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Soil Tests to Relate Responses of Grain Sorghum (*Sorghum vulgare*) to Superphosphate Treatments on a Calcareous Indian Soil

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Michael Lyle Colegrove

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Date of Approval:

November 15, 1971 — Dale E. Baker
Dale E. Baker
Professor of Soil Chemistry
Chairman of Committee
Thesis Co-Adviser

November 15, 1971 — Richard H. Cole
Richard H. Cole
Associate Professor of Agronomy
Thesis Co-Adviser

Nov 15. 1971 — James L. Starling
James L. Starling
Head of the Department of Agronomy

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TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	iv
LIST OF FIGURES	v
LIST OF APPENDIX TABLES	vi
INTRODUCTION	1
OBJECTIVES	4
MATERIALS AND METHODS	5
RESULTS AND DISCUSSION	13
Stover and Grain Yields	13
Soil Chemical Analyses	16
Leaf and Seed Analysis	17
Phosphorus Uptake	17
Utility of Hybrid Sorghum in India	18
Bray No. 1 Extractant	20
Bray No. 2 Extractant	21
Olsen's $NaHCO_3$ Extractant	26
Baker Adsorption Method	27
Correlations	31
Evaluation of the Adsorption Method	33
SUMMARY	37
CONCLUSIONS	39
REFERENCES	40
APPENDIX	47

LIST OF TABLES

Table		Page
1	Selected chemical and physical properties of the soil samples taken from the Gram Sevak Training Centre Farm at Manjri, in Maharashtra State, India, before the first treatment date	6
2	Treatment and sampling and harvest schedule for field studies on crop response to phosphorus applications at the Gram Sevak Training Centre Farm at Manjri in Maharashtra State, India	9
3	Outline of the four testing procedures used in soil samples taken from the Gram Sevak Training Centre Farm at Manjri in Maharashtra State, India, in 1969, 1970, and 1971	10
4	May 1971 harvest data for sorghum stover yields, grain yields, and total amount of P taken up by the grain as influenced by treatment dates and P treatments	14
5	Regression values (r) calculated for final stover yield, grain yield and P uptake by the grain (Y), against the logarithm of soil P (X) as determined by four test procedures	19
6	Soil phosphorus levels in samples collected in June 1971 as determined by four test procedures and influenced by treatment dates and P treatments	22
7	Correlation coefficients (r) relating sorghum stover yield in May 1971 harvest, to the logarithm of soil P levels as measured by four test procedures before planting (B) and after harvest (A)	24
8	Correlation coefficients (r) relating sorghum grain yield in May 1971 harvest, to the logarithm of soil P levels as measured by four test procedures before planting (B) and after harvest (A)	25
9	Phosphorus evaluation levels for the four test procedures used in the study	36

LIST OF FIGURES

Figure		Page
1	Scatter diagram relating per cent of maximum sorghum grain yield for the May 1971 harvest with the logarithm of the P concentration in equilibrium solution measured by Baker's procedure	34

LIST OF APPENDIX TABLES

Table		Page
10	The effects of harvest dates, treatment dates and P treatments on sorghum stover shown as per cent of maximum possible yield on a dry weight basis . . .	48
11	The effects of harvest dates, treatment dates and P treatments on sorghum seed shown as per cent of maximum possible yield on a dry weight basis	49
12	Phosphorus levels in soil samples measured by Bray No. 1 extraction method as influenced by sampling dates, treatment dates, and P treatments	50
13	Phosphorus levels in soil samples measured by Bray No. 2 extraction method as influenced by sampling dates, treatment dates, and P treatments	51
14	Phosphorus levels in soil samples measured by Olsen's $NaHCO_3$ extraction method as influenced by sampling dates, treatment dates, and P treatments	52
15	Phosphorus levels for soil samples measured by Baker's adsorption method as influenced by sampling dates, treatment dates, and P treatments	53
16	Correlation coefficients (r) relating sorghum stover yields to the logarithm of soil P levels as measured by four methods	54
17	Correlation coefficients (r) relating sorghum grain yields to the logarithm of soil P levels as measured by four methods	58
18	Effect of P treatments on the soil test levels of other soil components within sampling dates and treatment dates. Results from the Pennsylvania State University Soil and Forage Testing Laboratory and by Baker's modified equilibrium solution	61
19	Effect of P treatments on the uptake of certain elements by sorghum leaf and grain, within sampling dates and treatment dates. Results from the Pennsylvania State University Horticulture Department	62

INTRODUCTION

Multiple season studies of residual responses to fertilizer applications on calcareous soils have been neglected for many years. Phosphorus (P) studies, for the most part, have been designed to study P in acid soils under long-term rotations, P extracted by various reagents or P uptake by plants. When studies on calcareous soils have been carried out, they have usually dealt with (a) one-year field experiments, (b) samples from greenhouse experiments carried out for other purposes, or (c) 'pure systems' (13, 23, 30, 37, 51, 54, 67). Notable exceptions to this are the investigations reported by Hunter, et al. (28), Webb, et al. (80), and Yurtsever, et al. (85).

