HARD RED WINTER WHEAT CULTIVAR RESPONSES
TO A pH AND ALUMINUM CONCENTRATION GRADIENT

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
In partial fulfillment of
the requirements for
the Degree of
Doctor of Philosophy
May, 2007
HARD RED WINTER WHEAT CULTIVAR RESPONSES
TO A pH AND ALUMINUM CONCENTRATION
GRADIENT

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ACKNOWLEDGEMENTS

I would like thank my Lord and Savior Jesus Christ for everything. I am grateful to the Department of Plant and Soil Sciences for the opportunity to work and study at Oklahoma State University. Special thanks to my adviser, Dr. Hailin Zhang, for the training, professional advice, and together with Dr. William Raun, for providing me the assistantship. I am also indebted to my advisory committee members Drs. Mark Payton, William Raun, and Jeff Edwards for their time and willingness to serve in this capacity and for sharing their wisdom with me. Dr. Eugene Krenzer started off in this program and for that I will always be thankful. My gratitude further goes to Jack Schroder and Mark Gregory for their contribution to fruition of this work. To OSU’s wheat research technicians Richard A. and Melanie I., the Soil, Water, and Forage Analytical Laboratory (SWFAL) personnel: Barbara M., Mike K., and Travis H. thank you for all your assistance and availability. Thanks also to my friends, David S., Fitry P., Robert K., Eunice M., Charles K., Nancy G., Samuel K., Jim B., Julie L., Yumi B., and Mendy H. for the support they rendered me in the course of my studies. Lastly but not least, I wish to thank my wife, Wambui, for her love and encouragement. This work is dedicated to my Mom who passed on a few months before my graduation. “I love you Mom and I thank you and Dad for teaching me responsibility.”
PREFACE

There are three chapters in this dissertation. Each chapter is a complete manuscript, including abstract, introduction, material and methods, results and discussion, conclusion and references, ready to be submitted for publication. All manuscripts follow the styles established by the Agronomy Society of America. Chapter 1 has been submitted and accepted for publication by the Agronomy Journal. Permission from the publisher is granted to include it in this dissertation.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>HARD RED WINTER WHEAT CULTIVAR RESPONSES TO A pH AND ALUMINUM CONCENTRATION GRADIENT</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Introduction</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Materials and Methods</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Results and Discussions</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Conclusion</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter</th>
<th>SPATIAL VARIABILITY AND SOIL SAMPLING IN A GRAZED PASTURE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Abstract</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Introduction</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Materials and Methods</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Results and Discussions</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Conclusion</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>50</td>
</tr>
</tbody>
</table>
### Chapter III

THE RESPONSE OF DUAL-PURPOSE WINTER WHEAT TO PHOSPHORUS RATES AND APPLICATION METHODS IN AN ACID SOIL

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>63</td>
</tr>
<tr>
<td>Introduction</td>
<td>64</td>
</tr>
<tr>
<td>Materials and Methods</td>
<td>70</td>
</tr>
<tr>
<td>Results and Discussions</td>
<td>75</td>
</tr>
<tr>
<td>Conclusion</td>
<td>82</td>
</tr>
<tr>
<td>References</td>
<td>84</td>
</tr>
</tbody>
</table>
LIST OF TABLES

CHAPTER I

Table                                                                 Page
1. Slopes and coefficients of determination ($r^2$) for the relationship between grain or forage yield and aluminum saturation ($\text{Al}_{\text{sat}}$) (combined data for two years). Also included is the threshold pH, i.e., pH at which yields in all cultivars are maximized (Fig. 6 and 7)....................................................................................................................19
2. Cultivar comparisons for mean grain and forage yield (kg ha$^{-1}$) (combined data for two years) at aluminum saturation ($\text{Al}_{\text{sat}}$) $>$ 30% and aluminum saturation ($\text{Al}_{\text{sat}}$) $<$ 30%.................................................................................................................................20
3. Previous winter wheat cultivar rankings for Al tolerance .........................21

CHAPTER II

1. Semivariance statistics for five soil properties: Nitrogen (NO$_3$-N), phosphorus (M3P), soil test potassium (STK), soil pH, and organic carbon (OC) at Sites 1 and 2.....................................................................................................................54
2. Comparison of soil property means and their variability among methods of soil sampling in NO$_3$-N, Mehlich 3 P (M3P), K, pH, and organic carbon (OC) at Site 1 and 2 including the min, max, and CV of soil test values of various characteristics...................................................................................................................55
3. A summary of the number of soil subsamples requirement to form a composite sample computed from “R” computer program based on different soil characteristics. The 5% and 10% are the percentage errors allowed within the means (as illustrated in Figure 4 in M3P example)...............................................................................................56

CHAPTER III

1. Comparison between Furrow and Broadcast Methods of P application in Limed and Un-limed Plots in 2005 and 2006 Grain .................................................................................................................................88
2. The effects of phosphorus fertilizer application methods, liming, and season on winter wheat grain and forage yields .................................................................................................................................89
<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Comparison of P placement methods based on wheat forage yields at different levels of M₃P</td>
<td>90</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

## CHAPTER I

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Field configuration illustrating cultivar growth differences (left to right) along the pH gradient (bottom to top). Smaller arrows points to 8 different cultivars and the big arrow to the direction of soil pH increase</td>
<td>22</td>
</tr>
<tr>
<td>2. Relationship between aluminum concentration (1.0M KCl extraction) and pH for a Konawa soil at Perkins, OK</td>
<td>23</td>
</tr>
<tr>
<td>3. Relationship between aluminum saturation (AlSat%) (1.0M KCl extraction) and pH for a Konawa soil at Perkins, OK</td>
<td>24</td>
</tr>
<tr>
<td>4. Effect of Al saturation on forage yields for different winter wheat cultivars</td>
<td>26</td>
</tr>
<tr>
<td>5. Effect of Al saturation on grain yields for different winter wheat cultivars</td>
<td>28</td>
</tr>
<tr>
<td>6. Effect of pH on forage yield for different winter wheat cultivars</td>
<td>30</td>
</tr>
<tr>
<td>7. Effect of pH on grain yield for different winter wheat cultivars</td>
<td>32</td>
</tr>
</tbody>
</table>

## CHAPTER II

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. A digital map projecting experimental sites in Jay, Oklahoma and the grid divisions</td>
<td>57</td>
</tr>
<tr>
<td>2. Soil properties’ spatial variability at two sites (1 and 2) in Jay Oklahoma. The contour maps were interpolated by Kriging</td>
<td>59</td>
</tr>
<tr>
<td>3. Relationship between Mehlich 3 P (M3P) and organic matter at experimental Site 1 and 2</td>
<td>60</td>
</tr>
</tbody>
</table>
4. Relationship between number of samples collected and soil phosphorus (M₃P) level estimate in two farms in (Site 1) southern and (Site 2) northern Jay Oklahoma. For each number of samples, we calculated the M₃P level for all possible combinations of samples. Error bars denote standard deviation, and horizontal lines denote ±5% of the field mean M₃P level (based on all samples collected in the entire field). Similar figures were generated for other soil characteristics and the results summarized.

5. Change in M₃P standard deviation (SD), generated by “R” computer program, with change in soil sub-samples. An illustration of an alternative method for deriving the number of sub-samples necessary to make a composite sample.

CHAPTER III

1. Experimental design indicating two methods of P application, furrow and broadcast (FPA and BPA) in five extractable Mehlich 3 P categories (M₃Pcat) within three soil pH categories (pHcat).

2. Comparison of the effect of broadcast and furrow methods of P placement at pH < 4.8 (A), 4.8 -5.0 (B) and >5.0 (C) on 2005 wheat forage yields.

3. Response surface for the combined effect of M₃P and broadcast (A) and furrow (B) P placement methods on forage yields (2005).

4. Relationship between applied P and M₃P generated from response surface and quadratic methods for predicting winter wheat P requirement compared with the existing Oklahoma’s and previously derived P recommendation curve (Kariuki, 2003).

5. Comparison of the effect of broadcast and furrow methods of P placement at 17 (A), 23 (B), 26 (C), 28 (D), 30 (E), and 33 (F) mg kg⁻¹ M₃P on wheat forage Yields.

APPENDICES
CHAPTER I
HARD RED WINTER WHEAT CULTIVAR RESPONSES TO A pH AND ALUMINUM CONCENTRATION GRADIENT

ABSTRACT

Aluminum (Al) toxicity is a major yield-limiting factor in winter wheat production in many parts of the world. The use of Al-tolerant cultivars reduces the impact of this problem and is common to the southern Great Plains where wheat is managed as a dual-purpose (DP) crop. However, no quantitative data exists on the Al-tolerance ranking of winter wheat cultivars often grown in a DP management system. This study was established to classify on a field scale the Al tolerance of common winter wheat cultivars (Ok101, Ok102, 2137, 2174, Jagger, Jagalene, Custer and AP502CL). Fall forage yield of each cultivar was harvested by hand clipping. Soil samples were collected at the same time and analyzed for pH and Al saturation (Al_{sat}). Grain was hand-harvested in June of each year from the same rows harvested for forage. Cultivar differences ($P < 0.1$) were found in forage and grain yields for Al_{sat} > 30% range. Al tolerance based upon grain yield ranked as follows: 2137 > Jagalene = Ok101 > Jagger = 2174 ≥ Ok102 > Custer = AP502CL. Al tolerance based upon forage yield ranking was similar to that of grain: 2137 > Ok101 = Jagalene = Jagger > 2174 = Ok102 > Custer = AP502CL. Grain yield appeared less impacted by Al_{sat} than forage yields. The use of Al-tolerant winter wheat cultivars may minimize producers’ risk of crop loss; therefore, this ranking of Al
tolerance should help winter wheat producers make informed decisions if they have acid soils with high Al content and no other remedies available.

**INTRODUCTION**

Wheat is a major commodity in Oklahoma, where 49% of the total acreage is produced with dual-purpose (DP) intentions (Hossain et al., 2004), whereby forage is grazed in fall and winter, cattle are removed at or near first hollow stem, and the grain is harvested in the summer. This practice has been successful in diversifying producers’ income in spite of significant amount of wheat acreage having been planted in a strongly acid (pH < 5.0) to moderately acidic (pH 5.0-6.0) soils.

Soil acidity, with a resultant elevation in available soil Al concentration, has been a major cause of crop failure in central and western Oklahoma (Zhang and Raun, 2006). There are several causes of soil acidity: the nitrification process, organic matter decomposition, and acid rain contribute to increased soil acidity (Prasad and Power, 1997; Sparks, 2003). Intensive and continuous crop production accelerates the acidification of soil because the conversion of ammonium-based N fertilizer sources to nitrate causes a net H⁺ release, which lowers the soil pH in the plant rooting zone (Tang, 2004; Garvin and Carver, 2003; Prasad and Power, 1997). A survey conducted in 1996 revealed that over 35% of the total wheat production acreage in Oklahoma was planted in soils with a pH less than 5.5 (Zhang et al., 1998). There is no evidence that this level of soil acidity has changed since.

Potassium chloride-extracted Al and Al saturation (Al_sat) have an inverse relationship with pH (Chartres et al., 1990; Evans and Kamprath, 1970). Increased soil
acidity causes solubilization of Al, which is the primary source of toxicity to plants at pH below 5.5 (Bohn et al., 2001; Ernani, et al., 2002 Parker et al. 1989). Aluminum chemistry varies with soil pH, but only the soluble ions such as $\text{Al}^{3+}$, which exists between pH 4.7 and 6.5, are toxic to plants. When $\text{Al}^{3+}$ concentration is high relative to the basic cations, $\text{Al}_{\text{sat}}$ percentage increases. If the soil is not corrected for acidity and remains at high concentrations of toxic Al ions, then poor stand establishment and growth for vulnerable crop species and/or cultivars may result, a condition referred to as Al toxicity.

Crops grown in soils with acceptable levels of basic cations may not show Al toxicity symptoms even when the levels of KCl-extractable Al are considered high. Therefore, the mere presence of Al in the soil is not an indicator of Al toxicity (Johnson et al., 1997). A more reliable measure of the potential for Al toxicity is $\text{Al}_{\text{sat}}$, which is the Al concentration (commonly measured in 1.0 M KCl extraction) expressed as a percentage of exchangeable cations (i.e., Ca, Mg, K, and Na) (Sumner and Miller, 1996).

Liming is the most widely used long-term method of soil acidity amelioration, and its success is prominently documented (Haynes, 1982; Conyers et al., 1991; Scott et al., 2001; Zhang et al., 2004; Kaitibie et al., 2002). In Oklahoma, lime is recommended for continuous wheat producers in low-pH soils (Zhang and Raun, 2006). However, the use of lime is not without limitations. Among these are that liming does not always increase yields. For instance, Boman et al. (1993) found no difference between limed and non-limed plots even when compared in the same low-pH soil. Other reasons why some producers are reluctant to use lime in ameliorating soil acidity are the economics of lime application (Ruiz-Torres et al., 1992) and disease pressure in heavily limed soils (Garvin
and Carver, 2003).

The use of Al-tolerant cultivars to ameliorate the effects of Al toxicity has been a successful alternative to liming in winter wheat production (Johnson et al., 1997; Delhaize et al., 2004). Plant Al tolerance has been associated with the ability to exude organic anions such as citrate and malate, which may complex Al and reduce its negative effects on the plant (Yang et al., 2004; Blamey et al., 1997; Tang et al., 2002; Zheng et al., 2004). Plant uptake of P, K, N, Ca, Mg, and other essential nutrients decreases with increased Al levels in a plant (Lidon et al., 2000), due to inhibition of root elongation in low-pH soils (Kochian 1995). Although an Al-tolerant plant is capable of taking up these nutrients in the presence of elevated levels of Al in the root zone, Al-tolerant cultivars grow best at Alsat levels less than 12% (Johnson et al., 1997). Aluminum saturation ranging from 15 to 30% was found to cause a 98% loss in winter wheat forage yield and a grain-crop failure (Wise, 2002).

