SOIL TEST PHOSPHORUS VARIABILITY ACROSS LANDSCAPES AND PROJECTED EFFECTS OF VARIABLE RATE P FERTILIZATION

By

MICHAEL WILLIAM GOEDEKEN

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1995

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 1998

SOIL TEST PHOSPHORUS VARIABILITY ACROSS

LANDSCAPES AND PROJECTED EFFECTS OF

VARIABLE RATE P FERTILIZATION

Thesis Approved:

Thesis Adviser

Dean of the Graduate College

ACKNOWLEDGEMENTS

I would like to thank my major advisor Dr. Gordon V. Johnson, for his encouragement, guidance, support, and confidence throughout my graduate training. The opportunity to study with him has been both an honor and a privilege. I would also like to extend my sincere appreciation to Dr. William R. Raun and Dr. Eugene G. Krenzer for the time and effort that they have spent directing my studies as members of my committee.

I would also like to thank Dr. Robert L. Westerman, the Soil, Water, and Forage Analytical Laboratory, and the Soil Fertility Project in the Department of Plant and Soil Sciences, for financial support and facilities made available for obtaining my M.S. degree at Oklahoma State University. A special thanks also to the employees of the Soil, Water, and Forage Analytical Laboratory for their support, assistance, and understanding during my graduate program. I also would like to thank the employees and students of the Soil Fertility Project for the time and effort that they have given me when I needed assistance in the field. A special thanks also to Dr. Nicholas T. Basta, Dr. Frederick N. Kojima, Mr. Robert D. Murphy, Mr. M. W. (Bill) Goedeken, Ms. Barbara Transue, and the many other friends whom have helped and supported me.

This thesis is dedicated to my wonderful wife Suzanne and my mother Connie who have always, loved and supported me, put up with me, and pushed me to do nothing but my best. Lastly, I would like to thank the Lord for all the gifts that he has given me and for health and happiness in the future.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER 1

INTRODUCTION

This thesis consists of two chapters, each summarizing research problems conducted during my masters program. Each chapter is presented in a format suitable for publication in professional journals.

Chapter I

SOIL TEST PHOSPHORUS VARIABILITY ACROSS LANDSCAPES AND PROJECTED EFFECTS OF VARIABLE RATE P FERTILIZATION

ABSTRACT

Soil nutrient availability has been known to vary across landscapes. Consequently, variable rate fertilization is being studied throughout the United States. The objective of this study was to predict the long-term effects of variable P fertilization and constant rate P fertilization on variably responsive sites in addition to investigating methods of reducing within field variability at accelerated rates. A 15.2 x 152.3m area was divided into five transects each containing fifty 3.1 x 3.1m cells and a 30.5 x 76.2 m area within the same field was divided into ten transects each containing twenty-five 3.1 x 3.1 m cells for the second year of the study. Soil samples from the 250 cells were collected in the summers of 1996 and 1997. Phosphorus was extracted with Mehlich III and analyzed with a Milton Roy spectrophotometer with color development achieved by using a modified Murphy and Riley procedure. Data from P analysis was then used to determine the long-term (50-year) effects of both constant and variable rate application of P fertilizers. Projections from the data were made using a model that considers both crop uptake and soil P change due to fertilizer. Annual application of 24 kg P ha^{-1} resulted in increased soil test P, however

variability remained unchanged. A consistent use of variable rate application of P fertilizer resulted in reduction of variability. Marginal profit of variable rate application over a conventional rate application increased as the treated field element size decreased. Furthermore, as field element size decreased P fertilizer use and grain yield also increased for the entire area. Marginal profit may be increased by applying constant rates of P fertilizer different from the standard average recommendation if P response is variable within a field. The use of 3 or 5 times the required fertilizer P reduced field variability, however, this was not an economically feasible method of treating P variability. Optimum field response was achieved when each 3.1 x 3.1m cell was treated individually.

INTRODUCTION

Nutrient and pH variability have been encountered for many years however it was not until the recent past that the technology and database management capabilities to deal with such variability became available. In 1929 the University of Illinois practiced intensive soil sampling in order to map soil pH variability to determine variable limestone application rates (Sawyer 1994). More recently throughout the United States researchers have been focusing their interests on variable rate fertilization with their primary concentration on N, P, and K nutrient management. A number of these studies have demonstrated that soil nutrient levels and crop yields can vary considerably within fields (Karlen et al., 1990; Robert et al., 1990; Carr et al., 1991; Colven, 1993; Franzen and Peck, 1993; Vetsch et al., 1993; Wibawa et al., 1993; Raun et al., 1997).

Explanations for soil nutrient variability can be attributed to many factors. Khakural *et. al.* (1996) stated that soil properties vary across landscape due to differences in topographic variables, parent material, and soil development. Another explanation is that a combination of soil type and past management (previous crop, tillage, and fertilizer rates) will cause nutrient variability (Wollenhaupt et. al., 1994). Mallarino (1996) concluded that typical methods for applying P and K fertilizers often results in cyclic patterns of nutrient availability as seen in many fields today. Additionally erosion, sedimentation, slope position, and water availability strongly influence soil properties, soil nutrient availability and crop yield (Ciha ,1984; Kliess, 1970; Malo et. al., 1974; Miller et. al., 1988). These factors can however, all be linked to each other in order to help explain inherent variability found in fields under traditional management practices.

A major concern of researchers is how should the treating of soil nutrient variability be approached. Khakural *et al.* (1996) stated that sampling and management strategies for precision farming should consider the relationships between landscape characteristics, soil development, soil fertility, and soil productivity. While Hammond (1988) suggested identifying P and K variability using geostatistical methods and grouping similar areas into fertilizable management zones. Grid point and cell sampling of different intensities have been utilized to asses pH, P, and K variation, and these studies found that grid point sampling was superior to either soil type or cell sampling when assessing soil nutrient variability (Franzen and Peck, 1993; Wollenhaupt and Wolkowski, 1993). However, with research continuing there is still no consensus as to how variability should be treated because of differences in approach to identifying variability and differences between locations.

Sawyer (1994) stated that variable rate technology has the potential to improve input efficiency, field profit, and environmental stewardship. Research on variable rate P and K application conducted by Buchholz (1991) concluded that economic improvement is dependent on the field, variation of P and K within the field, the predicted yield responses, and costs of variable rate application. To properly asses the profitability of variable rate fertilization it must be decided at what resolution the variability will be detected and treated and what equipment will be utilized to treat the variability.

Current interest in variable rate fertilization has caused researchers to focus their efforts on treating nutrient variability. Because N, P, and K are the three most limiting nutrients they have received the most attention and will be the leading influences in the implementation and commercial use of variable rate technology. Because it is believed that variable rate fertilization will improve efficiency of nutrient use while limiting environmental pollution due to excessive fertilization, its use could potentially have a massive impact on production agriculture.

This study was designed to evaluate the long-term effects of variable rate phosphorus fertilization of continuous winter wheat *(Triticum aestivium L.)*. Of particular interest in this study was the influence of variable rate inputs on yield, P fertilizer use , and marginal profit while identifying the most responsive variable field unit (field element size). Additionally we intuitively believed that annual use of variable rate P fertilizer application techniques should reduce the variability of available P within a field while use of constant P rates may change soil test P (STP) but not affect variability. In order to build STP levels, rates of P fertilizer adequate to prevent plant deficiencies, and in excess of plant uptake must be applied. Conversely, areas testing high which receive no fertilizer P should test lower over time as a result of crop removal. Therefore, over time use of variable rate P fertilization should decrease P variability. We recognize that it may be possible to accelerate the soil test P increase of P deficient areas by applying more than the recommended rate for maximizing crop yield in the year of fertilizer application. However accelerated reduction of high STP cannot be manipulated by field management since it is yield dependent. Therefore, methods for decreasing the amount of time required to reduce P variability were also investigated in this study.

The objectives of this study were to predict the long-term effects of variable P fertilization on variably responsive sites, to evaluate the long-term effects of both single and constant rate P fertilization on variably responsive sites, to examine fertilizer strategies to reduce field variability and to determine the effect of field element size on field response.

MATERIALS AND METHODS

In the first year of the study a 15.5 x 152.3 meter area was divided into five transects each containing fifty 3.1 x 3.1 meter cells (Figure. 1). For the second year a 30.5 x 76.2 m area within the same field was divided into ten transects each containing twenty-five 3.1 x 3.1 m cells (Figure. 2). The field is a cultivated Norge loam (fine-silty, mixed, thermic Udic Paleustoll) located at the North end of the North Stillwater research station in Stillwater Oklahoma. The treatment resolution of 3.1 x 3.1 m used for this study is consistent with equipment used for a field plot study conducted on the same sites. In the summers of 1996 and 1997 soil samples were collected from the 250 cells of the appropriate study area. Ten cores 2 cm in diameter and 15 cm deep were randomly collected and mixed to form a composite sample for each cell. P was extracted from the composite samples using the Mehlich III extractant (Mehlich, 1984) and analyzed using Phosphorus was extracted with Mehlich III and analyzed with a Milton Roy spectrophotometer with color development achieved by using a modified Murphy and Riley procedure.(Murphy and Riley 1962, Watanabe and Olsen, 1965). Data from P analysis was used to predict the effects of single, constant, and variable rate P fertilizer application over a 50 year period of continuous winter wheat (*Triticum aestivium L.*). Projections from the data were made from a model that predicts yield in relation to soil test P and fertilizer P addition (Johnson 1991). The model assumes that all other nutrients and moisture are available in adequate but not excessive supply. After each iteration (cropping season) with the model, initial soil test levels were adjusted one unit for each 9 kg ha^{-1} input (1996) and 7 kg ha^{-1} input (1997) (fertilizer) or removal (crop) of soil P. The change in adjustment levels was due to new unpublished findings from long term wheat production trials at Oklahoma State University. Analysis of the effect of changing STP calibrations were conducted in the same manner by means of either adding or subtracting 11 kg P ha^{-1} from the existing P fertilizer recommendations that were developed from the current Oklahoma State STP calibration tables (Allen and Johnson, 1993).

