	4418
41	5480	4936	5247	4690	5130
42	3666	4288	3394	3394	3537
43	5428*	3796	3485	3485	2954
44	3355	3109	2876	2474	2941
45	3796	3278	3899	3006	3588
46	1529	1257	2461	2526	2138
47	1529	1788	2047	1878	2112
48	3446	2733	3226	3563	3861
49	1930	1671	2021	2397	2682
50	2526	2928	2811	2552	2513
51	4469	3666	4638	4171	4314
52	1801	2021	1762	1529	1503
53	3886	3511	3550	3679	3951
54	3213	3899	3511	3187	2746
55	1568	2980*	1775	1671	1801
56	2708	3278*	2474	2695	2138
57	2189	1762	1684	1606	1827
58	4638	2967	3161	3342	5389
59	3601	5519	4754	4690	4664

* indicates significance at 0.05 significance level, respectively

Table 22. Straw biomass weight (kg ha^{-1}) for all treatments and harvested locations in 2012-2013

Location	N Rich Strip	P Rich Strip	K Rich Strip	S Rich Strip	Farmer Practice
31	6382*	5996	3752	5532	3990
32	6314*	6212*	3775	4761	4477
33	6166*	6688*	4988	5430	4818
34	7855	6847	5872	7209	6926
35	6892	6484	6427	6813	5804
36	6246	5316	4716	4092	4840
37	7187	7323	7164	7062	6246
38	7719*	4829	4251	4863	4874
39	8536	8241	6745	7368	7459
40	9023*	7005	7425	7821	7017
41	7765*	6370	6529	6541	6257
42	6937	7107	5634	5974	6507
43	9658*	6246	5033	5203	4840
44	8184	7515	6677	6484	7085
45	8876	7674	8263	6994	7765
46	8592	7470	8139	8229	6495
47	7651*	4795	5112	5203	5656
48	6110	4659	5339	5305	4852
49	6869	5747	4863	6189	6563
50	6336	6597	5849	5679	5622
51	6869	5736	6484	6960	6166
52	4092	4217	3911	3616	3582
53	6325	5668	5362	5770	5928
54	5611	7368*	6450*	6405*	4115
55	6132*	7051*	4205	4852	4239
56	3877	5747*	3253	4262*	3151
57	5350*	4126	3095	3786	3491
58	11970*	11845*	8615	10531	9567
59	9839	10168	10156	11233	10020

* indicates significance at 0.05 significance level, respectively

Table 23. Grain nutrient concentration for all treatments and harvested locations in 2012-2013