One method of assessing wheat tolerance to elevated levels of Al is to measure root development of plants grown in different concentrations of Al (Bolt, 1996). The degree of Al tolerance varies not only from crop to crop but also from cultivar to cultivar within a crop. Plant breeders have developed and recommended several Al-tolerant wheat cultivars (Tang et al., 2002) based on their degree of tolerance, primarily in nutrient-solution culture. There is, however, insufficient quantitative data on how these cultivars’ compare for Al tolerance under actual field conditions.

Carver et al. (2003) used an experimental site with a uniform low pH of 4.2 and a limed control site in their study to compare and rank winter wheat cultivar tolerance to Al toxicity. However, the use of a site with only extreme pH levels may limit the possibility
of optimizing pH for a given genotype, because it restricts the range of the pH necessary to obtain a threshold. Testing in a site with a pH gradient, varying from very strongly acidic to slightly acidic soil would provide information useful to quantitatively rank cultivars across a pH range. Such information is vital in guiding wheat producers in choosing appropriate cultivars suitable for acid conditions. Johnson et al. 1997 found cultivar differences in grain and forage yield under low pH soil conditions; however, this conclusion was not consistent across environments. The objective of this study was to examine and quantitatively rank the acid-soil and Al tolerance of common winter wheat cultivars grown in the Southern Great Plains of the United States based on forage and/or grain production potential.

MATERIALS AND METHODS

Experimental Site Establishment and Treatment Application

The experiment was established in the spring of 2003 at a low and variable pH site at Perkins, Oklahoma (Latitude 35.99°N & Longitude 97.04°W), in Konawa (fine-loamy, mixed, thermic ultic haplustalfs) soil series. Initial soil samples indicated a pre-existing pH gradient of 4.2 - to 5.3 distributed in several parts of the field. To understand the spatial pH variability of the site, “Custer”, a winter wheat cultivar known for its susceptibility to low-pH soils, was planted as a test crop. At Feekes 5 (Nelson et al., 1988) growth stage, a vegetation-greenness map derived from normalized difference vegetation index (NDVI) data were used to delineate growth variability and was then verified with soil pH tests. With this information, the experiment was established across the pH gradient in a complete randomized design with three replications measuring 12 x
6 m. In each replication the soil-pH gradient was identified and augmented by liming at 2,500 kg ha\(^{-1}\) effective calcium carbonate equivalent (ECCE) six months before planting at the high pH end of the gradient to extend the pre-existing pH range. Lime was incorporated by rotor tilling. Each replication was tested for pH, immediately before planting, to assess the range of the new pH gradient (Figure 1), which was found to vary from 4.2 to 6.5. The gradient for the second year of the study was confirmed by soil testing.

Eight commonly grown hard red wheat cultivars in the Southern Plains (Ok101, Ok102, 2137, 2174, Jagger, Jagalene, Custer and AP502CL) were seeded in rows 15 cm apart side-by-side along the 4.2 to 6.5 pH gradient path (Figure 1). Planting occurred in early September 2003 and 2004 at a rate of 110 kg ha\(^{-1}\), using an eight-row drill. Four rows per cultivar of two different randomly selected cultivars were created in one drill strip during the initial planting. For 2004, cultivars were not randomized but were planted into the same plot area. This is typical of land management practices in Oklahoma where winter wheat is often grown continuously (Kaitibie et al., 2002; Stone et al., 2006).

**Plant Harvest**

Wheat forage was harvested in mid-December 2003 and 2004. For each cultivar and within each block, plants were sampled by hand-clipping the two center rows to the ground along the pH gradient at a spacing of 2.0 m (Figure 1). Thus, six plant samples per cultivar per replicate per year for a total of 288 forage samples were collected. The unclipped forage was mowed to homogenize the experimental site. Forage was oven-dried for 3 d at 105° C before measuring dry weight.
Grain was hand-harvested in June 2004 and June 2005 from the same rows where forage was hand-clipped at the same spacing as described for forage (Figure 1). Each sample was bagged and stored to air dry, then manually threshed after 14 d. Weight measurements were then determined and data analyzed.

**Soil Sampling and Analysis**

Soil samples were collected in 2003 and 2004 at the same spacing as described above for plant samples. Six soil samples per cultivar per replicate per year for a total of 288 samples were taken at a depth of 15 cm for every cultivar along the same pH gradient where forage was sampled (Figure 1). Each sample was a composite of 10 cores that were taken in the area of the two center rows that were harvested for forage and grain. Soil samples were oven-dried at 65°C for 24 h and ground to pass a 2-mm sieve (SERA-IEG-6, Southern Extension Research Activity-Information Exchange Group-6, 2001).

A routine soil analysis for N, P, and K was made to determine fertility needs for the crop. Soil pH was measured in a 1:1 soil: water ratio using a combination pH electrode (Thomas, 1996). Levels of extractable cations (Ca, Mg, K, and Na) were determined according to the method of Sumner and Miller (1996). Soil (2.5 g) was mixed with 25 ml of 1M NH₄OAc at pH 7.0. Extractable Al was measured using the Bertsch and Bloom (1996) method where 5.0 g of soil was mixed with 25 ml of 1.0M KCl. Aluminum, Na, K, Mg, and Ca in the extracts were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Effective cation exchange capacity (ECEC) was determined using equation 1.1 by Sumner and Miller (1996).

\[
\text{ECEC (meq./100g) = [Na] + [K] + [Ca] + [Mg] + [Al KCl]} \quad [1.1]
\]

Al sat was calculated using the following equation:
\[ \% \text{Al}_{\text{sat}} = \left( \frac{\text{Al}_{\text{KCl}}}{\text{ECEC}} \right) \times 100 \]  

**Data Analysis**

Soil and plant data from were analyzed using PC SAS Version 9.2 (SAS Inst. Cary, NC). The Levene’s test was performed for each cultivar to determine homogeneity of variance for the two years of data. Because the variances within each cultivar were homogeneous, the data from the two years was combined for statistical analysis. To discriminate the cultivar soil-acidity tolerance, analysis of variance procedures were used with PROC MIXED. To separate the means, a DIFF option in an LSMEANS statement was used. Regression analyses were performed using PROC REG to determine cultivar sensitivity to soil acidity and slopes associated with the cultivars were compared using indicator variables (Equation 1.3).

\[
\text{Yield} = \beta_0 + \beta_1 X + \beta_2 (DV) + \beta_3 (DV \times X) + \text{error} \tag{1.3}
\]

where,

- \( X \) = Aluminum saturation or pH
- \( DV \) = Indicator or dummy variable for pairwise comparison of cultivars.

Linear -plateau models, performed with PROC NLIN, were used to obtain the threshold pH for each cultivar (Equation 1.4).

\[
\text{Yield} = \beta_0 + \beta_1 (pH) + \text{error}; \quad \text{if } X < \gamma
\]

\[
\text{Yield} = \gamma + \text{error}; \quad \text{if } X \geq \gamma \tag{1.4}
\]

where \( \gamma \) = plateau (level of pH in which yield fails to increase).
RESULTS AND DISCUSSION

Relationships between Soil pH, and Extractable Al and Al Saturation

Soil pH varied from 4.2 to 6.5, whereas 1 M KCl extractable Al (Al\textsubscript{KCl}) and Al\textsubscript{sat} varied from 0 to 159 mg kg\textsuperscript{-1} and from 0 to 70%, respectively (Figure 2 and 3). A significant inverse exponential relationship ($P < 0.001$, $r^2 = 0.92$) existed between Al\textsubscript{KCl} and soil pH (Figure 2). At pH below 5.5, a slight change in pH resulted in a dramatic change in Al. For example, a pH increase from 5.0 to 5.5 decreased Al\textsubscript{KCl} from 60 to 20 mg kg\textsuperscript{-1}. In contrast, a pH increase from 5.5 to 6.0 caused relatively small decrease in Al\textsubscript{KCl} from 20 to 4.5 mg kg\textsuperscript{-1}.

Similarly, a significant inverse exponential relationship ($P < 0.001$, $r^2 = 0.89$) existed between Al\textsubscript{sat} and pH (Figure 3). Comparable to the Al-pH relationship, changes in Al\textsubscript{sat} were more pronounced at lower than higher pH. An increase in pH from 5.0 to 6.0 resulted in an estimated decrease in Al\textsubscript{sat} from only 7.3 to 2.2%, compared to a pH increase from 5.0 to 5.5 which caused an estimated decrease in Al\textsubscript{sat} from 23.5 to 7.3%. Al solubilizes in low pH conditions and is precipitated at high pH by OH\textsuperscript{-}. The higher the soil acidity, the higher the level of Al solubilization, giving rise to increased Al\textsubscript{sat}. These findings were in agreement with previous studies by Chartres et al. (1990) and Evans & Kamprath (1970).

A relationship was found between threshold pH, a point beyond which further pH increase resulted in no increase in yield, and the level of Al tolerance. This supports the strong correlation between Al\textsubscript{sat} and pH (Figure 3). In general, cultivars with higher Al tolerance exhibited tolerance to lower threshold pH than those less tolerant to high Al...
concentrations (Table 1) and were more vulnerable to Alsat > 30% (Table 2). This means that in comparison to the less Al tolerant cultivars, more tolerant cultivars can maximize their yields in soils otherwise considered too acidic for winter wheat production (Zhang and Raun, 2006).

**Cultivar Sensitivity to Changes in Al Saturation**

The linear responses to Alsat differed among cultivars and, therefore, the magnitude of the slope was used to explain differences in cultivar sensitivity to Alsat. In both grain and forage data, cultivars with greater slope (absolute value) were considered more sensitive to changes in Alsat, an implication of poor Al tolerance. For example, two extreme cultivars in Al sensitivity, AP502CL and 2137, recorded slopes of -38.7 and -10.8 kg ha\(^{-1}\) grain Alsat\(^{-1}\), respectively (Figure 4). This was interpreted to mean that 2137 was more Al tolerant than AP502CL because, a 1% increase in Alsat caused only a 10.8 kg ha\(^{-1}\) grain yield decrease for 2137 but a 38.7 kg ha\(^{-1}\) yield decrease for AP502CL (Table 1). The Alsat response for forage yields produced a narrower range of slope values than those for grain yield. Jagger, one of the most Al tolerant cultivars, had a slope of -21.1 kg ha\(^{-1}\) compared to -40.4 kg ha\(^{-1}\) of 2174, a low Al tolerant cultivar (Table 1, Figure 5).

**Ranking Winter Wheat Cultivars for Al Tolerance**

All eight wheat cultivars showed an inverse linear relationship between yield (grain or forage) and Alsat (Table 1), an implication that none of them was absolutely tolerant to Al toxicity. A regression analysis between yields and Alsat indicated greater cultivar variability in yields at Alsat > 30% than with the entire Alsat range. Because of the severe toxicity associated with Alsat > 30%, yield differences were driven by cultivar Al
tolerance and not by cultivar yield potential in an Al-stress free environment.

There were highly significant differences \((P < 0.001)\) between yields at \(\text{Al}_{\text{sat}} > 30\%\) and \(\text{Al}_{\text{sat}} < 30\%\) for all cultivars (Table 2). Cultivars with greater tolerance showed smaller difference between yields at \(\text{Al}_{\text{sat}} > 30\%\) versus \(\text{Al}_{\text{sat}} < 30\%\). With tolerant cultivars, a large reduction in soil acidity resulted in only a slight increase in yields. For example, the percentage grain yield increase from \(\text{Al}_{\text{sat}} > 30\%\) to \(\text{Al}_{\text{sat}} < 30\%\) was 28\% for Jagalene, one of the most Al-tolerant cultivars, as compared to approximately 3200\% for AP502CL, one of the least Al-tolerant cultivars (Table 2). Similar comparison could be made for forage yield. Where there was only a 65\% increase in Jagalene forage yield between \(\text{Al}_{\text{sat}} > 30\%\) and \(\text{Al}_{\text{sat}} < 30\%\), AP502CL recorded about 1200\% increase (Table 2). This qualified the use of mean-cultivar yields in this \(\text{Al}_{\text{sat}}\) range (\(> 30\%\)) to discriminate \((P < 0.1)\) and further rank cultivars (Table 2). A cultivar producing relatively high yields in the presence of severe Al toxicity was considered Al tolerant. For example, where 2137 yielded an average of 1972 kg ha\(^{-1}\) of grain, AP502CL yield was only 44 kg ha\(^{-1}\). Similarly, 2137 yielded 1236 kg ha\(^{-1}\) forage versus 95 kg ha\(^{-1}\) by AP502CL. Hence 2137 is much more Al tolerant than AP502CL.

The grain response to Al tolerance cultivar ranking agrees somewhat with the qualitative ranking by Krenzer et al. (2004) (Table 3) in that Ok101, Jagger, Jagalene, and 2137 were the most Al tolerant (Table 2). However, our analysis provided improved discrimination among 2137, Jagalene, Ok101, and Jagger. According to previous ratings, all four cultivars were considered to have the same Al tolerance (Krenzer et al., 2004) (Table 3). The cultivars 2174 and Ok102, and then Custer and AP502CL exhibited their inferiority in the Al toxic environment as previously documented. The order of grained-
based Al tolerance was as follows: 2137 > Jagalene = Ok101 > Jagger = 2174 ≥ Ok102 > Custer = AP502CL. The ranking (comparison at Al_{sat} > 30%) corresponded with cultivar sensitivity to Al_{sat} analysis (Table 1) whereby the more sensitive to Al_{sat} a cultivar was, the less Al tolerant it was found to be. The grain yield for 2174 (809 kg ha^{-1}) was not different from that of Ok102 (718 kg ha^{-1}), or from Jagger (1039 kg ha^{-1}) at (P > 0.1) even though Jagger’s yield was greater (P < 0.1) than Ok102. This was the basis for using the “greater-than-or-equal-to” sign between 2174 and Ok102.

Forage-based rankings were similar grain-based rankings and agreed well with Krenzer et al. (2004) in that, except for Jagger, which showed the same Al tolerance as Jagalene, and Ok101, all the other cultivars displayed the same tolerance as grain based as follows: 2137 > Ok101 = Jagalene = Jagger > 2174 = Ok102 > Custer = AP502CL. The cultivar 2137 was exclusively the most Al tolerant with Ok101, Jagalene, and Jagger placing second.