P rates were determined from existing soil test P calibration tables (Allen and Johnson, 1993) when considering single and variable rate P fertilization methods. Single P fertilization rates were established by calculating the mean soil test P value for 50 cells in a single transect or group from the study area in 1996 and for 50 cells in two adjacent transects of the study area in 1997. The effect of the single rate of P fertilizer application was then projected for all 50 cells based on the mean STP index. The effect of variable rates of applied P fertilizer were projected for individual cells based on the STP index for that cell. The effect of a constant P rate of 23 kg ha^{-1} was also evaluated because this rate is conventionally utilized by producers. Yield for each of the 50 cells was predicted based on soil test P for the cell and response to the indicated rate of P fertilizer. Additionally the 1997 data was used to evaluate methods of reducing the P variability in a shorter amount of time by utilizing 3x and 5x rates. These rates were calculated by multiplying the fertilizer P requirement by 3 or 5 for cells that had a STP lower than the median. The median was chosen in order to raise STP levels in the lower one-half of the data that was being analyzed for treatment with x rates in order to reduce field variability.

A concern of precision agriculture is field element size (FES), or treatment resolution. FES is the resolution or area to which different rates are applied to best treat the encountered variability within a field. We examined the effects of changing FES by calculating an average soil test P for all 50 cells from a single transect or group (1996) or 50 cells from two adjacent transects (1997) and projected the effect of treating all plots with a single rate of P fertilizer. Next, we treated the first and last 25 cells as separate areas with average soil test P values and continued this breakdown until each 3.1 x 3.1m cell was treated individually. Each time the groupings were made, yield, P fertilizer used, and marginal profit totals for the entire 50 cells were projected and compared to using a single P rate for all 50 cells. Marginal profit was calculated for wheat using a value of

$0.11 kg^{-1} for wheat grain, P fertilizer at a cost of $1.44 kg^{-1} P, and an optimum yield of 2688 kg ha^{-1}. For purpose of discussion data from the study was converted to hectare equivalent.

RESULTS AND DISCUSSION

The model projections demonstrated how different approaches for P fertilization might effect future variability within a field. When field variability was treated by variable P fertilizer rates over the projected fifty years, the variability was reduced dramatically by the 20th year and nearly eliminated by the 50th year (Figure. 3 a-f). In the first year of the 1996 data from transect 5 the average soil test P index was 47 parts per 2 million (pp2m) with a standard deviation of 13.97, by the twentieth year the average was 41 pp2m and the standard deviation had decreased to 6.57. In the fiftieth year the average had decreased to 37 pp2m and the standard deviation reduced to 1.49. Reduced variability over time is a result of the high soil test P areas of the field experiencing crop removal of soil P without fertilizer P addition, and low testing areas of the field receiving fertilizer P in excess of crop removal. Results for additional data sets are summarized (Table. 1) and follow the same standard for the reduction of variability. Mean STP changed at faster rates for areas with higher mean STP and variability than areas with lower mean STP and variability.

Variable rate P fertilization resulted in a greater marginal profit than application of a single rate application until variability was reduced (Table 2). By treating each cell individually the largest marginal advantage of variable P fertilization over single rate application was \$4.49 ha^{-1} in the first year of projections for transects 9 & 10 in 1997. Marginal advantage of variable P fertilization decreased with variability over time when the initial average STP was below or slightly above the critical soil test value (65 pp2m). However, when initial average STP for the area was more than 10 pp2m higher than the critical soil test level the marginal advantage of variable rate P fertilization increased over time then began to decrease. This occurred because even though the average STP was greater than the critical soil test value there were cells that were below that level that required P fertilizer in order to achieve maximum production. Further investigation of data from this study indicates that transects with an average STP up to 106 can still contain areas under 65 pp2m. Future decisions about the use of variable rate P fertilization must consider the economic benefit of its use over single rate application in relation to application costs.

When initial mean STP was lower than 36 pp2m as in the case of the first 50 samples from the 1996 data (28 pp2m) the mean STP increased to 36 pp2m over the projected 50 years. Further projection for an additional 30 years (80 years total) resulted in no further change in mean STP. The apparent equilibration of mean STP at 36 pp2m was not a matter of coincidence, but was proven to be a function of the soil test calibration. When P variability was treated using the existing Oklahoma State University STP calibration tables (Allen and Johnson, 1993), mean STP approached 36 pp2m as variability was decreased. However, when the calibration was changed by an additional 11 kg ha^{-1} of P fertilizer being added to the plant requirement, mean STP stopped fluctuating at 45 pp2m rather than at 36 pp2m (Table. 3). In addition when P requirement was decreased by 11 kg ha^{-1} the mean STP began to level off near 33 pp2m (Table. 3). This settling occurs because the STP calibration does not result in addition of an adequate amount of P, based on average STP, to replace P utilized by crop removal at the indicated yield potential. Consequently the mean STP value will continue to increase or decrease over time, and converge at a value where the recommended fertilizer input is equal to crop removal at the indicated yield potential. Furthermore, increasing P requirement of the calibration caused variability reduction to occur at faster rates while decreasing P requirement caused a slower decrease in variability. Therefore, the effect of using variable rate fertilization will be dependent on STP calibrations, however, variability reduction should be similar to results found in this study.

Reduction of STP variability was enhanced by application of either 3 or 5 times the amount of P fertilizer required for maximum production (Table. 4). In a projected five year period the 3x rate had decreased variability to lower levels than normal fertilization for plant requirement reached in ten years. The 5x rates reduced variability over a ten year period to levels lower than twenty years of fertilizing plant requirement. Either method would help to decrease variability over a shorter time period however, based on current wheat prices and fertilizer costs it would not be economically feasible to treat the variability with these methods. It would be more advantageous to treat the variability within a field to meet plant needs annually or apply a single P rate to an entire field rather than to try to cause drastic changes in variability.

When field variability was ignored and a single conventional rate of P fertilizer (23 kg ha^{-1}) was applied to the area the variability remained constant while the STP increased (Table 5). The average STP for data from 1996 in transect 5 increased from 47 pp2m to

106 pp2m over the projected fifty year period while the standard deviation remained the same. Additionally variable P rates, had a higher projected marginal profit than application of 23 kg P ha^{-1} over the projected fifty year period (Table. 2). The marginal advantage of variable rate fertilization over the constant rate application increased yearly until all areas that were in the group were above the critical STP level. At this point variable rate fertilization would not occur because there would be no need for additional P however, in the projection model constant rate P (23 kg P ha^{-1}) was still being applied resulting in a marginal advantage for variable rate fertilization. With the wheat prices and cost of P fertilizer used for this study a marginal savings of \$31.83 ha^{-1} was predicted by using variable rate P fertilization or essentially not fertilizing when there were no longer any areas that would respond to fertilizer addition. Treatment of fields with a single rate of P fertilizer or with constant P rates will result in excessive fertilization of a portion of the field and inadequate fertilization in other areas with only a small area receiving the proper amount of fertilizer. With this practice the proportion of the areas that are over fertilized will be dependent upon the STP, range in STP, and variability. Due to variability within fields optimum P fertilizer rates cannot be achieved using traditional fertilization practices. Therefore, traditional practices of P fertilization are ineffective methods of treating field variability and can reduce the potential for profit for the field.

Evaluation of field element size shows that as field element size decreases, there is an increase in grain yield, P fertilizer applied, and marginal profit for the entire treated area (Table. 6). Data from the first fifty cells in 1996 demonstrated a decrease in grain yield and profit after the first breakdown when the area was treated as two separate groups. This was because there were only two cells in this set of data that did not require P fertilizer and both of these cells were in the same group after the first breakdown causing the average for the group to be skewed. The skewed average resulted in insufficient fertilization of the remaining cells. Therefore, when utilizing variable rate fertilization it will be important to avoid grouping areas of high soil test levels with areas of low levels. As the FES resolution was decreased grain yield, profit, and P fertilizer use increased at proportional rates with yield and profit producing mirror images of each other at different scales when graphed (Figure. 4a-b). Two distinct responses were seen when FES resolution was decreased. The first and most typical response was a gradual then rapid increase in yield, profit, and P fertilizer use (Figure. 4a). This response occurred when the variability was random throughout the area. The second type of response occurred when there where two or more large areas with different STP means and similar variability. When the FES was reduced for these areas the increase in yield, marginal profit, and P fertilizer occurred more rapidly followed by a gradual increase until each individual cell was treated (Figure. 4b). The responses of increased yield, profit, and fertilizer use with reduction of FES will hold true at any resolution because the increases are a function of population statistics. This treatment of data clearly demonstrates that wheat producers will benefit economically in relation to the extent to which they are able to detect and treat the variability on the land that they manage. However until a resolution to treat the variability is agreed upon and a cost of application is known it is difficult to determine how beneficial variable rate fertilization will be.

CONCLUSIONS

Long-term use of variable rate P fertilization will lead to reduction of soil test P variability in treated landscapes or fields. The degree to which variability is reduced will be dependent on other growth factor variations in the field since they will influence how much of the applied P is in excess of crop requirement (in P deficient areas) and how much soil P depletion from crop removal occurs in areas of excess soil P. Use of a constant rate P fertilizer will not affect P variability, however, it will increase STP if the constant rate exceeds crop removal. The amount that soil test P increases will once again be dependent on other growth factors. Soil test P build-up will likely occur faster when yield is limited by another growth factor. Field response, marginal profit, and P fertilizer used will increase as field element size decreased. Consequently, managing fields, and different areas within fields (e.g. soil type, topography etc.) independently should improve fertilizer use efficiency and, in many instances, profit. Fertilizer strategies to reduce field variability should be further investigated, however, results from this study suggest that reduction of variability at accelerated rates is not an economically sound strategy. Future research in variable rate fertilization should concentrate on methods of identifying and treating variability while keeping in mind that as FES is decreased, yield, profit, and fertilizer use have the potential to increase. Optimum field response was achieved when each 3.1 x 3.1m cell was treated individually in this study.