Coupled with the lack of field studies under calcareous soil conditions has been the lack of consistency as to what portion of the 'available' P gives the best index for plant growth. Investigators have found that the Bray and Kurtz No. 1 (14) and the Bray and Kurtz No. 2 (14, 26) extractants are best used on acid soils for P indices, but references are still cited for calcareous soils (11, 35, 54). In this manuscript they will be referred to as the Bray No. 1 and No. 2 methods respectively. The sodium bicarbonate technique developed by Olsen, et al. (47) is accepted by many as giving the best measure of available P in calcareous soils, and has gained wide acceptance in arid regions throughout the world (73, 85). Objections to the use of this technique arise from the need for a colorless filtrate and its temperature dependence (48).

Perhaps the oldest technique, that of water extraction has resulted in the greatest amount of inconsistency in the literature. Many investigators under varying soil and cropping conditions, have reported successful use of this technique (54, 75, 78), while others had poor or erratic results (11, 41, 82).

The use of water soluble P as an availability index for plant use has many objections. The prevalent aluminum, iron and calcium phosphates have such low solubility products that P concentrations in solution are hard to measure accurately. It has been noted (23, 75) that either prolonged agitation or successive extractions continue to bring P into solution, making it difficult to determine how much and what fraction is available for plant growth. A new approach to soil testing under development by Baker (5) seeks to overcome some of these objections. The Baker approach will be referred to as the adsorption technique in this manuscript.

Colorimetric techniques to measure P concentrations have led to contradictory conclusions. The use of ammonium molybdate and stannous chloride as proposed by Dickman and Bray (20) has long been used as the standard technique. However the narrow range of sensitivity and the poor color stability have caused it to come under attack. The use of isobutyl alcohol (59) greatly increased the range of sensitivity and eliminated the problem of particulate matter in the filtrate. The use of a single solution which contains ascorbic acid as a reductant as proposed by Murphy and Riley (43) has eliminated almost all procedural objections to water soluble P extraction and subsequent color development. Watanabe and Olsen (78), compared the ascorbic acid

technique with stannous chloride and the isobutyl alcohol technique for determining water soluble P, and P extracted with $NaHCO_3$. They found that the ascorbic acid technique gave the same degree of accuracy with fewer procedural problems. In studying 74 soils from all over the world, van der Paauw (75) found the Murphy and Riley technique to give excellent results for all soils and seemed to measure P concentrations independent of O.M. content, particle size, $CaCO_3$ content and P fixing capacity.

OBJECTIVES

The lack of comprehensive field studies and the variability of phosphorous soil testing procedures have led to contradictory conclusions concerning fertilizer management practices for calcareous soils. Because of these inconsistencies this study was undertaken to study the fixation and availablility of P on a calcareous soil in India. Through the use of different soil testing procedures and plant responses to fertilizer treatments over time, it was hypothesized that reliable tests for measuring soil P requirements for adequate plant growth could be developed.

India, as a developing country, has limited resources for the application of modern management practices in agriculture. The lack of machinery, high yielding crops, inexpensive fertilizers, and exploitable land, combine to make better management the most viable approach for increasing crop production.

At the present time, P availablity is measured, in India by the method of Olsen, et al. (47), which will be referred to in this manuscript as Olsen's technique. Certain objections have been raised concerning the use of this procedure (48) and for this study three other techniques were used to evaluate their applicability and potential use in India. Bray No. 1, and Bray No. 2 as modified by Graham (26), were included as reference procedures. A new procedure developed by Baker (5) which utilizes an equilibrium solution was tested to evaluate its effectiveness on calcareous soils and to determine whether it might be as suitable a P test procedure as Olsen's method.

MATERIALS AND METHODS

The study was divided into two parts: (1) the gathering of the field data in India and (2) the chemical analyses of soil and plant samples and statistical analyses of crop yield and chemical data at The Pennsylvania State University.