	N Rich Strip				P Rich Strip				K Rich Strip				S Rich Strip				Farmer Practice			
Location	%N	%P	%K	%S	%N	%P	%K	%S	%N	%P	%K	%S	%N	%P	%K	%S	%N	%P	%K	%S
31	3.41	0.37	0.61	0.19	3.42	0.43	0.63	0.19	3.44	0.43	0.58	0.19	3.42	0.42	0.57	0.19	3.43	0.41	0.53	0.19
32	2.98*	0.35	0.52	0.18	2.49	0.39*	0.55	0.16	2.25	0.34	0.54	0.15	2.19	0.33	0.54	0.15	2.60	0.32	0.53	0.17
33	2.89	0.35	0.54	0.17	2.55	0.42*	0.63	0.16	2.68	0.30	0.54	0.17	2.69	0.27	0.49	0.18	2.67	0.28	0.55	0.17
34	2.54	0.40	0.52	0.17	1.94	0.44	0.55	0.15	2.15	0.37	0.54	0.15	2.27	0.41	0.56	0.17	2.21	0.41	0.55	0.16
35	2.69*	0.45	0.61	0.17	2.05	0.46	0.53	0.14	2.40	0.45	0.58	0.16	2.27	0.43	0.58	0.16	2.10	0.40	0.52	0.15
36	2.53*	0.45	0.82*	0.17*	2.13	0.46	0.69	0.15	2.10	0.47	0.67	0.14	2.08	0.43	0.64	0.15	2.13	0.47	0.70	0.15
37	2.79	0.47	0.69	0.18	2.59	0.50	0.68	0.18	2.58	0.48	0.72	0.18	2.56	0.45	0.68	0.19	2.63	0.48	0.78	0.19
38	2.37*	0.53	0.71	0.15*	2.00	0.53	0.60	0.13	2.03	0.54	0.62	0.13	1.95	0.53	0.62	0.13	1.97	0.53	0.63	0.13
39	2.54	0.45	0.58	0.16	2.29	0.55	0.66	0.16	2.43	0.47	0.61	0.16	2.58	0.50	0.62	0.18	2.45	0.48	0.61	0.16
40	2.85	0.50	0.68	0.18	2.48	0.52	0.61	0.16	2.63	0.49	0.63	0.17	2.57	0.49	0.62	0.16	2.58	0.49	0.63	0.16
41	2.69	0.38	0.58	0.17	2.45	0.47*	0.64*	0.16	2.55	0.43	0.60	0.17	2.51	0.39	0.58	0.17	2.54	0.40	0.54	0.17
42	2.66	0.34	0.66	0.17	2.30	0.42*	0.66	0.15	2.50	0.32	0.59	0.16	2.46	0.34	0.66	0.17	2.52	0.33	0.63	0.17
43	2.10*	0.39	0.64*	0.14*	1.52	0.36	0.50	0.11	1.55	0.31	0.48	0.11	1.63	0.32	0.52	0.12	1.68	0.34	0.52	0.12
44	2.70	0.39	0.56	0.16	2.68	0.45	0.62	0.16	2.69	0.42	0.67	0.16	2.73	0.42	0.64	0.17	2.81	0.39	0.57	0.16
45	3.25	0.47	0.82	0.19	2.68	0.54	0.77	0.18	2.63	0.52	0.84	0.19	2.60	0.51	0.82	0.19	2.71	0.48	0.84	0.18
46	2.66*	0.46	0.79	0.18*	2.52	0.47	0.87	0.18	2.41	0.50	0.84	0.17	2.29	0.46	0.78	0.17	2.43	0.46	0.81	0.17
47	2.60	0.47	0.83	0.17	1.96	0.47	0.71	0.14	2.08	0.42	0.65	0.13	2.08	0.40	0.63	0.14	2.26	0.44	0.70	0.15
48	2.78	0.40	0.49	0.18	2.60	0.47*	0.53	0.17	2.65	0.43	0.53	0.17	2.48	0.39	0.53	0.17	2.51	0.38	0.53	0.17
49	2.96*	0.50	0.71	0.20*	2.60	0.46	0.55	0.18	2.64	0.48	0.63	0.19	2.64	0.50	0.69	0.18	2.40	0.44	0.60	0.17
50	2.55	0.41	0.66	0.18	2.42	0.50	0.73	0.17	2.48	0.45	0.70	0.17	2.51	0.46	0.69	0.18	2.62	0.48	0.75	0.19
51	1.96	0.47	0.51	0.12	2.02	0.49	0.51	0.13	1.86	0.47	0.48	0.12	1.88	0.46	0.48	0.12	1.80	0.45	0.47	0.12
52	2.85*	0.40	0.56	0.20*	2.35	0.45	0.62	0.17	2.59	0.43	0.64	0.19	2.51	0.44	0.62	0.19	2.56	0.43	0.59	0.18
53	2.70	0.39	0.48	0.18	2.37	0.45*	0.52*	0.16	2.37	0.38	0.47	0.16	2.49	0.38	0.47	0.17	2.38	0.37	0.44	0.16
54	2.42*	0.29	0.39	0.17*	2.58*	0.44*	0.48*	0.15	2.51*	0.38	0.44	0.15	2.44*	0.40	0.44	0.15	2.16	0.38	0.42	0.14
55	2.69	0.28	0.38	0.16	2.42	0.42*	0.48	0.16	2.59	0.32	0.43	0.16	2.51	0.28	0.40	0.17*	2.54	0.31	0.43	0.16
56	2.88*	0.32	0.42	0.17	2.34	0.38	0.48	0.16	2.70	0.33	0.43	0.17	2.57	0.35	0.46	0.18	2.70	0.33	0.43	0.16
57	2.20	0.35	0.43	0.15	1.91	0.40	0.44	0.12	2.17	0.38	0.46	0.14	2.07	0.39	0.48	0.14	1.92	0.39	0.46	0.14
58	2.82	0.54	0.59	0.19*	2.59	0.50	0.58	0.18*	2.28	0.49	0.55	0.15	2.39	0.51	0.59	0.17	2.31	0.50	0.54	0.16
59	2.98	0.54	0.53	0.18	2.23	0.50	0.49	0.16	2.54	0.49	0.46	0.17	2.56	0.51	0.48	0.17	2.74	0.58	0.58	0.18