REFERENCES

Allen, E., and G. Johnson. 1993. OSU soil test interpretations. OSU Extension Facts No. 2225. Oklahoma St. Univ. Cooperative Extension Serv. Stillwater, OK.

Buchholz, D.D. 1991. Missouri grid soil sampling project. P. 6-12. *In* Proc. 21st North Cent. Ext.-Ind. Soil Fert. Worksh., St. Louis, Mo. 28-29 Oct. Potash and Phosphate Inst., Manhattan, KS.

Carr, P.M., G.R. Carleson, J.S. Jacobsen, G.A. Nielsen, and E.O. Skogley. 1991. Farming soils, not fields: A strategy for increasing fertilizer profitability. J. Prod. Agric. 4:57-61.

Chia, A.J. 1984. Slope position and grain yield of soft white winter wheat. Agron. J. 76:193-196.

Colvin, T. 1993. Farming by location. p. 25-31. *In* M.E. Gray and M.E. Ostroski (ed.) Proc. 1993 19th Annu. Illinois Crop Prot. Worksh., Champaign, IL. 3-5 Mar. Univ. of Illinois, Urbana.

Frazen, D.W., and T.R. Peck. 1993. Soil sampling for variable rate fertilization. P. 81-90. *In* R.G. Hoeft (ed.) 1993 Illinois Fert. Conf. Proc. Springfield, Il. 25-27 Jan. Univ. of Illinois, Urbana.

Hammond, M.W., D.J. Mulla, and D.S. Fairchild. 1988. Development of management maps for spatially variable soil fertility. P. 67-76. *In* Proc. Faaar West Regional Fert. Conf. Bozeman, MT. 11-13 July. Far West Fertilizer AgChem Association, Pasco, WA.

Johnson, G.V., 1991. General model for predicting crop response to fertilizer. Agron. J. 83:367-373.

Karlen, D.L., E.J. Sadler, and W.J. Busscher. 1990. Crop yield variation associated with coastal plain soil map units. Soil Sci. Soc. Am. J. 54:859-865.

Khakural, B.R., P.C. Robert, and D.J. Mulla. 1996. Relating corn/soybean yield to variability in soil and landscape characteristics. pp. 117-128. *In* P.C. Robert, R.H. Rust, and W. E. Larson (eds.) Proc. 3rd Int. Conf. Precision Agriculture., Minneapolis, MN. Jun. 23-26, 1996.

Kleiss, H.J. 1970. Hillslope sedimentation and soil formation in northeastern Iowa. Soil Sci. Soc. Am. Proc. 34:287-290.

Mallarino, A.P. 1996. Spatial variability patterns of phosphorus and potassium in no-tilled soils for two sampling scales. Soil Sci. Soc. Am. J. 60:1473-1481.

Malo, D.D., B.K. Worcester, D.K. Cassel, and K.D. Matzdorf. 1974. Soil landscape relationships in a closed drainage system. Soil Sci. Soc. Am. Proc. 38:813-818.

Mehlich, A. 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Comm. Soil Sci. Plant Anal. 15(12):1409-1416.

Miller, M.P., M.J. Singer, and D.R. Nielson. 1988. Spatial variability of wheat yield and soil properties on complex hills. Soil Soc. Am. J. 52:1133-1141.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Whitney, H.L. Lees, H. Sembiring, and S.L. Taylor. 1997. Small-scale variation in soil test phosphorus and bermudagrass yield. pp. 14-16. *In* D.L. Armstrong (ed.) Better Crops with Plant Food Volume 81 1997, No. 1, Potash & Phosphate Institute, Norcross, GA.

Robert, P., S. Smith, W. Thompson, W. Nelson, D. Fuchs, and D. Fairchild. 1990. Soil specific management. Univ. of Minnesota Project Rep.

Sawer, J.E. 1994. Concepts of variable rate technology with considerations for fertilizer application. J. Prod. Agric. 7:195-201.

Vetsch, J.A., G.L. Malzer, P.C. Robert, and D.R. Huggins. 1993. Nitrogen specific management by soil condition. *In* Univ. of Minnesota Field Res. In Soil Sci. 1993. Univ. of Minnesota Misc. Pub. 79-1993.

Watanabe, F.S., and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Am. Proc. 29:677-678.

Wibawa, W.D., D.L. Dludlu, L.J. Swenson, D.G. Hopkins, and W.C. Dahnke. 1993. Variable fertilizer application based on yield goal and soil map unit. J. Prod. Agric. 6:255-261.

Wollenhaupt, N.C., R.P. Wolkowski and M.K. Clayton. 1994. Mapping soil test phosphorus and potassium for variable-rate fertilizer application. J. Prod. Agric. 7:441-448.

Wollenhaupt, N.C. and R.P. Wolkowski. 1993. Soil sampling for developing variable rate fertilizer programs. P. 1-15. *In* Proc. 1993 Fertilizer, Aglime and Pest Manage. Conf., Vol. 32, Middleton, WI. 19-21 Jan. Univ. of Wisconsin, Madison.

Figure 1. Diagram of 1996 study area, five transects each containing 50, 3.1 x 3.1 m cells, randomly sampled as 250 individual 3.1 x 3.1 m cells, Stillwater, OK.

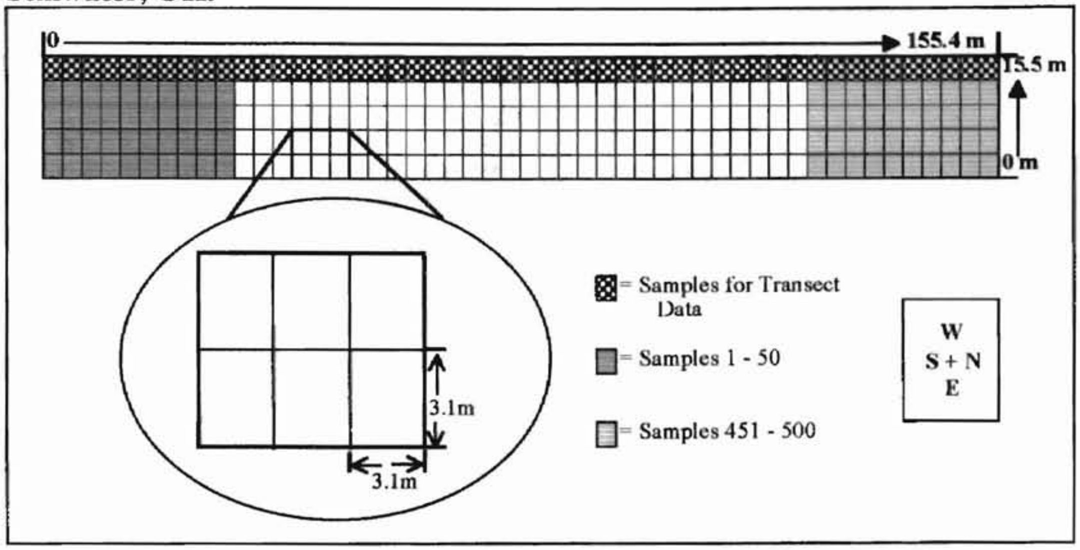


Figure 2. Diagram of 1997 study area, ten transects each containing 25, 3.1 x 3.1 m cells, randomly sampled as 250 individual 3.1 x 3.1 m cells, Stillwater, OK.

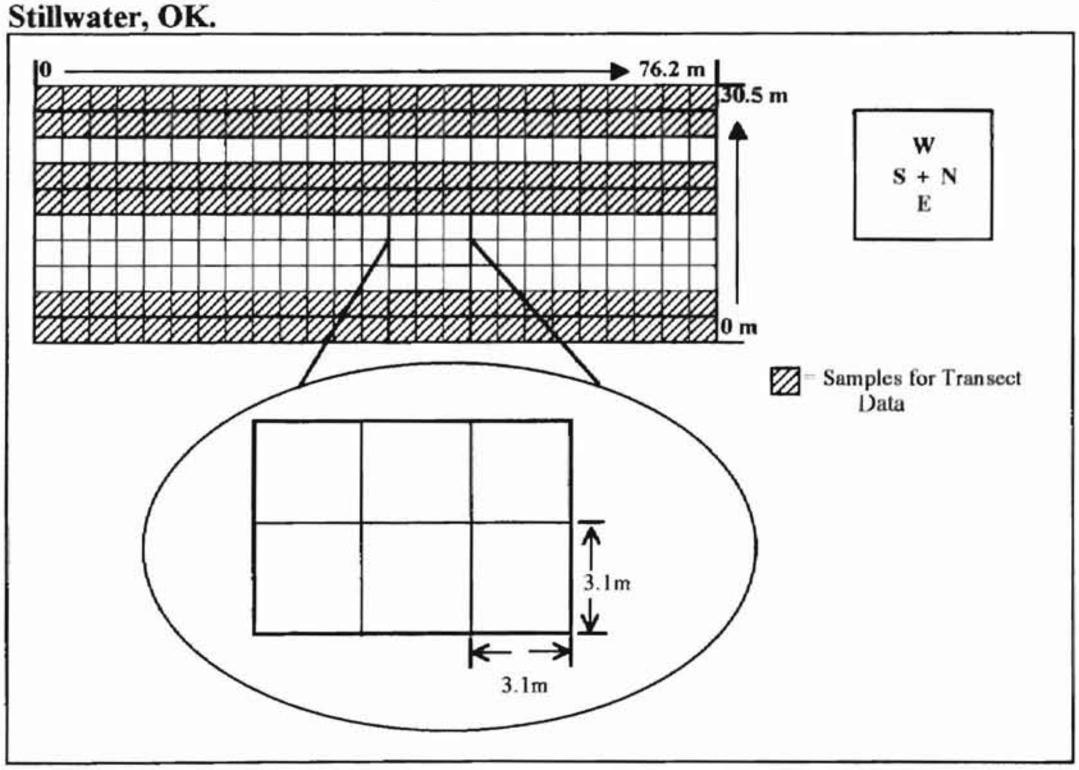


Figure 3. Projected effects of variable rate P fertilization on mean STP and variability over a 50 year period among 50 independent field units (cells).