The field site was the Gram Sevak Training Centre Farm at Manjri, 7.5 kilometers (12 miles) southeast of Poona in Maharashtra State, India. A field measuring 0.2 hectare (0.5 acres) with a uniform soil that had not received phosphorus fertilizer was selected. The soil was mainly composed of alluvial deposits from basaltic parent materials. It had a high montmorillinite content and would be classified as a Grumaquert (65, 66). Data concerning some of the properties of the soil are presented in Table 1.

Three replications of 10 plots each were set out in a completely randomized block design. Individual plots were 6.1 x 9.1 meters (20 x 30 ft.) in dimension and each was surrounded by a bund to facilitate irrigation separately from neighboring plots. Of the 10 plots, one was designated as a check and received no P fertilizer during the three growing seasons encompassed by this study. The remaining nine plots were randomly assigned to three date-of-treatment groups of three plots each. At each of the three dates (10 October 1969, 8 July 1970, and 4 November 1970) three plots were fertilized with 90, 270, or 810 kg. of P per hectare (kg/ha), respectively. The P was applied as ordinary superphosphate (16%

Table 1. Selected chemical and physical properties of the soil samples taken from the Gram Sevak Training Centre farm at Manjri, in Maharashtra State, India, before the first treatment date.

CHEMICAL PROPERTIES[1]

Nitrate N (ppm)	P (ppm)	K	Mg	Ca
		(meq. per 100 g)		
17.0	6.0	0.53	13.2	72.5

% Base Saturation	Water pH	Organic Matter (%)	Soluble Salts (mmhos)
99.8	8.1	4.6	64.0

PHYSICAL PROPERTIES[2]

% Sand (2-.02mm)	% Silt (.02-.002mm)	% Clay (.002mm)	Textural Class	Coeff. of Linear Expansion
21.8	33.5	44.7	Clay	0.198

Bulk Density at:		% Moisture Retained at:		Avail. Moisture
1/3 Atm.	Oven Dry	1/3 Atm.	15 Atm.	(% weight basis)
0.94	1.61	50.9	28.3	22.6

[1]Properties determined by The Pennsylvania State University Soil and Forage Testing Laboratory.

[2]Properties determined by The Pennsylvania State University Soil Characterization Laborory.

P_2O_5 or 7% P). At each of the dates of P fertilization all plots received KNO_3 in amounts to provide 56 and 21 kg/ha of N and K, respectively. At the same time NH_4NO_3 was applied to provide N at a rate of 92 kg/ha, making a total N treatment of 112 kg/ha or 100 pounds per acre. All materials were broadcast on the surface and incorporated into the soil to a depth of 15 cm. (six inches).

Sorghum (Sorghum vulgare) seeds were planted five centimeters (2 inches) apart in 9.14 meter (30 ft.) rows spaced 60 cm. (2 ft.) apart. A bird-resistant, hybrid variety, McNair 546, was planted to minimize potential bird damage. Endrin at 0.05% concentration was sprayed 10, 20 and 30 days after emergence to reduce stem borer (Chilo zonellus) infestation. Phorate was applied at 2.5 kg/ha (2.2 lb/ac) at planting in July and November to decrease shoot fly (Antherigona indica) damage.

The plots were harvested and stover and grain yields taken in February and October 1970 and May 1971. Mature seedheads were harvested from two rows in each plot and weighed when wet, after drying and after threshing. All stover was cut from the same two rows and weighed after drying in the field for one week. Green forage yield was also taken in February 1971. At each harvest date a composite sample of the upper-most leaf or 'flag leaf' and/or grain sample was taken for analyses.

Leaf and grain material was packaged and sent from India to the Pennsylvania State University to be prepared and spectrographically analyzed for P, K, Ca, Mg, Fe, Cu, B, Al, Zn, Mn and Na by methods reported by Baker, et al. (6).

Surface soil samples to a depth of 15 cm. (6 in.) were taken from each plot and composited as 1-2 kg. (2.5-5.0 lb) subsamples, packaged and sent to the Pennsylvania State University for analyses. Samples were taken from the subsequently treated plots in February, June and November of 1970 and in February and June of 1971. The complete treatment, sampling and harvest schedule is presented in Table 2.

A subsample of soil from each treated plot was analyzed for pH on a 1:1 soil to water paste, and K, Ca, and Mg were extracted with 1 N NH_4OAc using a 1:10 soil to extractant ratio and a 30 minute shaking time. Nitrate N was determined colorimetrically using a modified phenol-disulfonic acid procedure (29). Organic matter (O.M.) was determined by a modified Walkley-Black technique (56). Soluble salts were measured by conductivity of a water extract (74). A second soil sample was equilibrated with a solution as outlined by Baker (5) and analyzed for K, Ca, Mg, and Na using a Perkin-Elmer 303 Atomic Absorption Spectrometer.