Unlike the grain-based ratings, there was no apparent association for forage yield between Al sensitivity at >30% Al_{sat} and rankings for Al-tolerance based on slopes. This was attributed to the fact that forage was impacted more by severe Al toxicity (Al_{sat} > 30%) than grain. At Al_{sat} > 30%, forage yield was found to be constantly close to zero in the less tolerant cultivars, such as AP502CL, which decreased the slope making it appear as if it was not sensitive (Figure 4).

**Impact of Soil Acidity on Grain and Forage Yields**

Grain and forage yields responded to changes in soil acidity but at different magnitudes. A mean slope of 25 kg ha^{-1}Al_{sat}^{-1} obtained for grain was significantly less (P < 0.1) than 31 kg ha^{-1}Al_{sat}^{-1} for forage (Table 1). Likewise, threshold pH was found to be
cultivar-dependent (Table 1). This was in contrast with a pH of 5.5 previously reported as the ideal pH for wheat production (Bohn et al., 2001; Ernani, et al., 2002). At a range of 5.3 to 6.6, threshold pH for grain was more variable among cultivars than for forage, where it ranged between 6.2 and 6.6 (Table 1). Forage yield in most of the cultivars failed to plateau within the pH range of the experimental site (Figure 6), which may imply that forage requires a higher pH than available at the site to generate a plateau response. This was not the case with grain data where most of the cultivars generated plateaus (Figure 7). The mean percentage grain yield increase (82%) between $\text{Al}_{\text{sat}} < 30\%$ and $\text{Al}_{\text{sat}} > 30\%$ was lower than that for forage yield (159%) (Table 2). Overall, it appears that forage yield in winter wheat is impacted more by Al toxicity than grain yield. This could be related to the difference in expected nutrient demand at different stages of growth. Most essential nutrients and water are needed during the vegetative stage and Al interferes with the uptake of these nutrients; therefore, the younger the plant the more vulnerable it is to Al toxicity. For example, magnesium, whose uptake decreases in the presence of Al (Lidon et al., 2000), links the ATP molecule to the active site of the enzyme (Hopkins, 1999). However, during flowering and subsequent grain-filling less mineral nutrients are needed (Stichler and McFarland, 2001) or may be taken up, reducing the impact of Al toxicity. Another possible reason that forage is impacted more by Al toxicity than grain is that much of the fall forage growth occurs before the root system is full developed. Many of theses soils have very depressed soil pH near the surface where acid conditions have been induced by fertilizer application but adequate pH for normal plant growth exists deeper in the soil profile. As grain yield components are determined later in the season, they may be less impacted by Al-toxicity due to an
expanded and deeper root system.

CONCLUSION

Overall, the increase in pH resulted in significant increases in forage and grain yields. Differences were found in cultivar response to changes in pH and Al saturation. These differences, which were the basis for ranking the cultivars for Al tolerance, revealed that grain based ranking was similar to that in the literature, where 2137, Jagalene and Ok101, and then Jagger, in that order were the most Al tolerant. The cultivars 2174 and Ok102 had moderate tolerance while Custer and AP502CL ranked the lowest. Whereas limited data existed previously on forage based Al tolerance ranking, our study revealed similarities with grain-based ranking. Forage yield was found to be impacted more severely by Al toxicity than grain yield.
REFERENCES


Table 1. Slopes and coefficients of determination ($r^2$) for the relationship between grain or forage yield and aluminum saturation (Al$_{sat}$) (combined data for two years). Also included is the threshold pH, i.e., pH at which yields in all cultivars are maximized (Fig. 6 and 7).

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Slope (kg ha$^{-1}$ Al$_{sat}$$^{-1}$)</th>
<th>$r^2$</th>
<th>Threshold pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2137</td>
<td>-10.8a†</td>
<td>0.20</td>
<td>5.3</td>
</tr>
<tr>
<td>Ok101</td>
<td>-14.3a</td>
<td>0.32</td>
<td>5.5</td>
</tr>
<tr>
<td>Jagger</td>
<td>-16.3a</td>
<td>0.38</td>
<td>5.8</td>
</tr>
<tr>
<td>Jagalene</td>
<td>-17.6a</td>
<td>0.32</td>
<td>6.0</td>
</tr>
<tr>
<td>2174</td>
<td>-30.3b</td>
<td>0.66</td>
<td>5.9</td>
</tr>
<tr>
<td>Ok102</td>
<td>-30.7b</td>
<td>0.70</td>
<td>6.4</td>
</tr>
<tr>
<td>Custer</td>
<td>-34.2bc</td>
<td>0.78</td>
<td>6.6</td>
</tr>
<tr>
<td>AP502CL</td>
<td>-38.7c</td>
<td>0.80</td>
<td>6.2</td>
</tr>
<tr>
<td>Mean‡</td>
<td>-25.0</td>
<td>0.39</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>Forage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jagger</td>
<td>-21.1a</td>
<td>0.51</td>
<td>6.4</td>
</tr>
<tr>
<td>Jagalene</td>
<td>-22.3a</td>
<td>0.51</td>
<td>6.2</td>
</tr>
<tr>
<td>2137</td>
<td>-24.6a</td>
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<td>6.5</td>
</tr>
<tr>
<td>AP502CL</td>
<td>-32.1b</td>
<td>0.84</td>
<td>6.3</td>
</tr>
<tr>
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<td>-33.8bc</td>
<td>0.71</td>
<td>6.3</td>
</tr>
<tr>
<td>Custer</td>
<td>-33.8bc</td>
<td>0.75</td>
<td>6.6</td>
</tr>
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<td>Ok101</td>
<td>-34.1bc</td>
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</tr>
<tr>
<td>2174</td>
<td>-40.4c</td>
<td>0.81</td>
<td>6.6</td>
</tr>
<tr>
<td>Mean‡</td>
<td>-31.0</td>
<td>0.59</td>
<td>6.3</td>
</tr>
</tbody>
</table>

†Values with the same letter are not statistically different ($P > 0.10$).
‡Mean values were obtained by analyzing all cultivars combined.
Table 2. Cultivar comparisons for mean grain and forage yield (kg ha\(^{-1}\)) (combined data for two years) at aluminum saturation (Al\(_{\text{sat}}\)) > 30% and aluminum saturation (Al\(_{\text{sat}}\)) < 30%.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Al(_{\text{sat}}) &gt; 30%</th>
<th>Al(_{\text{sat}}) &lt; 30%</th>
<th>Difference</th>
<th>Increase (%) (^{\ddagger})</th>
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<tbody>
<tr>
<td></td>
<td>Yield (kg ha(^{-1}))</td>
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<tr>
<td><strong>Grain</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2137</td>
<td>1972a†</td>
<td>2217a</td>
<td>245</td>
<td>12</td>
</tr>
<tr>
<td>Jagalene</td>
<td>1496b</td>
<td>2008a</td>
<td>512</td>
<td>34</td>
</tr>
<tr>
<td>Ok101</td>
<td>1400b</td>
<td>1817ab</td>
<td>417</td>
<td>30</td>
</tr>
<tr>
<td>Jagger</td>
<td>1039c</td>
<td>1576bc</td>
<td>537</td>
<td>52</td>
</tr>
<tr>
<td>2174</td>
<td>809cd</td>
<td>1793b</td>
<td>984</td>
<td>122</td>
</tr>
<tr>
<td>Ok102</td>
<td>718d</td>
<td>1731b</td>
<td>1013</td>
<td>141</td>
</tr>
<tr>
<td>Custer</td>
<td>141e</td>
<td>1292d</td>
<td>1151</td>
<td>816</td>
</tr>
<tr>
<td>AP502CL</td>
<td>44e</td>
<td>1450c</td>
<td>1406</td>
<td>3195</td>
</tr>
<tr>
<td>Mean</td>
<td>952</td>
<td>1736</td>
<td>783</td>
<td>82</td>
</tr>
<tr>
<td><strong>Forage</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>2137</td>
<td>1236a</td>
<td>1958a</td>
<td>722</td>
<td>58</td>
</tr>
<tr>
<td>Ok101</td>
<td>962b</td>
<td>2011a</td>
<td>1049</td>
<td>109</td>
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<td>865b</td>
<td>1564ab</td>
<td>699</td>
<td>81</td>
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<td>Jagger</td>
<td>838b</td>
<td>1556ab</td>
<td>718</td>
<td>86</td>
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<tr>
<td>2174</td>
<td>448c</td>
<td>1797a</td>
<td>1349</td>
<td>301</td>
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<tr>
<td>Ok102</td>
<td>421c</td>
<td>1597ab</td>
<td>1176</td>
<td>279</td>
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<tr>
<td>Custer</td>
<td>189d</td>
<td>1341b</td>
<td>1152</td>
<td>610</td>
</tr>
<tr>
<td>AP502CL</td>
<td>95d</td>
<td>1253b</td>
<td>1158</td>
<td>1219</td>
</tr>
<tr>
<td>Mean</td>
<td>632</td>
<td>1635</td>
<td>1003</td>
<td>159</td>
</tr>
</tbody>
</table>

\(^{\dagger}\) Mean values with the same letter are not statistically different (\(P > 0.10\)).

\(^{\ddagger}\) Percent Increase = (Yield at Al\(_{\text{sat}}\) < 30% − Yield at Al\(_{\text{sat}}\) > 30%) / Yield at Al\(_{\text{sat}}\) > 30%) X 100
Table 3. Previous winter wheat cultivar rankings for Al tolerance

<table>
<thead>
<tr>
<th></th>
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<tr>
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<td>Rankings</td>
<td>Rankings</td>
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<tr>
<td>Ok101</td>
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<td>1</td>
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<tr>
<td>2137</td>
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<td>1</td>
</tr>
<tr>
<td>Jagger</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>Jagalene</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>2174</td>
<td>3.1</td>
<td>3</td>
</tr>
<tr>
<td>Ok102</td>
<td>3.0†</td>
<td>3</td>
</tr>
<tr>
<td>Custer</td>
<td>3.9</td>
<td>4</td>
</tr>
<tr>
<td>AP502CL</td>
<td>-</td>
<td>4</td>
</tr>
</tbody>
</table>

†Ranking from Carver et al. (2004).
Figure 1. Field configuration illustrating cultivar growth differences (left to right) along the pH gradient (bottom to top). Smaller arrows points to 8 different cultivars and the big arrow to the direction of soil pH increase.
y = \(2.0 \times 10^7 e^{-2.5468x}\), \(r^2 = 0.92^{***}\)

Figure 2. Relationship between aluminum concentration (1.0M KCl extraction) and pH for a Konawa soil at Perkins, OK. *** \(P < 0.001\).
Figure 3. Relationship between percent aluminum saturation (A_{sat}%) and soil pH for a Konawa soil at Perkins, OK. *** $P < 0.001$
Figure 4.
Figure 4. Effect of Al saturation on forage yields for different winter wheat cultivars. ***$P < 0.001$. 

- **Jagalene**: $y = 1781 - 22.3x$, $r^2 = 0.51^{***}$
- **Jagger**: $y = 1720 - 21.1x$, $r^2 = 0.51^{***}$
- **Ok101**: $y = 2325 - 34.1x$, $r^2 = 0.85^{***}$
- **2137**: $y = 2184 - 24.6x$, $r^2 = 0.54^{***}$
Figure 5.
Figure 5. Effect of Al saturation on grain yields for different winter wheat cultivars ***$P < 0.001$, **$P < 0.01$. 

Jagalene: $y = 2196 - 17.6x$, $r^2 = 0.32***$

Jagger: $y = 1709 - 16.3x$, $r^2 = 0.38***$

Ok101: $y = 1959 - 14.3x$, $r^2 = 0.32***$

2137: $y = 2346 - 10.8x$, $r^2 = 0.20***$
Figure 6.

AP502CL

\[ y = 1081x - 4827, r^2 = 0.79*** \]

Custer

\[ y = 975x - 4242, r^2 = 0.74*** \]

Ok102

\[ y = 952x - 3754, r^2 = 0.66*** \]

2174

\[ y = 898x - 3286, r^2 = 0.50*** \]
Figure 6. Effect of pH on forage yield for different winter wheat cultivars. ***$P < 0.001$
Figure 7.
Figure 7. Effect of pH on grain yield for different winter wheat cultivars. ***$P < 0.001$
CHAPTER II
SPATIAL VARIABILITY AND SOIL SAMPLING IN A GRAZED PASTURE

ABSTRACT
Spatial variability in soil test for essential plant nutrients influences how well producers accurately sample their fields for fertilization and compliance with environmental regulations. The objective of this study was to determine the effect of spatial variability on soil test in a pasture system. Soil samples were collected from a 6 ha and a manured 4 ha pasture fields; Site 1 and Site 2 respectively. The experimental sites were subdivided into equal grids and samples were collected using three different sampling methods: grid random (GR), circle random (CR), and single central (SC). All samples were tested for soil pH, organic matter, and plant available N, P, and K. A complete random design (CRD) was used to compute the treatment mean differences among the sampling techniques. Kriging, a geographical information system (GIS) tool, was used to interpolate spatial variability which was quantified with semivariance analysis. Finally, “R” computer program was used to optimize soil subsamples sufficient to form a representative composite sample. Nugget to sill ratio of less 23% in most of the analytes indicated spatial variability. Differences ($P < 0.1$) were found among the different methods of sampling. The technique of soil sampling is crucial in explaining spatial variability of measured soil properties and about 22 soil subsamples are sufficient to form a representative composite sample.
INTRODUCTION

Although soil sampling has been widely studied, there remains room for improving the current sampling methods and procedures in an effort to enhance the precision of samples for agronomic and environmental objectives. Information on soil properties is crucial not only as a guide to nutrient-management decision making, but also in controlling contamination of water resources by nutrients. For example, optimal threshold phosphorus (P) and nitrogen (N) application levels with agronomic and environmental restrictions will be attained only at the highest level of accuracy in soil sampling.