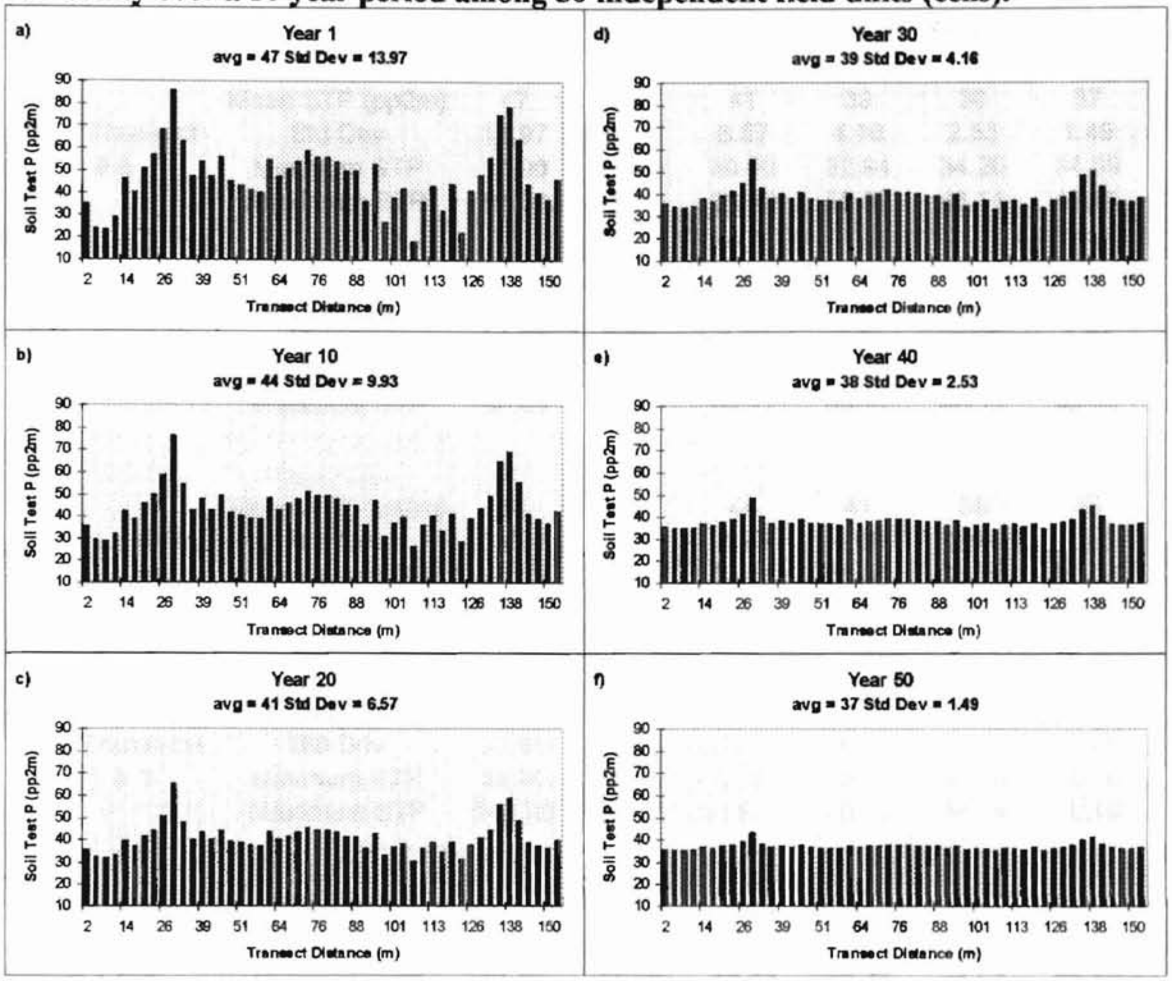


Table 1. Projected effects of variable rate P fertilization on mean STP and variability over a 50 year period.

Data Set ID		Year 1	Year 10	Year 20	Year 30	Year 40	Year 50
	Mean STP (pp2m)	47	44	41	39	38	37
1996 Transect	Std Dev	13.97	9.93	6.57	4.16	2.53	1.49
# 5	Minimum STP	18.00	26.08	30.60	32.94	34.20	34.89
	Maximum STP	86.00	76.11	65.12	55.37	48.11	43.21
	Mean STP (pp2m)	28	32	34	35	35	36
1996 First 50	Std Dev	14.08	9.35	6.00	3.74	2.27	1.34
Samples	Minimum STP	10.00	22.24	28.69	31.94	33.66	34.59
	Maximum STP	86.00	76.11	65.12	55.37	48.11	43.21
	Mean STP (pp2m)	55	49	44	41	39	38
1996 Last 50	Std Dev	11.66	8.97	6.25	4.06	2.51	1.50
Samples	Minimum STP	36.00	35.90	35.84	35.81	35.79	35.78
	Maximum STP	88.00	78.11	67.12	56.96	49.24	43.94
	Mean STP (pp2m)	78	68	58	50	44	41
1997 Transects	Std Dev	27.60	24.65	20.58	16.01	11.51	7.46
# 1 & 2	Minimum STP	33.00	34.41	35.15	35.48	35.63	35.70
	Maximum STP	142.00	128.81	114.15	99.50	84.84	70.19
	Mean STP (pp2m)	88	76	64	54	47	42
1997 Transects	Std Dev	22.86	21.87	19.29	15.42	10.90	6.60
# 4 & 5	Minimum STP	51.00	44.16	39.87	37.71	36.67	36.18
	Maximum STP	132.00	118.81	104.15	89.50	74.84	60.40
	Mean STP (pp2m)	67	58	50	44	40	38
1997 Transects	Std Dev	22.63	18.56	13.62	8.94	5.23	2.78
# 9 & 10	Minimum STP	26.00	31.20	33.73	34.84	35.34	35.57
	Maximum STP	119.00	105.81	91.15	76.50	61.93	50.42

Table 2. Economic benefit of variable rate P fertilization when compared to application of a single P rate or application of a constant P rate of 23 kg ha^{-1}.

Data Set ID		Variable Rate P Marginal Advantage \$ ha^{-1}					
		Year 1	Year 10	Year 20	Year 30	Year 40	Year 50
1996 Transect # 5	Single Rate	\$3.41	\$1.43	\$0.56	\$0.20	\$0.07	\$0.02
	Constant Rate 23 kg ha^{-1}	\$22.31	\$27.51	\$30.51	\$31.53	\$31.85	\$31.83
1996 First 50 Samples	Single Rate	\$2.34	\$0.46	\$0.09	\$0.01	\$0.00	\$0.00
	Constant Rate 23 kg ha^{-1}	\$8.31	\$16.98	\$24.42	\$29.36	\$31.68	\$31.83
1996 Last 50 Samples	Single Rate	\$1.72	\$1.05	\$0.51	\$0.21	\$0.08	\$0.02
	Constant Rate 23 kg ha^{-1}	\$26.86	\$30.19	\$31.65	\$31.83	\$31.83	\$31.83
1997 Transects # 1 & 2	Single Rate	\$2.62	\$4.32	\$4.33	\$2.63	\$1.04	-\$0.41
	Constant Rate 23 kg ha^{-1}	\$29.41	\$31.34	\$31.81	\$31.83	\$31.83	\$31.83
1997 Transects # 4 & 5	Single Rate	\$0.67	\$2.20	\$3.17	\$1.81	\$0.93	\$0.36
	Constant Rate 23 kg ha^{-1}	\$31.42	\$31.83	\$31.83	\$31.83	\$31.83	\$31.83
1997 Transects # 9 & 10	Single Rate	\$4.49	\$3.05	\$1.79	\$0.75	\$0.22	\$0.06
	Constant Rate 23 kg ha^{-1}	\$27.85	\$30.83	\$31.76	\$31.83	\$31.83	\$31.83

Table 3. Effect of differences in STP calibration on variability and mean STP when using long term variable rate fertilization.

Data Set ID		Year 1	Year 10	Year 20	Year 30	Year 40	Year 50
1997 Transects	Mean STP (pp2m)	67	58	50	44	40	38
9 &10	Std Dev	22.63	18.56	13.62	8.94	5.23	2.78
OSU Calibration	Minimum STP	26.00	31.20	33.73	34.84	35.34	35.57
	Maximum STP	119.00	105.81	91.15	76.50	61.93	50.42
1997 Transects							
9 &10	Mean STP (pp2m)	67	60	53	49	46	45
OSU Calibration	Std Dev	22.63	17.09	11.40	6.71	3.48	1.65
P Increased	Minimum STP	26.00	35.62	40.14	42.06	42.91	43.28
11 kg ha^{-1}	Maximum STP	119.00	105.81	91.15	76.50	62.08	52.58
1997 Transects							
9 &10	Mean STP (pp2m)	67	57	48	41	36	33
OSU Calibration	Std Dev	22.63	19.47	15.04	10.33	6.29	3.41
P Decreased	Minimum STP	26.00	28.52	29.79	30.35	30.60	30.71
11 kg ha^{-1}	Maximum STP	119.00	105.81	91.15	76.50	61.84	48.74

Table 4. Effect of adding three or five times the required amount of P fertilizer as a method of STP variability reduction.