* indicates significance at 0.05 significance level, respectively

Table 24. Grain nutrient removal (kg ha^{-1}) from the addition of N, P, K and S at all harvested locations in 2012-2013

	N Rich Strip				P Rich Strip				K Rich Strip				S Rich Strip				Farmer Practice			
Location	N	P	K	S	N	P	K	S	N	P	K	S	N	P	K	S	N	P	K	S
31	8.5	0.9	1.5	0.5	9.7	1.2	1.8	0.5	12.5	1.6	2.1	0.7	13.6	1.7	2.3	0.7	11.7	1.4	1.8	0.6
32	44.6	5.2	7.8	2.7	46.6	7.3*	10.4	3.1	35.9	5.5	8.7	2.4	40.3	6.1	9.9	2.8	38.1	4.7	7.8	2.5
33	59.7	7.2	11.2	3.5	61.8	10.3*	15.3	4.0	73.0*	8.1	14.8	4.6*	55.0	5.6	10.1	3.6	55.7	5.8	11.4	3.5
34	90.2	14.4	18.6	6.1	65.5	15.0	18.7	4.9	78.1	13.6	19.8	5.4	77.1	14.0	18.9	5.8	75.7	14.0	18.8	5.5
35	86.6	14.5	19.7	5.3	73.7	16.5	19.1	5.1	89.6*	16.7	21.7*	6.0*	87.1	16.4	22.3*	6.2*	68.4	12.9	17.1	4.7
36	42.1	7.6	13.7	2.8	37.6	8.1	12.3	2.6	41.9	9.3	13.4	2.8	29.2	6.0	8.9	2.1	38.4	8.4	12.7	2.6
37	101.7	17.3	25.3	6.7	89.1	17.1	23.3	6.1	99.4	18.6	27.9	7.1	94.8	16.5	25.2	6.8	91.7	16.7	27.0	6.5
38	88.7*	19.9*	26.5*	5.7*	51.6	13.6	15.5	3.3	49.5	13.1	15.2	3.2	51.6	14.1	16.4	3.4	53.1	14.3	16.9	3.5
39	101.6	18.0	23.4	6.6	108.5	25.9	31.5	7.5	87.6	17.1	21.8	5.8	100.5	19.6	24.4	7.1	92.5	18.0	23.1	6.2
40	116.6*	20.3	27.8	7.3	97.9	20.5	24.3	6.3	104.2	19.3	24.8	6.6	111.0	21.0	26.6	7.0	99.8	19.0	24.4	6.4
41	128.9*	18.2	27.8	8.0	105.6	20.3	27.7	7.1	117.3	19.7	27.7	7.6	102.8	16.0	23.7	7.2	113.8	17.8	24.4	7.5
42	85.4	10.8	21.1	5.5	86.5	15.6*	24.8	5.7	74.2	9.4	17.6	4.8	73.0	10.0	19.5	5.1	77.8	10.3	19.4	5.2
43	99.8*	18.3*	30.4*	6.7*	50.5	11.9	16.7	3.6	47.4	9.5	14.7	3.3	49.8	9.9	15.7	3.6	43.3	8.7	13.5	3.1
44	79.2	11.4	16.4	4.8	72.9	12.1	16.8	4.5	67.6	10.6	16.8	4.1	59.1	9.0	13.9	3.7	72.4	10.2	14.7	4.2
45	107.8*	15.7	27.1	6.1	77.0	15.4	22.1	5.1	89.6	17.7	28.8	6.5	68.3	13.3	21.6	4.9	85.0	15.1	26.2	5.6
46	35.6	6.1	10.6	2.4	27.7	5.1	9.5	1.9	51.9	10.7	18.1	3.6	50.5	10.1	17.3	3.8	45.5	8.5	15.2	3.1
47	34.8	6.3	11.1	2.2	30.7	7.4	11.1	2.2	37.2	7.4	11.7	2.4	34.2	6.6	10.3	2.4	41.7	8.1	12.9	2.7