Soil properties vary greatly in space and time due to anthropogenic and natural disturbances (Beckett and Webster, 1971; Starr et al., 1995). Absence of tillage in pastures, as opposed to cultivated fields, (Fisher et al., 1998) and also the irregular deposition of cow dung and urine as observed by Petersen et al. (1956), are some of the causes of soil nutrient variability. This variability could be spatial (i.e., vertical or horizontal), directional, or temporal (James and Wells, 1990). An understanding of soil variability is critical in minimizing sampling errors (Crepin and Johnson, 1993). Soil sample population needed for accurate mapping is dependent on this variability and spatial distribution of the studied variable (Warrick et al., 1986). However, specific quantitative information is lacking for selecting the optimum number of samples needed to quantify soil property with certain spatial variability patterns.

A soil sampling depth of 15 cm is predominantly used in the southern Great Plains (Vadas et al., 2005). This 15 cm depth is mainly critical for cultivated fields as
opposed to pastures where stratification of nutrients is likely to occur close to the surface (Daniels et al., 2001). Sampling depth irregularities may weaken the ability to determine nutrient distribution during soil testing, which is a frustration to nutrient management efforts because it may result in incorrect fertilizer recommendations and other soil fertility concerns (Friesen and Blair 1984; Bolland 1992; Zhang and Johnson, 2000).

Spatial and temporal variability has been blamed for difficulties in choosing the proper sampling method (Brown, 1993). In a pasture setting, besides the natural soil P occurrence and land application of manure and fertilizer, phosphorus variability is caused mainly by animal excretion which influences the irregular nature of nutrient distribution (Fisher et al., 1998). This consequential P variability makes it impractical to treat a pasture field as a single sampling unit (Daniels et al., 2001).

Soil chemical, physical, and biological quality indicators vary from season to season (Wick et al., 2002). For example, in both pastures and cropland, inorganic Mehlich 3 extractable P (M₃₃P) varies between winter and autumn (Magid & Nielsen 1992). A clear understanding of M₃₃P seasonal variability is critical in farm management planning because understanding the temporal variability of soil nutrients acts as guide for soil sampling frequency (Halvorson et al., 1997). Terrestrial temporal phosphorus variability has a direct correlation with P runoff into the streams, particularly in soils with low P sorption capacity (Sims et al., 1998).

Soil sample variability also arises from differences in methods used for sampling. Although surface sampling is usually restricted to 15 cm, some workers may drill their samplers deeper or shallower than others resulting in inconsistent samples. Other differences may occur due to the use of different sampling tools. Heavy clay and stony
sub-soils are only penetrable by auger samplers although such equipment have been
found to cause cross contamination (Brown 1993).

Different workers have personal preferences on the appropriate sampling method
and design. However, the best sampling method should be one that either maximizes
precision at a given cost or specifies precision at the lowest cost (Petersen and Calvin
1986). Some researchers have suggested that deep and shallow sampling is important for
accurate results, however, thorough soil sampling is labor intensive and sampling at two
different levels may result in a higher cost-to-benefit ratio. Brown (1993) observed that it
is typical for organic matter, nitrogen, phosphorus and potassium quantities to decrease
with depth. This phenomenon may result in samples with incommensurately low in
phosphorus and other soil nutrients (Zhang and Johnson, 2000). To avoid this problem
and to avoid possible environmental pollution through over application, information on
sampling depth and the number of subsamples necessary to form a site-representative
composite sample is crucial.

Several methods have been designed to quantitatively assess soil spatial
variability. Semivariance analysis is a geostatistical attribute used in quantifying soil and
plant spatial variability (Solie et al., 1996) by estimating the distance of sample spatial
correlation (Royle et al., 1980). It has been observed that, variables that are close to each
other are similar to each other but become more variable as the separation (lag) distance
increases (Solie et al., 1996). Spatial correlation patterns for soil samples are derived
from the sample semivariogram, where the average variance between neighboring
observations is spatially separated by the same lag distance, (Equation 2.1) (Warrick
1986).
The variables $Z(x_i + h)$ and $Z(x_i)$ are soil property observations at positions $x_i + h$ and $x_i$, respectively, where $h$ is the distance between observations and $N(h)$ denotes the number of pairs of observations separated by the same lag distance ($h$) (Warrick, 1986).

The magnitude of consequences suffered due to non-optimal soil sampling varies from element to element. Without minimizing the importance of other soil properties, P and N are the most limiting nutrients in plant and animal production and their application is necessary to maintain profitable crop and livestock production. For example, beef production earns Oklahoma close to two billion dollars a year (U.S.D.A. National Agricultural Statistics Services, 2005). However, P and N mismanagement may lead to excessive levels in soil and eventually in water bodies. Excessive levels of P and N may in turn cause eutrophication, a process characterized by an enrichment of an ecosystem with chemical nutrients such as compounds containing N or P. In an effort to strike a balance between production and pollution control, state and federal authorities are implementing stringent soil nutrient management controls at the farm level (Needleman et al., 2001). This effort cannot be achieved with limited or faulty information on farmland nutrient status.

Furthermore, the amount of dissolved P and N in runoff increases proportionately as P and N levels increase (Pierzynski et al., 2000); however, there is a need to test the accuracy of sampling strategies based on sampling designs and resolutions. Unfortunately, taking a single composite soil sample from a highly variable site may mislead the producer on soil fertility management decisions based on soil test results.
Non-research related soil sampling generally exhibit lower spatial resolution compared to those of research (Page et al., 2004). Compromise on ideal soil sampling intensity and method is often cost related because most producers are not motivated to send more samples to the lab than they deem necessary (Brown, 1993). Farming in the southern Great Plains of the U.S. is mainly large scale where farm operations are in hundreds to thousands of hectares (U.S.D.A. National Agricultural Statistics Services, 2005). As a result, a cost efficient zigzag sampling pattern has been recommended across the board (Daniels et al., 2001).

Characterization of sampling intensity is essential in determining the optimal number of subsamples necessary for an adequate composite sample because taking a non-optimal number of subsamples from a highly variable area may result in mistakes in soil fertility management decisions. Determining the optimal number of subsamples is critical because there is evidence that the fewer the subsamples, the higher the probability of inaccuracy (Daniels et al., 2001). However, there is not a consensus on the optimal number of subsamples necessary to make a population-representative composite sample to justify decision making.

A minimum of 20 subsamples are recommended in Oklahoma both for pasture and cultivated fields (Zhang and Johnson, 2000). However, this recommendation is only based on nitrogen. Daniels et al. (2001) made a P based sample size recommendation of at least 48 subsamples in contrast to the 20 subsamples generally recommended by the University of Arkansas (Daniels et al., 2000). Friesen and Blair (1984) recommended 40-80 subsamples, while Ball and Williams (1968) suggested a representative composite for P analysis should contain between 37 and 102 subsamples. Because of environmental and
soil fertility factors, soil subsamples should be taken with all the major soil chemical characteristics in consideration.

The objectives of this study were: (i) to quantify soil spatial variability of NO₃-N, M₃P, K, pH, and organic carbon (OC) in manured and non-manured grazed pastures, and (ii) to specifically determine the optimal number soil subsamples needed to form a representative composite sample for the measurement of the above soil characteristics.

MATERIALS AND METHODS

Experimental Site Locations

The experiment was established in the spring of 2006 in six- and four-hectare pasture sites at Jay, Oklahoma (Latitude 36.44°N & Longitude 94.80°W), in Dwight (Fine, smectitic, mesic Typic Natrustolls) soil series (NRCS USDA, 2001) (Fig. 1).

Sites Histories

Study Site 1, which was delineated from a 78 ha pasture with a light cow-calf stocking rate history of one head per four ha over about 10 yr, had not received any chicken litter application but had commercial fertilizers (17:17:17) applied as recommended by soil tests. However, Site 1 had been stocked with about 95 head averaging 250-kg for 14 days in the spring of 2005 and 2006 with no supplemental feed and 70 calves averaging 250-kg heads for 21 days in the fall of 2005 with half their diet coming from supplemental grain. The predominant vegetation on Site 1 was bermuda grass (*Cynodon dactylon* L.).

At the time of sample collection, all the four ha of Site 2 were being grazed of the predominant bermuda grass (*Cynodon dactylon* L.) which was harvested for hay during the last 5 yr. Prior to the last five years, the site was planted in alfalfa (*Medicago sativa*)
for approximately 3 yr. The site has received chicken litter applications for the last 10 years. The grazing system was not experimental at this site.

Site Establishment and Sample Collection

The study was designed to mimic the methods and protocols employed by producers to sample their soils. The two sites were divided into equal grids, measuring 64 x 64 m at Site 1 (resulting in 15 grids) and measuring 30 x 30 m at Site 2 (yielding 23 grids). Soil samples were then collected from each grid at a depth of 15 cm using three different methods: single-central (SC), circle random (CR), and grid random (GR). In the SC method, a single sample was taken at the center of every grid using a soil-sampling auger. In the circle method, 10 subsamples of soil were taken in a circular pattern at a radius of four m around the center of the grid using a JMC soil sampler (Clements Associates Inc., Newton, IA) to form a composite sample. Finally, a composite was formed by combining 15 soil subsamples taken at random from the entire grid area using a JMC soil sampler. Visible dung patches were avoided during sampling.

Laboratory Analysis

Soil properties (M₃P, NO₃-N, K, pH, and OC) were analyzed at the Oklahoma State University Soil, Water, and Forage Analytical Laboratory where soil samples were oven-dried at 65°C for 24 h and ground to pass through a 2-mm sieve (SERA-IEG-6, Southern Extension Research Activity-Information Exchange Group-6, 2001). Soil samples from each grid were analyzed separately. Soil P was extracted with Mehlich 3 (1984) at a ratio of 1: 10 (SERA-IEG-6, Southern Extension Research Activity-Information Exchange Group-6, 2001). It was then analyzed colorimetrically using a Quickchem 8000 automated flow-injection analyzer (Zellweger Analytics, Milwaukee,
WI), which was also used to analyze NO$_3$-N. Nitrate N (NO$_3$-N) was extracted with 1.0 M KCl with a shake time of 30 min (Mulvaney, 1996). Plant available potassium was extracted using Mehlich 3 extraction solution and analyzed using inductively coupled plasma-atomic emission spectroscopy (ICP-AES) (Spectro Ciros, Fitchburg). The soil pH was measured with a combination glass electrode in soil suspension containing 1:1 soil to di-ionized (DI) water (Thomas, 1996). Organic carbon was determined by dry combustion using a LECO CN 2000 (LECO Corporation, St. Joseph, MI) (Nelson and Sommers, 1996).

Standard reference samples from North American Proficiency Testing Program (NAPTP) were analyzed for quality assurance and quality control of M$_3$P, NO$_3$-N, K, soil pH, and OC. Reference samples were evaluated every ten samples with control limits set by NAPT.

**Data Analysis**

Geostatistical analysis was used to describe spatial variability while conventional statistics were used to compare the means of different samples from different sampling methods. Soil sampling grids were first digitized as polygons, then the soil test information were degitized as points within the polygons in Arcmap-Arcinfo software version 9.1 (ESRI Inc. Redland, Ca) a geographical information systems (GIS). The estimated soil characteristic value digitized at the center of the grid was assumed to be distributed within the entire grid area. Kriging, a geostatistical tool, was used in data interpolation (Equation 2.2) where the value of variable $Z$ at an unsampled location $x_0$, $Z^*(x_0)$ was estimated based on the data from the surrounding locations, $Z(x_i)$.

$$Z^*(x_0) = \sum_{i=1}^{n} w_i Z_i(x_i)$$

[2.2]
The variable \( w_i \) are the weights assigned to each \( Z(x_i) \) value, and \( n \) is the number of the closest neighboring sampled data points used for estimation (Warrick et al., 1986).

A semivariance analysis was conducted to quantify the spatial dependence by using the resulting nugget and sill in computing a nugget:sill ratio to classify levels of spatial variability in each soil characteristic (Isaaks and Srivastava, 1989). A nugget to sill ratio of less than 25% implies strong spatial variability, a ratio between 25 and 75% implied moderate spatial variability and greater than 75% is considered weak spatial variability (Cambardella, 1994). It should be noted that the use of Kriging methods for data interpolations requires the data to be normally distributed (Sepskhhah et al., 2004). Therefore, prior to GIS analysis, data were tested for normality using the Shapiro–Wilk test (Royston, 2005) in PC SAS Version 9.2 (SAS Inst., Cary, NC).

The optimal number of soil subsamples required for a single representative composite sample was determined by systematically selecting all possible samples, without replacement, of a particular size from the total number of soil samples from each site. A computer program in the R Version 2.3.1 language using nested loops was written to select all possible samples of sizes 2 through 15 from Site 1 and sizes 2 through 23 from Site 2 (Nansen et al., 2005). The mean of a given soil characteristic value was calculated for each sample of subsamples, and for each sample size, the mean, standard deviation, minimum, and maximum was calculated.

A second method referred to as the “Alternative” method was employed to verify optimal soil subsamples sufficient for a representative composite. First M_3P standard deviation (SD) was regressed against the number soil subsamples to obtain equation 2.3. The first derivative (Equation 2.4) of equation 2.3 was then determined and the first order
conditions were solved by setting equation 2.4 to “t” then solved for X as shown in equations 2.4 to 2.6.

\[ M_3P \text{ SD (}X\text{)} = \beta_0 + \beta_1 X + \beta_2 X^2 \]
\[ f'(X) = 2\beta_2 X + \beta_1 \]  
\[ 2\beta_2 X = t - \beta_1 \]  
\[ X = (t - \beta_1)/2\beta_2 \text{ subamples} \]

Where:  \( \beta_0 = \) a constant  
\( X = \) number of soil subsamples  
\( t = \) change in standard deviation of a soil characteristic value corresponding with 5% of the field mean  
\( \beta_1, \beta_2 = \) coefficients to be estimated

This means that the optimum number of subsamples was obtained when the change in standard deviation (SD) for a particular soil characteristic was within 5% of the mean (Equation 2.6).