			3 x Rate		5 x Rate	
Data Set ID		Year 1	Year 5	Year 10	Year 5	Year 10
	Mean STP (pp2m)	78	75	71	76	72
1997 Transects	Median	75.00	69.14	62.08	69.14	62.25
# 1 & 2	Std Dev	27.60	24.60	21.73	23.41	20.34
	Minimum STP	33.00	43.23	48.20	49.46	54.44
	Maximum STP	142.00	136.14	128.81	136.14	128.81
	Mean STP (pp2m)	67	65	62	67	65
1997 Transects	Median	64.50	59.84	55.33	60.47	56.87
# 9 & 10	Std Dev	22.63	18.37	14.67	16.71	12.93
	Minimum STP	26.00	40.73	47.26	48.17	54.10
	Maximum STP	119.00	113.14	105.81	113.14	105.81

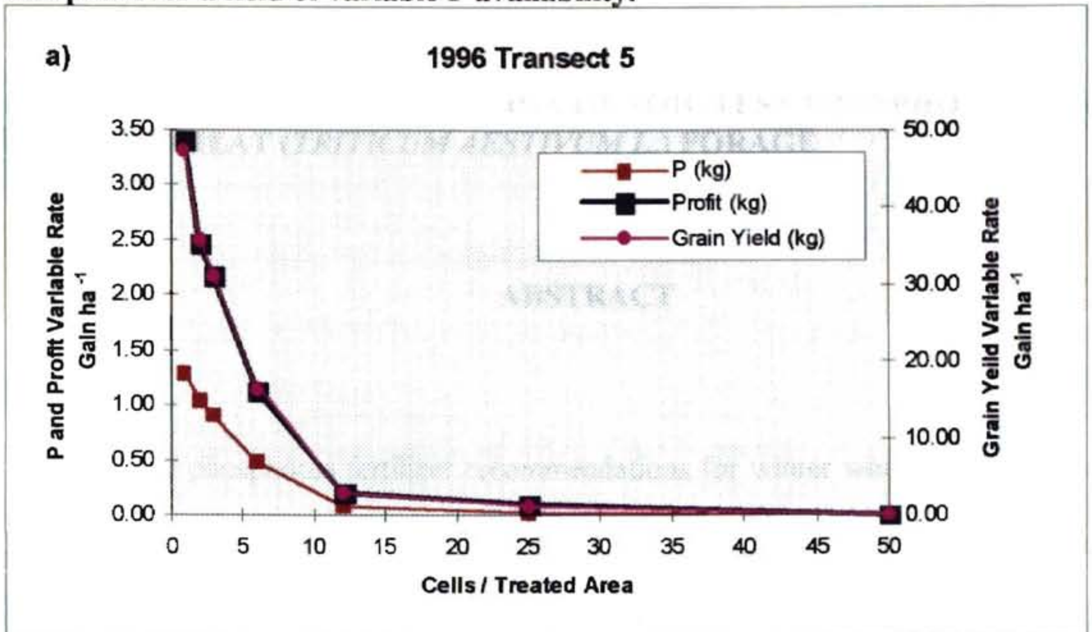
Table 5. Projected effects of constant 23 kg ha^{-1} rate P fertilizer on mean STP and variability over a 50 year period.

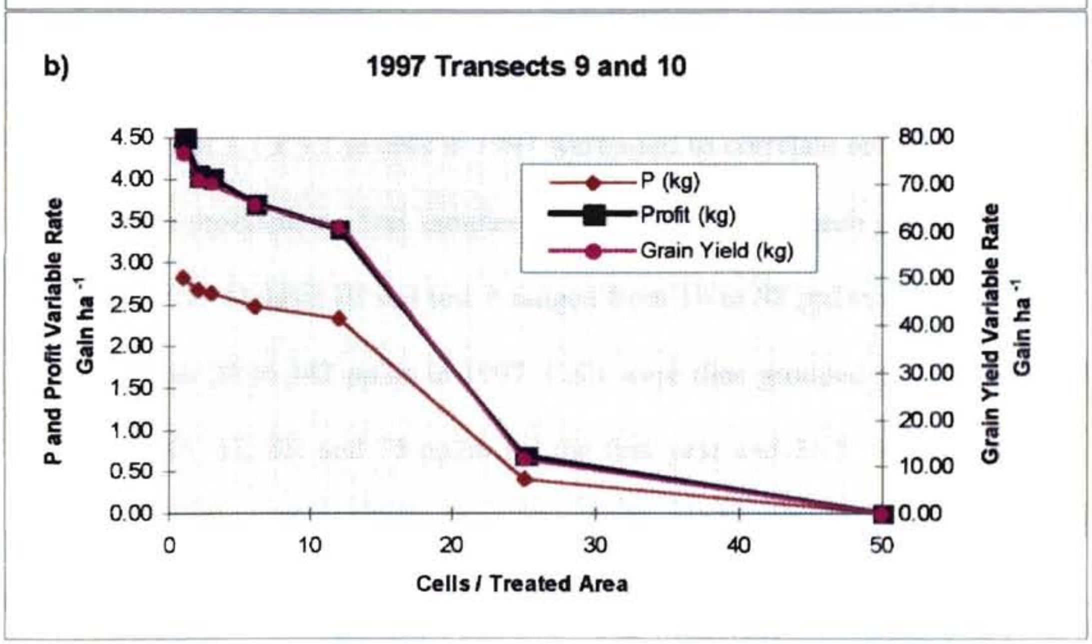
Data Set ID		Year 1	Year 10	Year 20	Year 30	Year 40	Year 50
1996 Transect # 5	Mean STP (pp2m)	47	58	70	82	94	106
	Std Dev	13.97	13.97	13.97	13.97	13.97	13.97
	Minimum STP	18.00	28.81	40.82	52.82	64.83	76.84
	Maximum STP	86.00	96.81	108.82	120.82	132.83	144.84
1996 First 50 Samples	Mean STP (pp2m)	28	39	51	63	75	87
	Std Dev	14.08	14.07	14.07	14.07	14.07	14.07
	Minimum STP	10.00	20.88	32.89	44.90	56.91	68.92
	Maximum STP	86.00	96.81	108.82	120.82	132.83	144.84
1996 Last 50 Samples	Mean STP (pp2m)	55	66	78	90	102	114
	Std Dev	11.66	11.66	11.66	11.66	11.66	11.66
	Minimum STP	36.00	46.81	58.82	70.83	82.84	94.84
	Maximum STP	88.00	98.81	110.82	122.82	134.83	146.84
1997 Transects # 1 & 2	Mean STP (pp2m)	78	92	109	125	141	157
	Std Dev	27.60	27.60	27.60	27.60	27.60	27.60
	Minimum STP	33.00	47.41	63.42	79.43	95.44	111.45
	Maximum STP	142.00	156.41	172.42	188.43	204.44	220.45
1997 Transects # 4 & 5	Mean STP (pp2m)	88	103	119	135	151	167
	Std Dev	22.86	22.86	22.86	22.86	22.86	22.86
	Minimum STP	51.00	65.41	81.42	97.43	113.44	129.45
	Maximum STP	132.00	146.41	162.42	178.43	194.44	210.45
1997 Transects # 9 & 10	Mean STP (pp2m)	67	82	98	114	130	146
	Std Dev	22.63	22.63	22.63	22.63	22.63	22.63
	Minimum STP	26.00	40.41	56.42	72.44	88.45	104.46
	Maximum STP	119.00	133.41	149.42	165.43	181.44	197.45

Table 6. The effect of decreasing field element size on grain yield, P fertilizer use, and profit of a field.

Data Set ID	Cells Per Treated Area	Grain Yield (kg/ha^{-1})	P (kg/ha^{-1})	Profit ($ ha^{-1})
1996 Transect # 5	50	0.00	0.00	0.00
	25	1.14	0.02	0.10
	12	2.87	0.08	0.20
	6	16.40	0.48	1.13
	3	31.07	0.89	2.17
	2	35.76	1.04	2.47
	1	47.44	1.29	3.41
1996 First 50 Samples	50	0.00	0.00	0.00
	25	-4.01	0.05	-0.52
	12	6.72	0.47	0.07
	6	21.02	0.87	1.09
	3	27.81	1.10	1.51
	2	32.99	1.20	1.94
	1	37.62	1.28	2.34
1996 Last 50 Samples	50	0.00	0.00	0.00
	25	3.28	0.17	0.12
	12	3.72	0.18	0.16
	6	3.40	0.19	0.11
	3	6.94	0.33	0.30
	2	15.72	0.62	0.85
	1	27.31	0.92	1.72
1997 Transects # 1 & 2	50	0.00	0.00	0.00
	25	0.00	0.00	0.00
	12	18.55	0.72	1.02
	6	26.52	1.01	1.49
	3	33.17	1.35	1.75
	2	37.56	1.49	2.03
	1	45.67	1.71	2.62
1997 Transects # 4 & 5	50	0.00	0.00	0.00
	25	0.00	0.00	0.00
	12	0.00	0.00	0.00
	6	0.00	0.00	0.00
	3	6.93	0.22	0.46
	2	7.59	0.24	0.49
	1	9.72	0.29	0.67
1997 Transects # 9 & 10	50	0.00	0.00	0.00
	25	11.52	0.41	0.70
	12	60.86	2.34	3.40
	6	65.50	2.48	3.71
	3	70.00	2.63	4.00
	2	71.14	2.67	4.06
	1	76.78	2.81	4.49

Figure 4. The effect of decreasing field element size on grain yield, P fertilizer use, and profit for a field of variable P availability.