48	83.8	12.2	14.8	5.4	62.1	11.2	12.6	4.0	74.7	12.2	15.0	4.8	77.4	12.3	16.5	5.2	84.9	12.7	17.8	5.6
49	50.0	8.5	12.0	3.4	38.0	6.7	8.1	2.7	46.6	8.5	11.1	3.3	55.3	10.4	14.6	3.8	56.4	10.4	14.0	3.9
50	56.5	9.0	14.5	3.9	62.1	12.8	18.8	4.3	61.0	11.0	17.3	4.2	56.1	10.4	15.5	4.0	57.5	10.6	16.6	4.1
51	76.8	18.4	20.0	4.8	64.7	15.6	16.5	4.1	75.4	19.2	19.7	5.0	68.6	16.9	17.7	4.5	67.9	17.1	17.8	4.4
52	44.9	6.3	8.8	3.1	41.6	8.0*	10.9	3.0	39.9	6.7	9.8	2.9	33.6	5.9	8.3	2.5	33.6	5.6	7.8	2.4
53	91.7	13.4	16.2	6.1	72.8	14.0	15.9	4.9	73.7	11.9	14.7	5.1	80.0	12.3	15.2	5.6	82.3	12.9	15.3	5.5
54	68.1	8.1	10.9	4.8	88.0*	14.9*	16.5*	5.2*	77.1	11.7	13.6	4.7	67.9	11.1	12.3	4.0	52.0	9.1	10.0	3.4
55	36.9	3.8	5.2	2.2	63.1*	10.9*	12.6*	4.1*	40.2	5.0	6.7	2.5	36.7	4.2	5.9	2.5	40.0	4.9	6.8	2.5
56	68.2	7.7	10.0	4.0	67.1	11.0*	13.6*	4.5	58.5	7.2	9.3	3.6	60.6	8.2	10.7	4.3	50.4	6.2	8.0	3.0
57	42.2	6.6	8.2	2.9	29.5	6.1	6.8	1.9	32.0	5.6	6.8	2.0	29.1	5.5	6.7	2.0	30.7	6.2	7.4	2.2
58	114.4	21.9	23.8	7.7	67.1	13.1	15.2	4.6	63.0	13.5	15.3	4.1	69.9	14.9	17.3	5.0	108.9	23.4	25.6	7.5
59	93.9	16.9	16.8	5.7	107.6	24.1	23.8	7.5	105.6	20.4	19.3	7.0	105.2	20.7	19.5	7.0	111.9	23.5	23.6	7.4

* indicates significance at 0.05 significance level, respectively

VITA

Lance Mitchell Shepherd

Candidate for the Degree of

Master of Science

Thesis: UTILIZING NPKS RICH STRIPS THROUGHOUT OKLAHOMA WINTER WHEAT PRODUCTION

Major Field: Plant and Soil Science

Biographical:

Education:

Completed the requirements for the Master of Science in Plant and Soil Science at Oklahoma State University, Stillwater, Oklahoma in July, 2013.

Completed the requirements for the Bachelor of Science in Agricultural Science at Northwest Missouri State University, Maryville, Missouri in 2011.

Experience:

Employed by Oklahoma State University, Department of Plant and Soil Sciences, as a Nutrient Management Research Assistant (2011-2013).

Professional Memberships:

American Society of Agronomy
Crop Science Society of Agronomy
Soil Science Society of America
National Angus Association
Alpha Gamma Rho