To discriminate between soil sampling methods (SSM), 3 grids were randomly selected and analyzed for the SSM differences. Each of the 3 grids was treated as replication; SSM was the treatment, and soil characteristic values was the response variable. The experimental design was a complete randomized design (CRD) where analysis of variance (ANOVA) procedures with PROC MIXED in PC SAS was used in data analysis. Population variability, MAX and MIN of various soil characteristic values from each SSM were generated using PROC UNIVARIATE and PROC TTEST was used to obtain real differences between coefficients of variability for the three SSMs.
RESULTS AND DISCUSSIONS

Spatial variability

Spatial variability for some of the soil characteristics was observed at Site 1 (Table 1). A nugget to sill (NS) ratio of 23% was found for NO$_3$-N, and 0% for M$_3$P, K, and OC (Table 1). This implied that except for pH, which had an NS ratio of 144%, all soil characteristics displayed strong spatial variability at this site. This spatial characteristic could also be observed in spatial maps (Figure 2) where levels of specific soil characteristics were randomly distributed across the entire pasture. Spatial variability of soil characteristics at Site 2 was also observed and had some similarities to that of Site 1 (Table 1). The NS ratio for P, K, and OC were less than 25% at 0%, 21%, and 5% respectively. Nitrogen and pH gave ratios of 96 and 500% respectively therefore putting them in the “weak” spatial variability category.

At both sites “hot spots” of every soil characteristic except pH were observed (Figure 2). Besides, the probable effect of uneven fertilizer and chicken litter application at Site 1 and 2 respectively, this variability may have been influenced, probably caused by decomposed cow dung as observed by Page et al. (2004). Because cow dung and urine contain several nutrients such as N, P and K, and organic matter (in the solid portion), it was no surprise that P “hot spots” corresponded with those of OC and K to a certain degree. Cows have been observed to prefer shaded areas for both shade, in hot periods, and shelter (Lyons and Machen, 2001). The NW corner of Site 1, which exhibited somewhat elevated levels of P, K and OC was populated with Eastern Red Cedar trees. Similar observation was made for N vs. K vs. OC (Figure 2), although without trees, this site had cattle drinking water located to the south of the pasture. A
significant correlation was found between OC and M$_3$P levels at Site 1 ($P < 0.001$, $r^2 = 0.63$) and at Site 2 ($P < 0.001$, $r^2 = 0.45$) (Fig. 3). This strengthened the probable cause of nutrient elevation spots.

**Comparison of Soil Sampling Methods (SSMs)**

Due to the previously described spatial variability, differences ($P < 0.10$) were found at both sites between GR, CR and SC SSMs for M$_3$P, soil test K, pH, and OC (Table 2). With the exception NO$_3$-N, the greatest soil characteristic values were obtained with GR and smallest values with the SC SSM. This means that these two methods had the biggest differences. This was important because it provided the basis for contrasting between taking a single soil subsample versus several subsamples to make a representative composite. Since a single subsample is associated with high sampling error (Fig. 4), it implies that the underlying risk of taking a single subsample would be in underestimating soil analysis lab results.

Nitrate nitrogen was found to be the same in all three SSMs. Because of soil N mobility both laterally and vertically, it may be that N was almost evenly distributed at this site resulting in limited variability responsible for SSM differences. An N: S ratio of N at this site was 24 which was close the borderline (25%) for explaining spatial dependence.

All soil test characteristics, including N, exhibited SSM differences ($P < 0.10$) at this site as well (Table 2). However, there was no consistency in the SSM generating extreme means even though the SC method was always at one extreme or the other. This can be construed to mean that there is always a probability that taking a single soil
sample will always be significantly different from taking either a few subsamples at the center of the plot, or randomly sampling the whole field.

At both sites the method of soil sampling resulted in different (P < 0.1) grid-to-grid coefficient of variation (CV) in all soil characteristic values, except for pH at Site 1 and N at Site 2 (Table 2). In all cases where these differences were observed, the GR method demonstrated the lowest variability which was taken to mean that more subsamples collected resulted in a better composite sample.

Differences in CV at the two sites implied that there was risk of loosing information on some of the soil test characteristics depending on SSM (Table 2). The significantly smaller CV generated by the GR method in all soil characteristics at both sites is an indication of lag distance effect. Because of sampling too close between two grids, there seems to be a grid to grid influence, which could be caused by P running off to the neighboring grid and thus lowering the variance. Conversely, the further away from the grid edge and closer to the center the sample was taken, the more the CV values appeared to decline.

**Determination of Optimum Number of Soil Subsamples**

The most important question following the determination of the best soil sampling method is determining the optimum number of soil subsamples needed to make up a representative sample. Taking fewer than optimal subsamples may result in misinformation, while taking more subsamples than necessary is inefficient.

The standard deviation (SD) of the predicted $M_3P$ level based upon at least 12 samples was within 5% of the known $M_3P$ at both Site 1 and Site 2 using 15 and 23 sampling soil subsamples, respectively (Fig. 4). Similar findings were made for all the
other soil characteristics (Table 3). As the number of sampled subsamples increased, corresponding soil characteristic variability decline as described in classical statistical theory (Starr et al., 1995) increasing the ability to estimate the number of soil subsamples sufficient to make a representative composite sample (Fig. 4). The high soil characteristic SD depicting variability at lower numbers of sampling subsamples was an indication that the lower the sampling resolution the higher the likelihood of giving misleading information of soil status. For example, on Site 1, by collecting a single sample there is an equal chance that it will be either 35 or 75 mg kg$^{-1}$ P. The lower extreme, 35 mg kg$^{-1}$, is above the agronomic threshold of 50 mg kg$^{-1}$ for Bermuda grass (Zhang and Raun, 2006) and therefore does not call for additional P application; however, it may result in over-application if the only concern is staying below the environmental threshold of 150 mg kg$^{-1}$, which may have devastating environmental consequences.

Using a series of equations (2.3-2.4), the optimal number of soil subsamples to make up a representative composite was verified by evaluating the first derivative of the $M_3$P (Equation 2.5), obtained from the regression of SD and the number of soil subsamples (Fig. 5). There was a significant relationship ($P < 0.001$, $r^2 = 0.93$) between $M_3$P SD and the number of soil subsamples for Site 1 (Fig. 5). Solving the first order conditions, steps 1-4 above, resulted in an optimum of 13 soil subsamples at Site 1, which was the same as that obtained with a systematic method. Similarly, a significant relationship ($P < 0.001$, $r^2 = 0.93$) existed between $M_3$P SD and the number of subsamples. The number of optimized soil subsamples at Site 2 generated from Figure 5 was 19. All the other soil characteristics showed identical results (Table 3).
There was a seven-subsamples difference between the optimal number of subsamples computed in this method and those generated from the systematic method for P on Site 2, when the horizontal lines, denoting variability within the field mean $M_3$P was $\pm 5\%$, was restricted to within $\pm 10\%$. However, the number of subsamples sufficient for a representative composite decreased to approximately 4 for P on Site 2 (Table 3) indicating that the more conservative the soil sampling regime is, the more samples are required to form a representative composite.

There no observable the need for higher numbers of soil subsamples when the soil test P level was less than 150 mg kg$^{-1}$ or fewer subsamples when soil test P level was greater than 150 kg ha$^{-1}$ as observed by Daniels et al. (2001). At both sites P-based soil sampling appeared to be sufficient at 12 subsamples with the $\pm 5\%$ error margin. However, the “alternative” method (Figure 5) seemed to agree, at least in trend, with Daniels et al. (2001) (Table 3). Using this method, 13 soil subsamples appeared adequate to make representative subsamples at lower soil test P and 19 subsamples at the site with higher soil test P.

**CONCLUSION**

Spatial variability was found in both manured (Site 2) and non-manured (Site 1) pastures. Since a good correlation ($r^2 > 0.40$, $P < 0.001$) was found between P and organic matter, fertilizer application and animal excreta may have been responsible for the spatial variability, especially at Site 1. However, variability could also have been caused by litter application. To obtain a representative soil sample, sampling at random in a pasture is superior to either taking one subsample at the center of the field, or taking samples around a circle at the center of the field. Since the optimal number of subsamples
was found to differ across soil characteristics and between low and high nutrient environments, the greatest predicted number of representative subsamples is recommended. This was found to be 22 subsamples, which is in agreement with the 20 subsamples recommended by the State of Oklahoma. However, this could differ if a higher error rate were allowed, for example ±10% in place of ± 5% (Table 3).
REFERENCES


Table 1. Semivariance statistics for five soil properties: Nitrogen (NO$_3$-N), phosphorus (M$_3$P), soil test potassium (STK), soil pH, and organic carbon (OC) at Sites 1 and 2.

<table>
<thead>
<tr>
<th>Property</th>
<th>Nugget</th>
<th>Sill</th>
<th>N:S ratio$^1$ (%)</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_3$-N (g kg$^{-1}$)</td>
<td>1.3</td>
<td>5.54</td>
<td>24</td>
<td>100</td>
</tr>
<tr>
<td>M$_3$P (g kg$^{-1}$)</td>
<td>0</td>
<td>5900</td>
<td>0</td>
<td>109</td>
</tr>
<tr>
<td>STK (g kg$^{-1}$)</td>
<td>0</td>
<td>9247</td>
<td>0</td>
<td>183</td>
</tr>
<tr>
<td>Soil pH</td>
<td>0.13</td>
<td>0.09</td>
<td>144</td>
<td>138</td>
</tr>
<tr>
<td>Soil OC g kg$^{-1}$)</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
<td>139</td>
</tr>
<tr>
<td><strong>Site 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_3$-N (g kg$^{-1}$)</td>
<td>4.03</td>
<td>4.22</td>
<td>96</td>
<td>260</td>
</tr>
<tr>
<td>M$_3$P (g kg$^{-1}$)</td>
<td>0</td>
<td>556</td>
<td>0</td>
<td>260</td>
</tr>
<tr>
<td>STK (g kg$^{-1}$)</td>
<td>168</td>
<td>784</td>
<td>21</td>
<td>239</td>
</tr>
<tr>
<td>Soil pH</td>
<td>0.06</td>
<td>0.012</td>
<td>500</td>
<td>250</td>
</tr>
<tr>
<td>Soil OC g kg$^{-1}$)</td>
<td>1.76</td>
<td>35.2</td>
<td>5</td>
<td>260</td>
</tr>
</tbody>
</table>

$^1$N:S is the nugget to sill ratio
Table 2. Comparison of five soil properties: NO$_3$-N, Mehlich 3 P (M$_3$P), K, pH, and organic carbon (OC) among methods of soil sampling at Site 1 and 2 including the min, max, and coefficient of variability (CV) of soil test values for various characteristics.

<table>
<thead>
<tr>
<th>Element</th>
<th>Treatment</th>
<th>Site 1</th>
<th>Site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO$_3$-N (mg kg$^{-1}$)</td>
<td>Grid Random (GR)</td>
<td>12a 8.0 16.5 23.7a</td>
<td>8.0a 4.0 14.0 33.7a</td>
</tr>
<tr>
<td></td>
<td>Circle Random (CR)</td>
<td>9.0a 5.50 21.0 40.4b</td>
<td>6.0b 2.50 10.0 34.3a</td>
</tr>
<tr>
<td></td>
<td>Single Central (SC)</td>
<td>10.0a 6.0 23.5 46.1b</td>
<td>12.0a 3.0 19.5 28.0a</td>
</tr>
<tr>
<td>M$_3$P (mg kg$^{-1}$)</td>
<td>GR</td>
<td>97a 43 136 17.7a</td>
<td>376a 302 588 28.4a</td>
</tr>
<tr>
<td></td>
<td>CR</td>
<td>76a 36 104 26.5b</td>
<td>368a 85.0 391 39.0a</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>47b 24 56 27.4b</td>
<td>280a 242 742 40.3c</td>
</tr>
<tr>
<td>K (mg kg$^{-1}$)</td>
<td>GR</td>
<td>186a 131 225 16.0a</td>
<td>306a 125 467 36.0a</td>
</tr>
<tr>
<td></td>
<td>CR</td>
<td>159b 113 210 17.0a</td>
<td>368a 85.0 391 39.0a</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>104c 82.0 241 33.0b</td>
<td>193b 80.0 879 64.0b</td>
</tr>
<tr>
<td>pH</td>
<td>GR</td>
<td>6.3a 5.90 6.6 2.90a</td>
<td>6.3a 5.90 6.6 2.90a</td>
</tr>
<tr>
<td></td>
<td>CR</td>
<td>6.0a 5.70 6.5 4.0a</td>
<td>5.4b 5.2 6.8 5.4ab</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>5.8ab 5.50 6.6 4.60a</td>
<td>6.5a 4.9 6.9 6.8b</td>
</tr>
<tr>
<td>OC (g kg$^{-1}$)</td>
<td>GR</td>
<td>25.0b 14.0 32.0 25.0ab</td>
<td>25.0b 14.0 32.0 25.0ab</td>
</tr>
<tr>
<td></td>
<td>CR</td>
<td>19.0a 11.0 24.0 21.0a</td>
<td>21.0a 11.0 31.0 31.0b</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>21.0a 11.0 31.0 31.0b</td>
<td>21.0a 11.0 31.0 31.0b</td>
</tr>
</tbody>
</table>

‡Means with the same letter within a column are not significantly different (P < 0.1)
§Coefficient of variation (CV) followed by the same letter within a column are not significantly different (P < 0.1)
Table 3. A summary of the number of soil subsamples requirement to form a composite sample computed from “R” computer program based on different soil characteristics. The 5% and 10% are the percentage errors allowed within the means (as illustrated in Figure 4 in M3P example).