Chapter II

CORRELATION AND CALIBRATION OF SOIL TEST PHOSPHORUS FOR WINTER WHEAT (*TRITICUM AESTIVUM L.*) FORAGE

ABSTRACT

Many phosphorus fertilizer recommendations for winter wheat production do not consider forage production. Production of fall forage is of great importance for management of wheat pasture in the Southern Great Plains. In this study a 15.2 m x 152.3 m area made up of 3.1 x 3.1 m cells in 1996 and a 30.5 x 76.2 m area within the same field made up of 3.1 x 3.1 m cells in 1997 were used to correlate soil test phosphorus with wheat forage production. Soil samples were collected from each cell in the summers of 1996 and 1997. Mehlich III soil test P ranged from 10 to 88 pp2m among the 250 cells in 1996 and from 26 to 142 pp2m in 1997. Cells were then grouped by STP into groups of 15, 25, 35, 45, 55, 65, and 75 pp2m for the first year and 36.5, 46.5, 56.5, 66.5, 76.5, 86.5, 96.5, and 106.5 pp2m for the second year and randomly assigned to treatment groups of 0, 9.6, 19.7, 29.3, and 39.3 kg P fertilizer ha^{-1}. P fertilizer was applied to the cells in September of 1996 and October of 1997 followed by a treatment of 112 kg N ha^{-1} over the entire plot. Winter wheat was planted in October, the forage was then harvested by hand in late December in 1996. No yield data was collected from the second year of the trial due to slow growth of fall forage due to the later planting date and environmental

conditions beyond our control. Data indicates that critical soil test P for forage production is at least 15% greater than the 73 kg ha^{-1} typically used for grain production.

INTRODUCTION

Soil P deficiency for wheat and other crops is common in the Central Great Plains area (Follet et al., 1987; Westfall et al., 1986). Work by Halvorson (1989) demonstrated that application of 34 and 67 kg P ha^{-1} increased wheat grain yields in field plots, however, his work did not discuss wheat forage. Most P soil-fertility work in the central Great Plains has concentrated on evaluating winter wheat response to P fertilizer application for only one crop (grain) harvest (Fiedler et al., 1987; Follett et al., 1987; Leikan et al., 1983; Peterson et al., 1981). Romer and Shilling (1986) stated that P uptake by wheat is the greatest during early growth stages due to high P requirements and not due to luxury consumption. This raises the question whether different responses to P fertilization would be obtained for early forage production, compared to grain yield responses.

Production of fall forage is of great importance for management of wheat pasture and the stocker cattle enterprise in the Southern Great Plains. In Oklahoma approximately 2.8 million hectare are planted in winter wheat each year. About 2.1 million hectare are planted with intentions of grazing and roughly 1.7 million hectare are actually utilized for grazing. Although wheat forage is of such economical importance, most phosphorus fertilizer recommendations for winter wheat do not consider fall forage production. Because 60% of the wheat grown in Oklahoma is utilized for grazing purposes and there is currently no phosphorus soil test calibration specifically for fall forage production it is important that we examine the relationship of soil test phosphorus to fall forage production. This study was developed in order to provide an estimate of how much P fertilizer should be added in order to maximize fall forage production in winter wheat.

Literature does not clearly define correlation or calibration of soil test values. Therefore, for this study we defined correlation as an examination of relative yield as a function of soil test P (STP). Calibration was defined as the process of determining the relationship of relative yield (at a specific STP level) as a function of fertilizer P rate.

Most correlation work is conducted in two steps consiting of a greenhouse trial with many soils and followed by field trials on less soils (Dahnke and Olson, 1990). Corey (1987) stated that results from the greenhouse trials cannot be directly transferred to field conditions. Fitts (1955) explained that plant growth and yield are functions of many variables that can be grouped into soil, crop, climate, and management variables. Because of the uncontrollable variables, results are less uniform and poorer correlations exist in field trials, therefore, fertilizer recommendations must be based on data collected from field trials. Correlation can be improved when the effects of some of the uncontrolled variables are minimized by calculating relative yield rather than an absolute yield (Bartholomew, 1972). This study was designed as a field trial utilizing one location in order to limit environmental effects. In addition, relative yield was used rather than absolute yield in order to improve the correlation.

The data from this study was used to evaluate correlation between Mehlich III STP and fall forage yield and to calibrate P requirements for fall wheat forage production on P deficient soils. Additionally data was used to compare colorimetric P analysis methods with analysis of P using an inductively coupled argon plasma (ICP) atomic emission spectrophotometer.

The objectives of this study were to evaluate the relationship between STP and fall forage yield using both colorimetric and atomic emission spectrometer methods, and to develop fertilizer recommendations for fall forage production.

MATERIALS AND METHODS

In the first year of the study a 0.23 ha area that measured 15.5 x 152.3 m was divided into five transects each containing fifty 3.1 x 3.1 m cells (Figure. 1). For the second year a 0.23 ha area that measured 30.5 x 76.2 m within the same field was divided into ten transects each containing twenty-five 3.1 x 3.1 m cells (Figure. 2). The field is a cultivated Norge loam (fine-silty, mixed, thermic Udic Paleustoll) located at the North end of the North Stillwater research station in Stillwater, Oklahoma. In the summers of 1996 and 1997 soil samples were collected from the 250 cells of the appropriate study area. Ten cores 2 cm in diameter and 15 cm deep were randomly collected and mixed to form a composite sample for each cell. P was extracted from the composite samples using the Mehlich III extractant (Mehlich, 1984) and Phosphorus was analyzed using a Milton Roy spectrophotometer with color development achieved by using a modified Murphy and Riley procedure.(Murphy and Riley 1962, Watanabe and Olsen, 1965).

Mehlich III soil test P (STP) by colorimetric methods for the first year ranged from 10 to 88 pp2m among the 250 cells and from 26 to 142 pp2m for the second year. Cells were then selected by mean STP and divided into groups of 15, 25, 35, 45, 55, 65, and 75 pp2m $\pm$ 2 pp2m for the first year and 36.5, 46.5, 56.5, 66.5, 76.5, 86.5, 96.5, and 106.5 pp2m $\pm$ 2 pp2m for the second year. Cells from each group were randomly assigned to treatment groups of 0, 9.6, 19.7, 29.3, and 39.3 kg P fertilizer ha^{-1} for both years. In the first year of the study P fertilizer was applied to treated cells in mid September followed by an application of 112 kg N ha^{-1} over the entire study area. 'Tonkawa' variety wheat was planted in early October and forage was harvested by hand clipping forage to the soil surface from a $0.4m^2$ area within treated cells in mid December. The forage was oven dried and yield was calculated using dry forage weights. In the second year of the study lime was added at the rate of 4.5 metric ton of ECCE lime ha^{-1} followed by application of 112 kg N ha^{-1} over the entire study area in mid October. Following incorporation of lime and N, P fertilizer was applied and incorporated, then 'Tonkawa' variety wheat was planted. However, no yield data was collected from the second year of the trial because of slow growth of fall forage related to the later planting date and wet conditions during the desired harvest period. During the second year of the trial P was re-extracted in duplicate using the Mehlich III extractant (Mehlich, 1984) then analyzed utilizing the inductively coupled plasma (ICP) atomic emission spectrophotometer followed by analysis using a Milton Roy spectrophotometer with color development achieved by using a modified Murphy and Riley procedure (Murphy and Riley 1962, Watanabe and Olsen, 1965).

After collection of (1996) yield data the relationship between soil test P and % maximum yield was examined. This was conducted by dividing the yield from the zero P fertilizer treatments (check plots) at a given soil test P level by the overall maximum yield and multiplying by 100%. Next we evaluated the correlation of % maximum yield with soil test P within the soil test P group. P fertilizer requirements were calibrated by creating response curves from the data in order to find the P fertilizer level that produced the maximum yield at each STP level. P fertilizer levels that produced maximum yields then were used to develop P fertilizer recommendations for fall forage production. The P fertilizer recommendations for fall forage were then compared to current recommendations for grain production (Allen and Johnson, 1993).

RESULTS AND DISSCUSSION

Results from the correlation of soil test P and % maximum yield (Figure. 3) demonstrated that a relationship existed between Mehlich III extractable P and fall forage production. A coefficient of determination of 0.59 was achieved with this method when utilizing a quadratic response model. These results where comparable to data from other field correlation trials (Corey, 1987). However, correlation trials customarily examine the relationships with respect to a particular soil test level. Therefore, we evaluated the correlation of % maximum yield with soil test P within the STP group (Figure. 4). When using this approach the coefficient of determination increased slightly to 0.60 when considering a quadratic response model. We were able to determine % maximum yield using STP as x in the regression equation developed from the correlation where % maximum yield = $-0.0022x^2 + 0.87x + 23.36$. We believe that either equation is strong enough to evaluate fall forage yield. However, the second approach was chosen to develop the STP calibration because we believe that it predicted the most realistic response to addition of P fertilizer, because this approach is based on response within a STP group rather than the entire data set.

Calibration determined that forage P requirement is higher than recommended P for grain production (Figure. 5). We found that forage production requires approximately 12 kg ha^{-1} more P fertilizer than current grain production recommendations, at STP levels between 15 and 45 pp2m in order to reach maximum yield. This indicates that fall wheat forage production can be improved by application of P in excess of current STP calibrations for wheat grain production. A STP value of 65 pp2m is considered as the critical level for wheat grain production. Results from the first year of this study indicate that the critical STP level for wheat forage production is 75 pp2m which is 15% greater than the critical level for grain production.