<table>
<thead>
<tr>
<th></th>
<th>10%</th>
<th>5%</th>
<th>Derived*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>9</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>P</td>
<td>8</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>K</td>
<td>6</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>pH</td>
<td>&gt;15</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>OC</td>
<td>6</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Site 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>15</td>
<td>22</td>
<td>18</td>
</tr>
<tr>
<td>P</td>
<td>4</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>K</td>
<td>16</td>
<td>21</td>
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</tr>
<tr>
<td>pH</td>
<td>15</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td>OC</td>
<td>3</td>
<td>8</td>
<td>18</td>
</tr>
</tbody>
</table>

*Values obtained by determining the first derivative of equation 2.3
Figure 1. An aerial map projecting experimental sites in Jay, Oklahoma and the grid divisions.
Figure 2.
Figure 2. Soil properties’ spatial variability at two Sites (1 and 2) in Jay Oklahoma. The contour maps were interpolated by Kriging.
Figure 3. Relationship between Mehlich 3 P (M$_3$P) and organic matter at experimental Sites 1 and 2, *** $P < 0.001$
Figure 4. Relationship between number of samples collected and soil phosphorus (M₃P) level estimate in two farms in (Site 1) southern and (Site 2) northern Jay Oklahoma. For each number of samples, we calculated the M₃P level for all possible combinations of samples. Error bars denote standard deviation, and horizontal lines denote ±5% of the field mean M₃P level (based on all samples collected in the entire field). Similar figures were generated for other soil characteristics and the results summarized in Table 3.
Figure 5. Change in $M_3$P standard deviation (SD), generated by “R” computer program, with change in soil sub-samples. An illustration of an alternative method for deriving the number of sub-samples necessary to make a composite sample, *** $P < 0.001$

$y = 0.43x^2 - 16.6x + 174, r^2 = 0.93^{***}$

$y = 0.13x^2 - 4x + 25, r^2 = 0.93^{***}$
CHAPTER III

THE RESPONSE OF DUAL-PURPOSE WINTER WHEAT TO PHOSPHORUS RATES AND APPLICATION METHODS IN AN ACID SOIL

ABSTRACT

Over 49% of total wheat in Oklahoma is produced with dual-purpose (DP) intentions where wheat forage is grazed in the fall through spring and grain harvested at maturity. Since this is a relatively new system, there is no existing data on fertilizer requirement and the best phosphorus fertilizer application method. This study was established in 2005 and 2006 at Marshall, Oklahoma on 240 plots to determine the phosphorus requirements for DP winter wheat, and to compare the response to furrow and broadcast P application methods. Soil samples were collected prior to planting and analyzed for Mehlich 3 extractable phosphorus (M3P), pH and aluminum. The experimental plots were grouped into 3 pH categories (i.e., pH < 4.8, 4.8 ≤ pH < 5.0, and ≥ 5.0) and each pH categories sub-divided into 5 M3P categories each of which received one of the eight P treatments (0, 12, 24, 36, 48, 60 kg ha⁻¹, 0 + lime, and 24 + lime) either in furrow or broadcasted. Fall forage yield was harvested by hand clipping and grain was combine harvested in June of each year. Response surface methodology and PROC MIXED were used in SAS for statistical analysis. Forage yields for 2005 increased with increasing P application...
rates under furrow and broadcast methods of P application. At the same time, yields
differences (P < 0.1) were found between the two methods of P application with the
furrow method having a higher return to P than broadcast. A new forage P application
curve was developed that has higher P recommendation than the currently existing one
based on grain yield. Furrow method of P application is more economical than the
broadcast method.

INTRODUCTION

Dual-Purpose Winter Wheat

The dual-purpose (DP) winter wheat production system involves both grazing
wheat forage during its vegetative stage in late fall through mid spring and harvesting
grain at maturity. The use of the DP production systems is increasing in Oklahoma with
49% of total wheat planted with DP intentions (Hossain et al., 2004). This system allows
farmers to increase their income from the sale of stocker cattle grazed on wheat forage
and grain harvested from the same field (Pinchak et al., 1996). Winter wheat is an
excellent cool season forage for Oklahoma’s 1.4 billion dollars beef cattle industry (Rao
et al., 2000).

Maximum forage production can be achieved by planting dual-purpose wheat
earlier than grain-only wheat (Epplin et al., 2000). This early planting date gives
producers an opportunity to graze their wheat fields before the first hollow stem growth
stage (Krenzer, 2000), thus optimizing forage and grain yields. The negative impacts on
grain production associated with grazing past the hollow stem stage has been extensively
studied (Redmon et al., 1996; Hossain et al., 2003).
Wheat P Requirements

Crop fertilizer P recommendations may be determined by knowing soil test P and the optimum P requirement for the crop (Kamprath and Watson, 1980). Wheat responds positively to P application at Bray-1 soil test P of $\leq 22$ mg kg$^{-1}$ (McCallister et al., 1987). At Bray-1 P of $22$ mg kg$^{-1}$ and above, it is uneconomical to apply P for barley (Nyborg et al., 1999). The Oklahoma State Soil Testing Laboratory does not recommend P application to wheat at Mehlich 3 P (M3P) of $\geq 32.5$ mg kg$^{-1}$ (Zhang and Raun, 2006). However, factors such as the chemistry of the soil may dictate the level of P application. For example, wheat producers in the State of Oklahoma commonly apply phosphate both for nutritional purpose and ameliorating soil acidity.

Current P recommendations for wheat were developed for grain-only production systems, thus there is a need for more precise P recommendation for DP wheat production or in low pH soils. It is likely that DP wheat requires different amount of P (Kariuki, 2003) and pH management from that of grain-only or full season forage wheat production systems.

Forage yield has previously been used as a response factor in phosphorus calibration studies for wheat forage (Goedeken et al., 1998; Kariuki, 2003). In spite of the reported strong correlations between forage yield and NDVI readings (Raun et al., 2001; Phillips et al., 2004), no data exist for P requirements determination using NDVI as the response factor.

Wheat P Requirement Methodologies

Crop yields respond to increasing soil P in a curvilinear manner where maximum yield plateau is achieved when P is no longer a limiting factor to plant growth (Hedley et
Several models to predict P requirements have been proposed. Examples include: (a) the Mitscherlich-Bray model: \( Y = A (1 - e^{-cx}) \)  
(b) Quadratic model \( Y = A + Bx + Cx^2 \)  
(c) Logarithmic model \( Y = a + b \log x \)  
(d) Sigmoidal model \( Y = a/(1 + bcx) \) where \( 0 < c < 1 \) and  
(e) the Linear-plateau model \( Y = A + Bx \), where \( x = 1 \), if \( x \) is above the critical level and where \( x = < 1 \) below critical level (Hedley et al., 1995). However, the use of the full quadratic model, which analyzes P requirements relative to soil test P all in the same equation, has not been given enough attention (Kariuki, 2003).

**Relationship between Soil Acidity and phosphorus Chemistry**

Soil acidity is a major limiting factor in crop production worldwide because of the solubilization of aluminum at low pH (Mariano and Keltjens, 2003) making it available to precipitate P in the soil. Chen and Barber (1990a) observed that KCl extractable Al increased 3 fold with a pH change from 4.7 to 3.8. High levels of soluble Al harm plants by root pruning and reduced nutrient and water uptake (Chen and Barber, 1990b).

Phosphorus deficiency has been associated with Al phytotoxicity (Foy, 1988). Phosphate is available to plants as orthophosphates (\( \text{H}_2\text{PO}_4^- \) and \( \text{HPO}_4^{2-} \)) and the speciation of orthophosphate is pH dependant (Lindsay and Moreno, 1960). The \( \text{H}_2\text{PO}_4^- \) species is predominant at pH < 6.5 while \( \text{HPO}_4^{2-} \) is abundant at pH > 6.5 (Chen and Barber, 1990b). The \( \text{H}_2\text{PO}_4^- \) species has been found to be more readily available to plants (Chen and Barber, 1990b) and is absorbed by maize roots 10 times faster than \( \text{HPO}_4^{2-} \). Orthophosphates are, however, weakly soluble anions. They react with Al to form variscite (\( \text{AlPO}_4 \cdot 2\text{H}_2\text{O} \)), and with Fe to form strengite (\( \text{FePO}_4 \cdot 2\text{H}_2\text{O} \)) in low pH soils. Strengite is less soluble than veriscite at all pHs and dominates solubility and thus
availability of P up to about pH 5.5. Above pH 5.5 orthophosphates react with Ca to form Ca phosphate and eventually fluoroapatite (\(\text{Ca}_{10} \text{H}(\text{PO}_4)_6\text{F}_2\)), the least soluble phosphate form (Bohn et al., 2001). Harrison and Adams (1987) found a positive correlation between P solubility and pH up to about pH 5.8. Above this pH, the correlation was negative, perhaps due to the accumulation of hydroxyapatite. According to Ro and Cho (2001), phosphate precipitates Al in acid soils. This results in an insoluble complex, which causes an increase in pH due to a decrease in monomeric Al in soil solution. High levels of aluminum in low pH soils may dictate the need for additional P beyond the current P recommendations for DP wheat due to adsorption or precipitation of P by Al and Fe (Foy, 1988).

**Fertilizer Application Methods (Broadcasting vs. Furrow)**

To minimize the effect of Al toxicity on wheat production, application of P in the furrow with the seed may increase P availability to the plant before it precipitates. However, conflicting views exist in literature regarding the appropriate method of fertilizer P application. Phosphorus is known to be immobile in the soil and so it’s proximity to the plant’s roots is of great importance because the amount available for plant uptake is limited to the concentration at the root-soil interface (Zhang and Raun, 2006). As a result, furrow application as opposed to broadcasting P application has been found to cause an increase in alfalfa yields, however, the furrow application effect is more evident at lower P application rates than high ones (Malhi et al., 2001). At high P application rates there is no apparent difference between furrow and broadcast methods. In soils with pH below 5.5, P uptake is reduced due to poor root growth associated with Al toxicity (Foy et al., 1999). Ron and Loewy (2000) found that furrow applied P resulted
in superior wheat grain yield as compared to broadcast P application method. Boman et al. (1992) found that at a pH of 4.8, P furrow application was superior to broadcast application for both forage and grain yields of winter wheat. However, their work was from one site year and M₃P was above Oklahoma’s critical sufficiency level of 32.5 mg kg⁻¹.

Since Al immobilizes P in the soil, higher P fertilizer rates can be used to precipitate exchangeable Al in acid soils. To determine the effect of furrow P fertilizer application on Al solubility in low pH soils, Sloan et al. (1995) simulated furrow P application technique in a laboratory experiment. They found an increase in Al-phosphate complexes was responsible for reducing Al in soil solution supporting the idea that, the furrow P application is a reliable solution to reduce aluminum toxicity in low pH soils. Long term field fertilization studies established to determine Al³⁺ and PO₄³⁻ activities in the soil revealed that the slight effect of P addition on Al³⁺ reduction was only noticeable at the 20 to 30 cm depth of soil (Hetrick and Schwab, 1992). This suggests deeply applied P reacted with Al more easily and thus was more effective in ameliorating Al toxicity. There is a need to verify these findings in a field experiment with DP wheat.

Phillips et al. (2000) reported that forage yield increased using furrow application as compared to broadcast at 29 and 58 kg P ha⁻¹. Furrow P application increased grain yield as compared to BPA at 29 kg P ha⁻¹ rate but no difference in grain yield was found between the two methods at application rates of 58 kg P ha⁻¹. Their study involved determining the long term availability of P by furrow application with gypsum. However, their experimental site was on a non-acidic soil. The benefits of furrow application of P in acid soils remain to be studied. Kaitibie et al. (2002) reported that furrow application
resulted in higher forage yields than those of broadcast but grain yields were not
dependent on application methods.

The technique of applying P in the furrow has not always been found superior to
other methods. Liekam et al. (1983) observed that, even though method of application
had no impact on winter wheat grain yield, knife application of P resulted in higher yields
and higher plant P concentration than broadcast application. Halvorson and Havlin (1992)
observed that grain yield increased as P rates increased. However, they found no
difference in forage yields due to P application methods. This observation was supported
by Gelderman et al. (2002) who found that, even though cool season grass responded to P
application, methods of P application did not influence forage yield.

Studies have shown that furrow application of P with seed increased forage and
grain yield (Boman et al., 1992; Hetrick and Schwab, 1992; Phillips et al., 2000). Other
studies have concluded that furrow application offers little or no advantage (Halvorson
and Havlin, 1992; Liekam et al., 1983; Gelderman et al., 2002). Because of these
contradictory findings on grain and forage yield response to furrow application of P, there
is a need for further investigation of the effects of broadcast versus furrow application for
DP wheat production system. Most of these studies were carried out in favorable soil pH
or soil test P environments. It is unclear how effective furrow application of P would be
in low pH and P deficient conditions.

**Economics of P Application Method**

Phosphate is effective in reducing the impact of low pH in wheat production;
therefore it is more economical to control Al toxicity by applying phosphate fertilizer in
the furrow when cost of lime is considered only on the year of application (Kaitibie et al.,
2002). However, when cost of lime is amortized over a period of five years higher returns to cost of wheat production are obtained when lime is applied with diammonium phosphate in the furrow (Kaitibie et al., 2002). Other studies have shown that liming of low pH soils is more economical than other methods of controlling Al toxicity in wheat forage and grain production (Zhang et al., 2004). Though both of these studies concluded that producer cost was recovered it is not clear which of the two would result in higher returns to P.

DP wheat production system is important for Oklahoma wheat producers (Hossain et al., 2004; Pinchak et al., 1996). However, limited information exists on the optimum P levels and the true benefits of method of application in DP wheat production system. Some wheat producers use P instead of lime to correct soil acidity. However, its chemical and economical effectiveness are not well documented.

**Objectives**

1. To evaluate phosphorus requirement for dual-purpose wheat in comparison with current calibration developed for grain-only;

2. To study the production and economic differences of dual-purpose wheat response to furrow and broadcast application of P.

**MATERIALS AND METHODS**

**Site Selection and Soil Sampling and Analyses**

The experiment was established in the fall of 2004 at Marshall, Oklahoma (Latitude 36°9’20”N & Longitude 97°37’30”W), in Mulhall (Fine-loamy, siliceous, thermic Udic Paleustoll) soil series (NRCS USDA, 2001). The site was selected because
of its relatively low soil pH (mean pH < 5.0) and extractable soil Mehlich 3 P (M₃P) (27 mg kg⁻¹) and the experiment was conducted for two growing seasons. Two hundred and forty plots of 1.5 x 6.0 meters were used. Following M₃P and pH laboratory analysis, the plots were grouped into three pH categories (pHcat) of 80 plots each as follows: pHcat one (pH < 4.8), pHcat two (4.8 ≥ pH < 5.0) and pHcat three (≥5.0). Each of the three pH categories was sub-divided into five M₃P categories (M₃P cat) with approximate means of, 23, 26, 30, 32.5, and 35 mg kg⁻¹ for a total of 16 plots per M₃P cat per pH category (Figure 1).

**Laboratory Soil Analysis**

A composite soil sample was collected from each plot and analyzed for pH, exchangeable Al, and M₃P. The soil pH was measured with a combination glass electrode in soil suspension containing 1:1 soil to di-ionized (DI) water (Thomas, 1996). Phosphorus was extracted using Mehlich 3 extractant (Mehlich, 1984) and quantified with a flow-injection auto-analyzer using the ascorbic acid method. One molar NH₄OAc was used to extract K, Ca, Mg and Na (Warncke and Brown, 1998) while 1 M KCl was used to extract exchangeable Al (Bertsch and Bloom, 1996). Their concentrations were then determined by inductively coupled plasma –atomic emission spectroscopy (ICP-AES). In both years, soils were pre-plant and post-harvest sampled and analyzed in the Soil Forage and Water Analytical Laboratory (SWFAL) of Oklahoma State University.

**Treatment Application**

Application rates of granulated triple super phosphate (TSP) were 0, 12, 24, 36, 48, and 60 kg P ha⁻¹. The 16 plots were split with 8 plots receiving TSP in a furrow and the other 8 plots were randomly broadcast with TSP. Additional treatments included
broadcast liming of the 0 and 24 kg P ha\(^{-1}\) treatments at a rate of 405 kg ha\(^{-1}\) as effective calcium carbonate equivalent (ECCE) (Zhang and Raun, 2006). (Figure 1). Lime was incorporated by rototilling.

For the broadcast treatment, phosphate was incorporated before planting while in the furrow application; phosphate was applied in the seed furrow during planting. Lime was broadcasted at a rate of and incorporated using a rototiller. Care was taken to ensure all other essential nutrients were in adequate levels and necessary agronomic practices observed.

Kaitibie et al. (2002) reported that an Al susceptible variety is more responsive to lime than resistant ones. However, in spite of access to commonly grown winter wheat Al susceptible varieties, none of them was tolerant to high temperature germination thus we seeded the plots with a discontinued variety, ‘2158’, which is susceptible to Al toxicity as well as having high temperature germination tolerance (E.G. Krenzer, 2004, personal communication). Planting occurred in early September 2004 and 2005 at a seeding rate of 67 kg ha\(^{-1}\) and a row spacing of 17.5 cm (Royer et al., 2005).

**Forage and grain harvest, and NDVI readings**

In the first week of November 2004 and 2005, at feekes 5 growth stage, forage biomass was scanned with a hand held green seeker to obtain NDVI readings and then harvested by hand clipping to the soil surface from two one-meter row segments within each plot. The remainder of the plot was mowed for uniformity. The harvested forage was oven-dried for 3 d at 105° C before measuring dry weights. Grain was harvested with a plot combine in June of 2004 and 2005 from an area of 1.5 x 4.5 meters of each plot and then weighed in a digital scale.
Experimental Design and Statistical Analysis

(1) Phosphorus Placement Method Comparison

A randomized complete block design (RCBD) was used in split-split-split plot design where three pH categories were treated as the main plot, five M3P categories as the sub-plot. The two methods of placement, BPA and FPA, were the sub-sub-plot and eight P application rates were the sub-sub-sub-plot (Figure 1).

A single plot, the smallest unit of experimental material to which a treatment was allocated independently of all other units was the experimental unit. Each plot was unique and therefore there were no “true” replications. Significant treatment differences for wheat grain and forage yield and P treatments at varying pH levels were determined using analysis of variance and the suitable contrasts (TS2MO version 8.2; SAS Inst., 2001).

(2) Determination of Dual-purpose Wheat P Requirement

Response surface methodology, which involves optimization of a specified response factor (Little and Hills, 1978) to applied treatments, was employed to determine P requirements. The resulting analysis of variance procedure from the regression output (TS2MO version 8.2; SAS Inst., 2001) was used to estimate the parameters in equation.

\[
Y(\text{estimate}) = f (P, M_3P) = \alpha + \beta_1P + \beta_2P^2 + \beta_3 M_3P + \beta_4 M_3P^2 + \beta_5 P^* M_3P \tag{3.1}
\]

where:

\[
Y = \text{Yield or NDVI}
\]

\[
\alpha = \text{intercept estimate}
\]

\[
\beta_1 = \text{P}_2\text{O}_5 \text{linear coefficient}
\]
\( P = \text{linear input estimate of } P_2O_5 \)

\( \beta_2 = P_2O_5 \text{ quadratic coefficient} \)

\( P^2 = \text{quadratic estimate of } P_2O_5 \)

\( \beta_3 = \text{Mehlich 3 Phosphorus (M3P) coefficient} \)

\( M_3P = \text{linear estimate of M3P} \)

\( \beta_4 = M_3P \text{ quadratic coefficient.} \)

\( M_3P^2 = \text{quadratic estimate of M3P.} \)

The full quadratic model was fitted and the equations inspected for non-significant terms. A \( P \) value of 0.1 significance level was used to determine significance of each variable. To arrive at the best fitting model, the concept of backward elimination and stepwise regression were applied (Ott, 1993). Backward elimination was used by first fitting a full quadratic equation then removing the non-significance variable with highest \( P \) value and refitting the model. However, differentiation of the resulting full quadratic equation with respect to applied \( P \) resulted in equation 3.2.

\[ Y_1 = \beta_1 + 2 \beta_2 P + \beta_3 M_3P \quad [3.2] \]

Other models of wheat \( P \) requirements determination were analyzed to justify the response surface model results. The 180 plots that did not receive lime were categorized into six \( M_3P \) based average classes, each containing all the six levels of \( P \), to mimic six unique producers’ fields. The quadratic method was then used to determine the level of \( P \) where yield was maximized in each “field” based on either broadcast or furrow applied \( P \). Differentiating the resulting equation in each field’s yield versus \( P \) rate and solving for the first order conditions, representing optimal \( P \) rate, accomplished this. These optimal \( P \) rates were the regressed against the six \( M_3P \) levels to give the desired \( P \) application curve.
**Economic Analysis for P Application Method**

Production function, the quantitative relationship between variable inputs and outputs, was used to compare returns to P in furrow vs. broadcast methods. Both 2 and 3 dimensional scenarios were considered; in the three dimensions, both forage and grain yields were used to calculate gross revenue with applied P relative to M₃P as the only variable cost. All other costs were considered fixed in both methods of P application. The multiple regression analysis resulted from equation 3.1 was first differentiated w.r.t. P to obtain the point at which yields were maximized in each method. Return to P was then obtained by multiplying forage and grain yield by 2005 market prices of $0.066 kg⁻¹ and $0.11 kg⁻¹ respectively. Returns to P from the two methods were obtained by subtracting the revenue from P cost of $0.24 kg⁻¹ and then compared.

In the two dimensions, yields were regressed against levels of P inputs at various M₃P levels. The resulting quadratic equation 3.3 of both placement methods were maximized to give the levels of inputs required at maximum yields.

\[ Y \text{ (estimate)} = f (P) = \alpha + \beta_1 P + \beta_2 P^2 \]  \quad [3.3]

The optimal input levels were then calculated by solving for the first order conditions of equation 3.3. These optimal values were then placed in the respective equations to quantify the maximum yield levels for both furrow and broadcast methods.

**RESULTS AND DISCUSSIONS**

**Wheat Forage and Grain response to P application rates**

Mean forage yields for 2005 both under broadcast and furrow application methods displayed a general increasing trend with increasing P application rates (Table
1). Zero P application rate produced 983 kg ha\(^{-1}\) of forage as compared to 1709 kg ha\(^{-1}\) forage for the furrow applied 60 kg ha\(^{-1}\) application rate in 2005. Similarly, the forage yield for the zero P application rate was 921 kg ha\(^{-1}\) and 2139 kg ha\(^{-1}\) for the broadcast applied 60 kg ha\(^{-1}\) in 2005(Table 1). Grain yield for both 2005 and 2006 as well as that of forage for 2006 were not significantly impacted by applied P (P < 0.1) (Table 1). Because P is needed mostly right after germination and during the vegetative stage of the plant than during the reproductive stage (Romer and Schilling, 1986), prediction of wheat P requirement is more accurate using forage as the response factor than grain. Also, unlike with forage, poor grain response to applied P may have been due to the effects of confounding factors as the season progressed. For example, root rot (\textit{Fusarium ssp}) was found to have infected about 30\% of the plots and field bind weed (\textit{Convolvulus arvensis}) invasion was also detected. Although an analysis of covariance (ANCOVA) with root rot as the covariate did not reveal any yield differences (P < 0.1), other environmental factors may have played a part. A severe drought in the 2006 season was blamed for lack of differences among P rates in both forage and grain of that season. Even in a case where differences were found among means for grain yield, with furrow applied P between rates above 12 and below 24 kg ha\(^{-1}\) rates, they were negative, indicating a decrease in grain yield with increasing P application (Table 1).

Mean forage and grain yields for 2005 in the unlimed plots were significantly higher than those of 2006 (1757 vs. 991 kg ha\(^{-1}\) forage under furrow applied and 1474 vs. 1088 kg ha\(^{-1}\) in broadcast applied) (Table 2). It also appeared as if these differences were predominant in P application rates of 36 kg ha\(^{-1}\), although 2005 grain responded to the 60 kg ha\(^{-1}\) P application rate which also presented differences in methods of application.
(Table 1) above which the response to P application somewhat supporting a previous study by Hedley et al. (1995).

However, a continuous yield response to P application was more obvious under different categories of soil pH. At mean pH of 4.7, both grain and forage yields increased until an application rate of 48 kg ha\(^{-1}\) before tapering off (Fig 2A). This trend was observed even in the other pH categories (mean pH = 4.9 and 5.1) in both P application methods even though it appeared to weaken as pH increased (Fig. 2B and C). This behavior could have been caused by soil P demand for low pH amendment and for wheat nutritional need in which case the need of soil amendment subsided as pH increased.

**Furrow vs. Broadcast P Placement Method**

Significant differences (P < 0.1) were found between the two methods of P application for 2005 forage (Table 1). However, as expected, zero P application resulted in the lowest mean forage yield of 983 kg ha\(^{-1}\) in the broadcast application and 921 kg ha\(^{-1}\) in the furrow application method. Also, the lowest application rate of 12 kg ha\(^{-1}\) P yielded 1283 kg ha\(^{-1}\) in the broadcast method and 1525 kg ha\(^{-1}\) in furrow method. Since in both cases, zero P and at 12 kg ha\(^{-1}\) P application, had minimum effect on yield no differences were found between the two methods. With the exception of 2005 forage in un-limed conditions, no differences were found between P application methods for both 2005 grain and 2006 grain and forage data (Table 1). This was contrary to expectations because several workers have documented FPA as superior to BPA method (Boman et al., 1992; Hetrick and Schwab, 1992; Phillips et al., 2000).

As would be expected, a significant interaction (P < 0.1) was found between P application method and pH with a few exceptions, furrow application method resulted in
greater yields as compared to furrow application in all pH categories (Figure 2A-C). However, these differences were more pronounced at an average pH of 4.9. At mean pH of 4.7, P application methods were generally significant at higher P application rates perhaps because lower P rates were not enough to fertilize the wheat and amend the soil regardless of the application method (Figure 2A). Similarly, at pH > 5.0 lack of P application method differences was probably due to lack need for soil pH amendment thus minimizing differences between the two P application methods (Figure 2C).

An analysis of the effect of lime on grain and forage yields in the 2005 and 2006 revealed no significant differences (P < 0.1) between the means yields of limed and the un-limed plots (Table 2). Although lime is the most effective means of controlling soil acidity, this was not the case at this site because even though low pH soil conditions are associated with aluminum toxicity, random investigation of soil samples indicated an aluminum saturation of less 30%, the level beyond which is considered aluminum toxic (Wise, 2002) (Appendix 1).

In the 2005 and 2006 grain data, there was no difference (P > 0.1) between P application methods for the zero application in both the broadcast and furrow methods. This is an indication that there was already enough P in the soil to warrant further P amendment. However, forage data in 2005 exhibited a positive response to fertilization (P < 0.001) and significant differences (P < 0.001) were observed between methods of application. To minimize the influence of M₃P on the effect of applied P, data were analyzed at M₃P and pH environments grouped as category one through five from low to high, and one through 3 respectively.
However, statistical tests revealed no differences (P < 0.1) among different M$_2$P categories. On the other hand, differences (P < 0.001) were found among pH categories which led us to compare the two methods of P application in similar pH environments at each P application rate. In pH category (pHcat) one, furrow application and broadcast application methods showed no differences (P > 0.1) in yield at 12 kg ha$^{-1}$ P rate (Fig. 2). The two methods were found different (P < 0.001) at 24 and 48 kg ha$^{-1}$ P application rates but not at 12, 36, and 60 kg ha$^{-1}$. Lack of statistical differences at the low P application rate of 12 kg ha$^{-1}$ may be because this rate was too low to cause yield differences. In spite of 48 kg ha$^{-1}$ showing an application method differences, 36 and 60 kg ha$^{-1}$ were not different probably because at such high rates the soil is saturated with P nullifying any impact from application method.

**Determination of P Requirements for Dual-purpose Wheat**

As a result of the differences obtained between broadcast and furrow application methods, wheat P requirements were considered under each method separately. Response surface model was significant (P < 0.1) only in 2005 forage data for both furrow and broadcast application methods (Equations 3.4 and 3.5). This was the only data that was considered in the determination of wheat P requirement. In both (Equations 3.4 and 3.5), it was apparent that M$_2$P and P rates were inversely related owing to the different signs of the linear terms indicating that less and less P was needed as the level of M$_2$P increased.