Mehlich III extracted P values were higher when analyzed by ICP compared to colorimetric methods used in this study. However a good linear correlation between ICP and the colorimetric procedure was obtained (Figure. 6). A coefficient of determination of 0.91 indicates that there is a strong relationship between the two methods. However use of the ICP may overestimate the availability of soil P. The ICP analysis of P correlated well with the 1996 forage yield data resulting in a coefficient of determination of 0.58 (Figure. 7). This is similar to the coefficient of determination that was found using the colorimetric method. Therefore, future P correlation work may want to consider the use of ICP analysis due to ease of analysis with ICP and requirement of less time of analysis compared to when using colorimetric methods.

CONCLUSIONS

Similar to other short season crops higher fertilizer P is required to correct deficiencies for fall forage compared to that for long season crops such as wheat grain. Initial results indicate that maximum forage production is reached when P fertilizer is added to soils with a Mehlich III soil test P of 75 pp2m or less. However, because of changes in management practices, yield potential, and wheat varieties, soil test correlation and calibration trials should be continuously examined. The increased P requirement of forage may be due to changes in management practices, yield potential, or varieties. Results from this study agree with the hypothesis that forage production will require more P fertilizer than grain production. However, this study should be continued in order to verify the results from a single years worth of data and to examine the amount of P fertilizer that would be required for the production of both wheat forage and grain.

REFERENCES

Allen, E., and G. Johnson. 1993. OSU soil test interpretations. OSU Extension Facts No. 2225. Oklahoma St. Univ. Cooperative Extension Serv. Stillwater, OK.

Bartholomew, W.V. 1972. Soil nitrogen-supply processes and crop requirements. North Carolina State Univ. Int. Soil Testing Ser. Tech. Bull.6.

Corey, R.B. 1987. Soil Test procedures: Correlation. P. 15-22. *In* J.R. Brown (ed.) Soil testing: Sampling, correlation, calibration, and interpretation. SSSA Spec. Publ, 21. SSSA, Madison, WI.

Dahnke, W.C. and R.A. Olson. 1990. Soil test correlation, calibration and recommendation. *In* R.L. Westerman (ed.) Soil testing and plant analysis, 3rd ed. SSSA, Madison, WI.

Fitts, J.W. 1955. Using soil tests to predict a probable response from fertilizer application. Better Crops Plant Food 39(3):17-20.

Halvorson, A.D. 1989. Multiple year response of winter wheat to a single a application of phosphorus fertilizer. Soil Sci. Soc. Am. J. 53:1862-1868.

Leikam, D.F., L.S. Murphy,,, D.E. Kissel, D.A. Whitney, and H.C. Moser. 1983. Effects of nitrogen and phosphorus application and nitrogen source on winter wheat yield and leaf tissue phosphorus. Soil Sci. Soc. Am. J. 47:530-535.

Mehlich, A. 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15(12):1409-1416.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

Peterson G.A., D.H. Sander, P.H. Grabouski and M.L. Hooker. 1981. A new look at row and broadcast phosphate recommendations for winter wheat. Agron. J. 73:13-17.

Romer and Shilling. 1986. Phosphorous requirements of the wheat plant in various stages of its life cycle. Plant and Soil 91:221-229.

Taylor, Robert E. 1994. Beef Production and Management Decisions. 2nd ed. Macmillan, New York, NY.

Watanabe, F.S., and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Am. Proc. 29:677-678.

Westfall, D.E., R.H. Follett, and J.W. Echols. 1986. Fertilization of dryland winter wheat. Colorado State Univ. Service-In-Action. No.114. Fort Collins.

Figure 1. Diagram of 1996 study area, randomly sampled as 250 individual 3.1 x 3.1 m cells, Stillwater, OK.

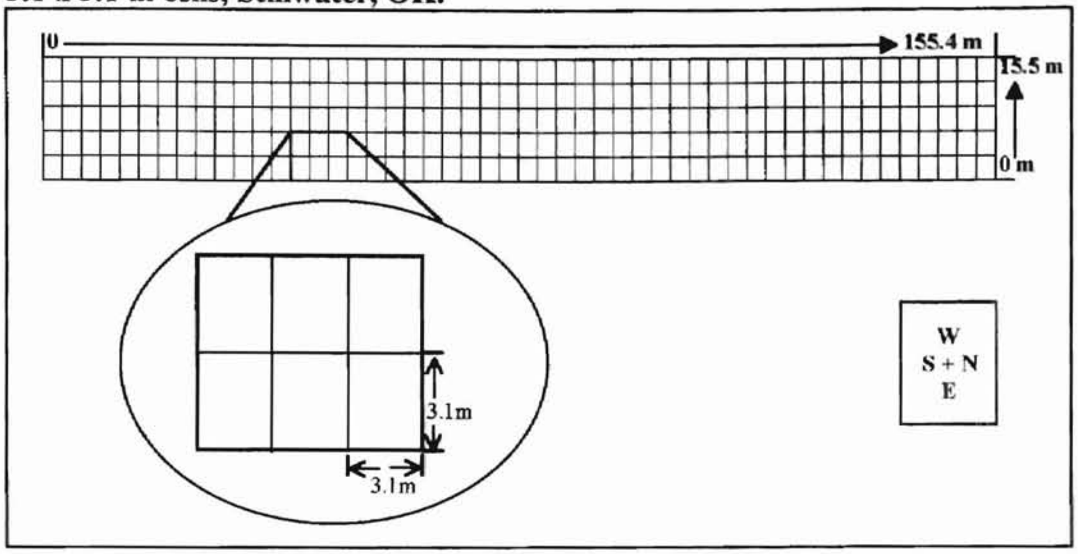


Figure 2. Diagram of 1997 study area, randomly sampled as 250 individual 3.1 x 3.1 m cells, Stillwater, OK.

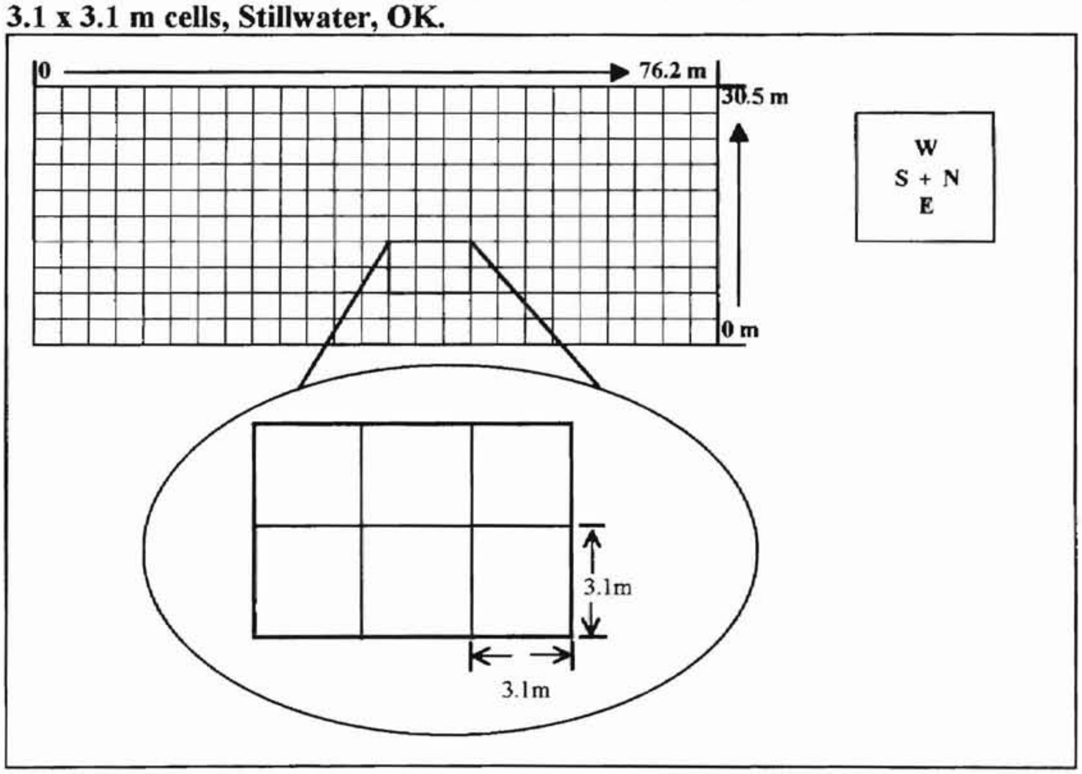


Figure 3. Correlation of overall % maximum yield with soil test P.

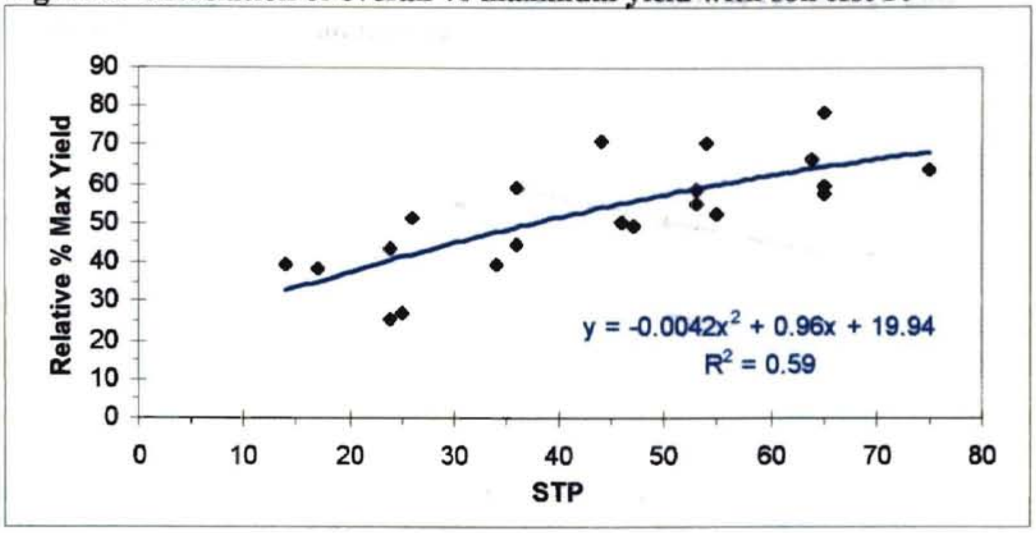


Figure 4. Correlation of STP group % maximum yield with soil test P.

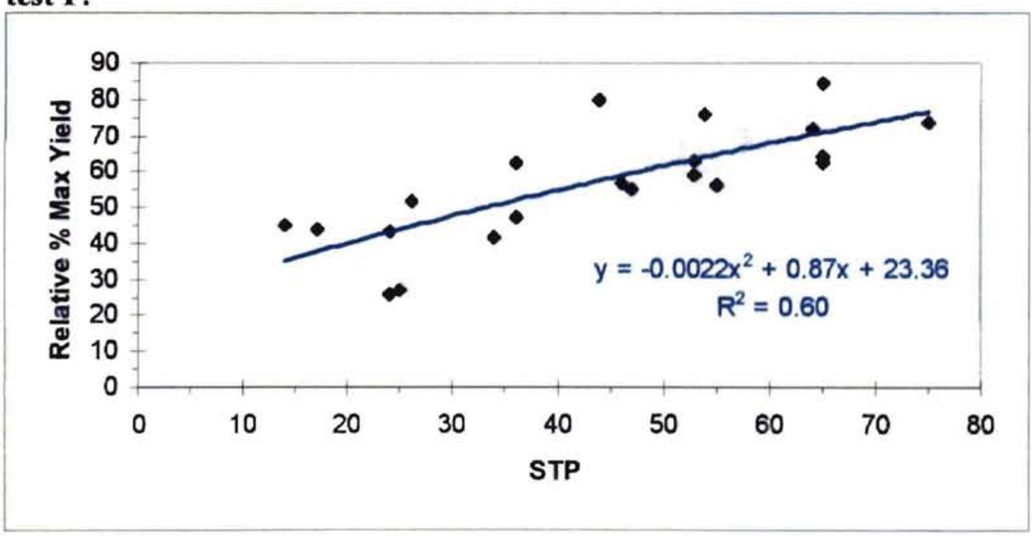


Figure 5. Comparison of P fertilizer recommendations for forage and current P fertilizer recommendations for grain.

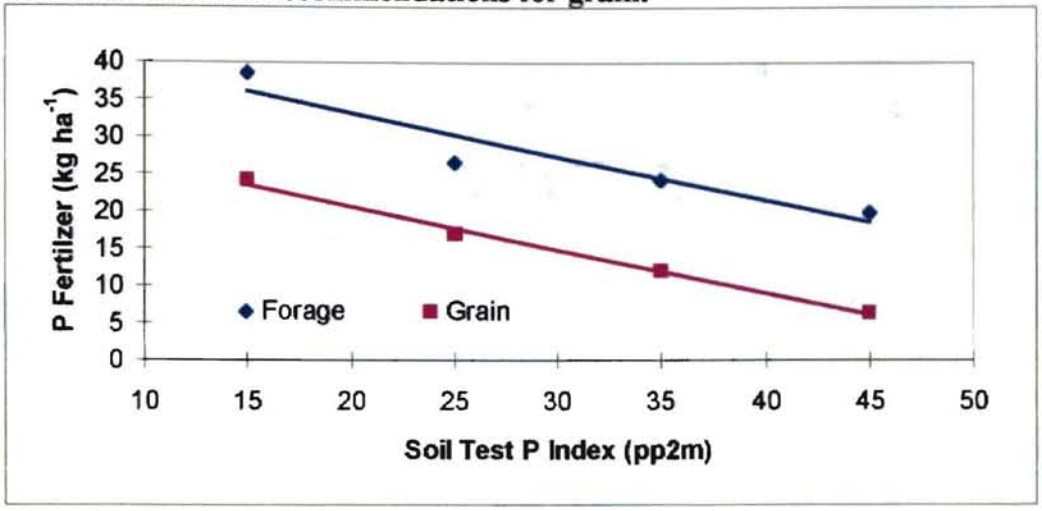


Figure 6. Comparison of P analysis by ICP and colorimetric procedure.

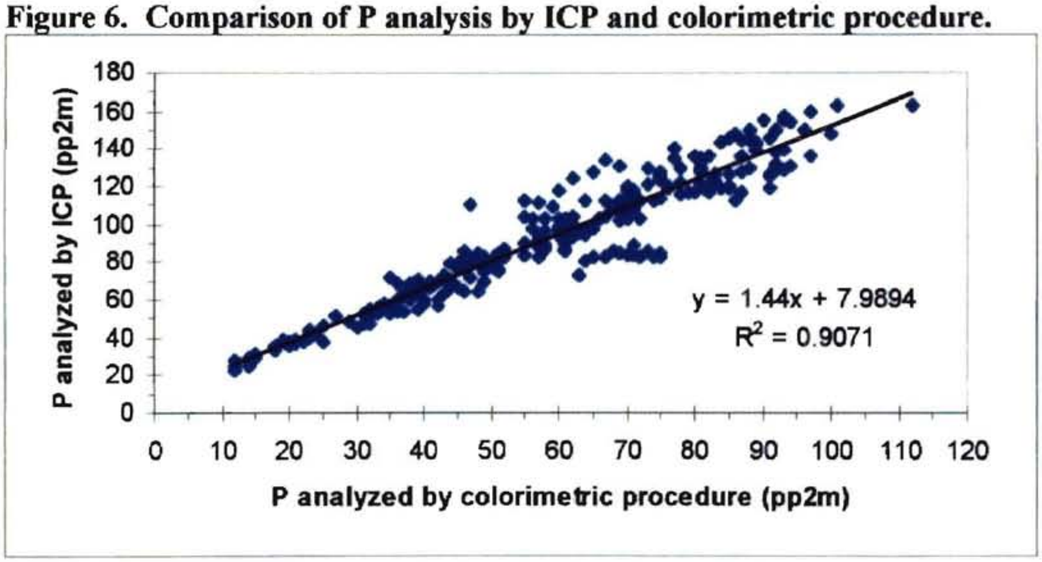
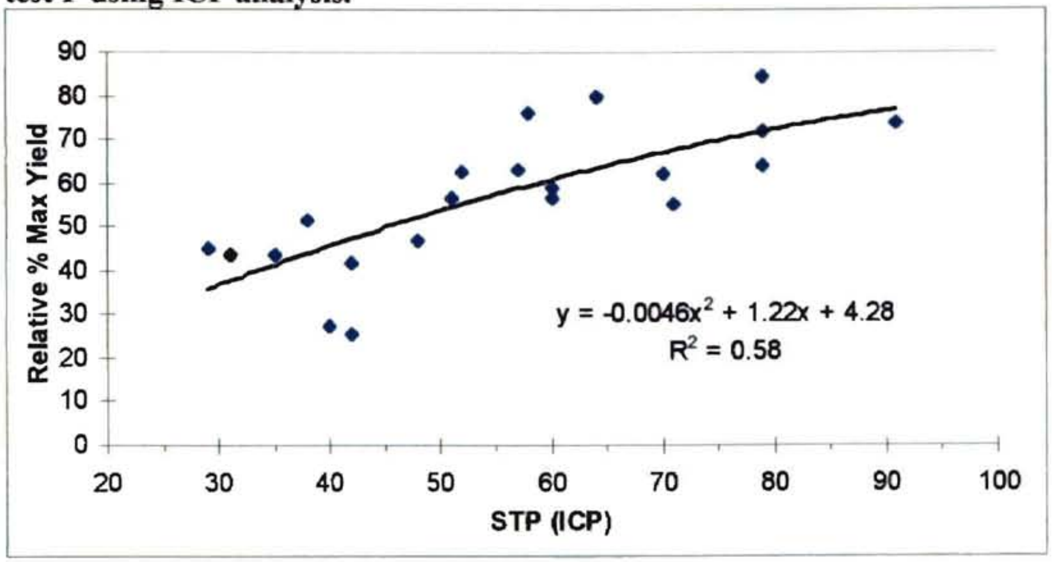


Figure 7. Correlation of STP group % maximum yield with soil test P using ICP analysis.



2

VITA

Michael W. Goedeken

Candidate for the Degree of

Master of Science

Thesis:

SOIL TEST PHOSPHORUS VARIABILITY ACROSS LANDSCAPES AND PROJECTED EFFECTS OF VARIIABLE RATE P FERTILIZATION

Major Field: Agronomy

Biographical:

Personal Data: Born in Columbus, Nebraska, On March 4, 1971, the son of M. W. (Bill) Goedeken and Connie J. Goedeken

Education: Graduated from Columbus High School, Columbus, Nebraska in May 1989; Attended the University of Nebraska, Lincoln, Nebraska Majoring in Animal Science August 1989 to December 1992, received Bachelor of Science degree in Animal Science from Oklahoma State University, Stillwater, Oklahoma in May 1995. Completed the requirements for the Master of Science degree in Plant and Soil Sciences at Oklahoma State University in May 1998.

Experience: Raised on a horse farm near Columbus, Nebraska; employed as a farm laborer during summers; employed by the University of Nebraska, Animal Science Department as an undergraduate assistant August 1989 to December 1992; employed by Oklahoma State University, Department of Plant and Soil Sciences, Soil, Water, and Forage Analytical Laboratory as a Laboratory Technician, February 1993 to present.