Linear equations 3.6 and 3.7 generated from the differentiation of equations 3.4 and 3.5 depicted the P application curve. However, due to lack of the interaction term in the furrow model, (Equation 3.6) was not adequate to determine P requirements for wheat and therefore only equation 3.7 was considered. This lack of significant interaction
between P and M₃P may be due to poor forage response to M₃P in FPA compared to BPA method (Figure 3). By making P the subject of the formula, the resulting P-M₃P relationship was plotted to generate the P application curve in Figure 4.

The quadratic method used to determine the level of P where yield was maximized in each “field” based on both BPA and FPA methods are illustrated in Figure 5. The resulting equation from each field was differentiated w.r.t. P rates to obtain the optimal P rates which were then regressed against the six M₃P levels giving the desired P application curve (Figure 4).

**NDVI based determination of P requirements for winter wheat**

A strong correlation (r² = 0.57; P < 0.001 in the furrow application method and r² = 0.72; P < 0.001 in the FPA method) was found between 2005 forage and NDVI data (Appendix 2). As a result, it was expected that NDVI, like forage, could be used to determine P requirements for winter wheat. However, even though the response surface models involving NDVI response to M₃P and applied P in both the FPA and BPA methods were highly significant (P < 0.0001; R² = 0.60), they were not useful in winter wheat P requirement determination (data not shown). The interaction term between M₃P and applied P in equation 3.1 was not significant (P < 0.1) unlike in the forage data and therefore, differentiating equation 3.1 in this scenario could not produce a linear function (Equation 3.2) necessary for estimating P requirements.

**Economic Analysis**

Equation 3.1 generated in multiple regression analysis was significant (P < 0.1) only in the 2005 furrow application and broadcast application methods based forage and although the model for FPA 2005 based forage was highly significant (P value <0.0001;
R² = 0.6) the interaction was not significant (P > 0.1) and was thus eliminated and the model refitted (Ott, 1993). Furrow and broadcast application methods generated equations 3.4 and 3.5 respectively and yield maximized in equations 3.6 and 3.7 for furrow application and furrow application methods respectively were derived.

\[ Y_f = 2849 - 136 M_3P*** + 47P*** - 0.46P^2*** + 2.4 M_3P^2*** \]  
\[ Y_b = 2612 - 125 M_3P*** + 42P*** - 0.25P^2** + 2.3 M_3P^2** + 0.56 P x M_3P * \]  
\[ Y'_f = 47 - 0.92P \]  
\[ Y'_b = 42 - 0.5P - 0.56 M_3P \]

Where \( Y_f \) = Forage yield based on furrow applied P  
\( Y_b \) = Forage yield based on BPA method  
\( Y'_f \) = First derivative of equation 3.3  
\( Y'_b \) = First derivative of equation 3.4

*** Significant at P <0.01; **significant at P < 0.05; * significant at P < 0.1

Since the interaction term for the furrow method caused the disappearance of the \( M_3P \) term in equation 3.6, returns to P in the furrow application method was compared to broadcast method when \( M_3P \) was zero and 32.5 mg kg⁻¹ optimal level (Zhang and Raun, 2006). This was accomplished by first determining the P rate that maximizes yield in equation 3.6 (P = 51 kg P ha⁻¹) and equation 3.7 (P = 75 kg P ha⁻¹). Substituting 51 kg P ha⁻¹ for P in equation 3.3 when \( M_3P \) was zero resulted in a maximum yield of 4050 kg ha⁻¹ with $255 ha⁻¹ (i.e., 267-12) returns to P in the furrow method. In the broadcast method, at zero \( M_3P \), maximum forage was obtained as 4376 kg ha⁻¹ and a return to P of $269 ha⁻¹ (i.e., 289-20).
On the other hand, yield maximizing P applications at optimal M3P was 2165 and 2790 kg ha\(^{-1}\) and return to P of $131 (143-12) ha\(^{-1}\) and $173 (184-11) ha\(^{-1}\) in the furrow application and broadcast application methods respectively. It appears broadcast P placement method resulted in higher returns to P than furrow application method. It was apparent that the higher the M3P in the broadcast method, the lower the cost of production was (i.e., $20 versus $11). This is because the higher the M3P the lower the need for P application.

Optimal P input levels obtained as a result of differentiations of the two dimensional production function equation 3.2, generated in Figure 5 are summarized (Table 3). Although it was expected for the P need to maximize yields be lower in the furrow than burrow methods of P placement, it was not consistent across various levels of M3P safe for 17, 23, and 28 mg kg\(^{-1}\) M3P (Table 3). Nevertheless, even when more P was applied with the furrow method, higher returns to P were realized than with the broadcast method (Table 3). Furrow P application with the seed caused efficient fertilizer utilization hence higher yields and higher returns to P.

**CONCLUSION**

Because of weather interferences in spring of 2006, the experiment was good for only 2005 season making it a one site year experiment. The wheat response to furrow and broadcast application methods is rate dependant. At rates of about 12 kg ha\(^{-1}\) P, the two methods appeared to be similar whereas between 24 and 36 kg ha\(^{-1}\) P, the rate typically applied by most producers, wheat response to P applied in furrow application method seemed greater than for the BPA method. These differences found between furrow and
broadcast application methods are an indication that when making P recommendations, method of P application has to be considered. However, with only one site year experiment we could not state with certainty the exact P requirement for dual-purpose wheat. Using the forage data for 2005 to analyze the P fertilizer recommendation curve, both the response surface and quadratic model generated recommendation curves, seems to dictate the application of P even at M₃P of 32.5 mg kg⁻¹ considered sufficient in the current state of Oklahoma P recommendations (Figure 4). In the meantime, the response surface is a better tool for estimating wheat P requirement; because of its capability to make the analysis all at once unlike the several steps required in the quadratic and the other methods. However, for accurate results, this method requires that all the terms in the full quadratic model be significant (P < 0.1) and directional.
REFERENCES


Table 1. Comparison of the effects of broadcast and furrow applied P at different rates on wheat forage and grain yields for 2005 and 2006.

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<td>1746aC</td>
<td>2077bD</td>
<td>923aA</td>
<td>1048aA</td>
</tr>
<tr>
<td>60</td>
<td>1709aC</td>
<td>2139bD</td>
<td>1067aA</td>
<td>1354bB</td>
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<td>Grain</td>
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<td></td>
<td></td>
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<td>2499aA</td>
<td>734aA</td>
<td>843aA</td>
</tr>
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<td>623aA</td>
<td>738aA</td>
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<td>2323aA</td>
<td>2399aA</td>
<td>592aA</td>
<td>554aB</td>
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<td>2387aA</td>
<td>2376aA</td>
<td>683aA</td>
<td>594aB</td>
</tr>
</tbody>
</table>

‡Within row means followed by the same lower case letter and within column means followed by the same upper case letter are not significantly different (P value > 0.1)
Table 2. The effects of phosphorus fertilizer application methods, liming, and season on winter wheat grain and forage yields.

<table>
<thead>
<tr>
<th>Category</th>
<th>P Placement Method</th>
<th>Mean Yield (kg ha(^{-1})) Limed</th>
<th>Mean Yield (kg ha(^{-1})) Non-limed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forage 2005</td>
<td>Furrow</td>
<td>1446aAi</td>
<td>1757aBi</td>
</tr>
<tr>
<td></td>
<td>Broadcast</td>
<td>1281aAi</td>
<td>1474bBi</td>
</tr>
<tr>
<td>Forage 2006</td>
<td>Furrow</td>
<td>1122aAii</td>
<td>991Aii</td>
</tr>
<tr>
<td></td>
<td>Broadcast</td>
<td>1184aAii</td>
<td>1088Aii</td>
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<tr>
<td>Grain 2005</td>
<td>Furrow</td>
<td>2426aAii</td>
<td>2389aAii</td>
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<tr>
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<td>Broadcast</td>
<td>2410aAii</td>
<td>2499aAii</td>
</tr>
<tr>
<td>Grain 2006</td>
<td>Furrow</td>
<td>681aAii</td>
<td>658Aii</td>
</tr>
<tr>
<td></td>
<td>Broadcast</td>
<td>710aAii</td>
<td>631Aii</td>
</tr>
</tbody>
</table>

Within column means followed by the same lower case letter; within row means followed by the same upper case letter; and within column means per response variable (forage or grain) followed by the same roman numeral are not significantly different (P value > 0.1).
Table 3. Production and returns to P comparison between broadcast and furrow applied P at various levels of Mehlich 3 P (M$_3$P).

<table>
<thead>
<tr>
<th>Method of P Placement</th>
<th>Broadcast</th>
<th>Furrow</th>
<th>Broadcast</th>
<th>Furrow</th>
<th>Broadcast</th>
<th>Furrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>M$_3$P (mg kg$^{-1}$)</td>
<td>Optimal P rates (kg ha$^{-1}$)</td>
<td>Maximum Yields (kg ha$^{-1}$)</td>
<td>Returns to P † ($ ha$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>72</td>
<td>40</td>
<td>2225</td>
<td>2130</td>
<td>130a</td>
<td>131a</td>
</tr>
<tr>
<td>23</td>
<td>174</td>
<td>43</td>
<td>2243</td>
<td>2340</td>
<td>106a</td>
<td>144b</td>
</tr>
<tr>
<td>26</td>
<td>55</td>
<td>71</td>
<td>1800</td>
<td>2313</td>
<td>106a</td>
<td>136b</td>
</tr>
<tr>
<td>28</td>
<td>76</td>
<td>36</td>
<td>1836</td>
<td>2107</td>
<td>103a</td>
<td>130b</td>
</tr>
<tr>
<td>30</td>
<td>47</td>
<td>115</td>
<td>1739</td>
<td>2601</td>
<td>103a</td>
<td>144b</td>
</tr>
<tr>
<td>33</td>
<td>39</td>
<td>43</td>
<td>1505</td>
<td>1848</td>
<td>90a</td>
<td>112b</td>
</tr>
</tbody>
</table>

†Maximum X $0.066$-Optimal P X $0.24$
Figure 1: Experimental design indicating two methods of P application, furrow and broadcast (FPA and BPA) in five extractable Mehlich 3 P categories (M3Pcat) within three soil pH categories (pHcat).
Figure 2. Comparison of the effect of broadcast and furrow methods of P placement at pH < 4.8 (A), 4.8 -5.0 (B) and >5.0 (C) on 2005 wheat forage yields. Means with same letter within a P rate are not statistically different (P > 0.1).
Figure 3. Response surface for the combined effect of M₃P and broadcast (A) and furrow (B) P placement methods on forage yields (2005).
Figure 4. Relationship between applied P and M₃P generated from response surface and quadratic methods for predicting winter wheat P requirement compared with the existing Oklahoma’s and previously derived P recommendation curve (Kariuki, 2003). ***P < 0.001, **P < 0.01.
Figure 5. Comparison of the effect of broadcast and furrow methods of P placement at 17 (A), 23 (B), 26 (C), 28 (D), 30 (E), and 33 (F) mg kg$^{-1}$ M$_3$P on wheat forage yields. ***$p < 0.001$. 

\[ y_f = -0.32x^2 + 45.3x + 710 \]
\[ r^2 = 0.72*** \]

\[ y_b = -0.38x^2 + 41.7x + 656 \]
\[ r^2 = 0.71*** \]

\[ y_f = -0.71x^2 + 57.1x + 982 \]
\[ r^2 = 0.39*** \]

\[ y_b = -0.22x^2 + 31.5x + 1098 \]
\[ r^2 = 0.44*** \]

\[ y_f = -0.62x^2 + 44.7x + 1301 \]
\[ r^2 = 0.69*** \]

\[ y_b = -0.22x^2 + 31.5x + 1098 \]
\[ r^2 = 0.44*** \]

\[ y_f = -0.13x^2 + 30.0x + 870 \]
\[ r^2 = 0.67*** \]

\[ y_b = -0.40x^2 + 37.7x + 851 \]
\[ r^2 = 0.65*** \]

\[ y_f = -0.72x^2 + 62.3x + 1005 \]
\[ r^2 = 0.75*** \]

\[ y_b = -0.04x^2 + 13.9x + 1036 \]
\[ r^2 = 0.47*** \]

\[ y_f = -0.57x^2 + 49.0x + 795 \]
\[ r^2 = 0.79*** \]

\[ y_b = -0.25x^2 + 19.5x + 1125 \]
\[ r^2 = 0.06 \]
Appendix 1. Random sample Soil pH and Aluminum Saturation ($Al_{sat}$) at Marshall Experimental Site

<table>
<thead>
<tr>
<th>Plot</th>
<th>pH</th>
<th>$Al_{sat}$ (%)</th>
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</thead>
<tbody>
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<td>4.7</td>
<td>6.98</td>
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<tr>
<td>308</td>
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<td>8.1</td>
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<tr>
<td>310</td>
<td>4.7</td>
<td>9.05</td>
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<tr>
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<td>4.7</td>
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<tr>
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<td>5.07</td>
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<td>6.89</td>
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<tr>
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<td>4.61</td>
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<td>4.9</td>
<td>2.76</td>
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<td>715</td>
<td>5.0</td>
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<tr>
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<td>1.18</td>
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<tr>
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<td>5.1</td>
<td>0.69</td>
</tr>
<tr>
<td>1219</td>
<td>5.1</td>
<td>0.51</td>
</tr>
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</table>
Appendix 2. Correlation between 2005 winter wheat forage yields and NDVI in furrow and broadcast methods. ***(P < 0.001

$r^2 = 0.57***$

$r^2 = 0.72***$

Yields (kg ha$^{-1}$)

NDVI
VITA

Solomon Kioni Kariuki

Candidate for the Degree of

Doctor of Philosophy

Thesis: HARD RED WINTER WHEAT CULTIVAR RESPONSES TO A pH AND ALUMINUM CONCENTRATION GRADIENT

Major Field: SOIL SCIENCE

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Professional Experience: Employed as a Research Assistant by the Agricultural Economics Department, Oklahoma State University, 1996 to 1998; Employed as a Research Assistant by the plant and Soil Sciences Department, Oklahoma State University, 2001 to present.