Phosphorus availability in all samples was measured by: Bray No. 1 with dilute acid-fluoride (14), Bray No. 2 (14, 26) extraction with concentrated acid-fluoride, Olsen's sodium bicarbonate extraction (47) and the P adsorption technique of Baker (5). Table 3 outlines each of the test procedures.

Statistical analyses and data conversions were done on the I.B.M. Model 360 computer using library programs from the Computation Center at the Pennsylvania State University. Raw data for stover yields,

Table 2. Treatment and sampling and harvest schedule for field studies on crop response to phosphorus application at the Gram Sevak Training Centre Farm at Manjri in Maharashtra State, India

Fertilizer Treatment	Planting Dates	Soil Sampled	Forage Harvest	Seed Harvest
October 10, 1969	October 14, 1969			
		February 23, 1970	February 11, 1970	February 9, 1970
		June 30, 1970		
July 8, 1970	July 8, 1970			
			October 28, 1970	October 26, 1970
November 4, 1970	November 4, 1970	November 1, 1970		
		February 15, 1971	February 15, 1971	
			May 12, 1971	May 12, 1971
		June 18, 1971		

Table 3. Outline of the four testing procedures used on soil samples taken from the Gram Sevak Training Centre Farm at Manjri in Maharashtra State, India, in 1969, 1970, and 1971.

Procedure	Test Solution	Soil: Solution Ratio	Shaking time	Color developed with:
Bray No. 1	0.03 N NH_4F + 0.025 N HCl	1:7	1 Min.	1.5% ammonium molybdate in 3.5 N HCl + $SnCl_2$
Bray No. 2	0.03 N NH F + 0.1 N HCl	1:7	1 Min.	1.5% ammonium molybdate in conc. HCl + p-methylaminophenol sulfate and $NaHSO_3$
Olsen	0.5 M $NaHCO_3$@ pH 8.5	1:20	30 Min.	1.5% ammonium molybdate and conc. HCl + 0.1 N $SnCl_2$
Adsorption Technique	1×10^{-4} M KH_2PO_4 + 1.5×10^{-4} M KCl + 10×10^{-4} M $MgCl_2$ + 50×10^{-4} M $CaCl_2$	1:10	1 Hour	1.056g of ascorbic acid added to 200 ml of reagent made up of 12g ammonium molybdate + 0.2908g antimony potassium tartrate + 350ml H_2O in 1000ml of 5 N H_2SO_4

grain yields, soil P, soil chemical data, elemental uptake by the plants and total P in the grain (yield x % P) were grouped for analysis of variance (AOV) by treatment date, sample date, and treatment x sample date. Even if mean values were not significantly different by AOV, Duncan's L.S.D. values (76) at the 0.05% significance level were calculated so that variance between treatment levels could be identified.

Linear correlations and regression values were calculated among stover yields, grain yields at each harvest and P availability as measured by each of the four extraction procedures. Since different P levels were found with each P test procedure, all correlation and regression values were checked by methods presented by Snedecor and Cochrane (63) to determine if the procedures were significantly different one from another.

Simple and multiple correlations were calculated for the final harvest (May 1971) data, to determine which would explain the greatest amount of variance. Correlation and regression equations were computed to relate stover yields, grain yields and P uptake by the grain to the logarithm of the amount of soil P measured by each P test procedure. Logarithmic scales for P concentrations have been used when values cover a wide range or the data fall in an exponential pattern (10, 22, 82) and were able to explain a greater amount of variance in this study.

A scatter diagram with the per cent of maximum yield for grain in

May 1971 plotted against the logarithm of P concentration in solution was used to evaluate the Baker adsorption procedure (5) for routine analyses.

RESULTS AND DISCUSSION

Stover and grain yields

Stover yields were erratic and not as useful as grain yields in differentiating between P treatments. With the October 1969 treatments, no significant differences were noted by AOV for the second and third harvests. Likewise, the July 1970 treatments showed no significant differences for the second harvest of mature stover. The November 1970 treatments showed highly significant differences in the February 1971 forage harvest but at maturity in May 1971, fewer significant differences were noted between treatments. The poor differentiation between treatments indicate that stover yields reflected fertilizer responses during the season following application only. In Table 4 the final harvest data are presented as a measure of the residual effects of P fertilizer treatments. With longer periods of time between P application and sampling, fewer significant differences were noted between the treatment levels. The overlapping significance values as measured by Duncan's L.S.D. (76) among treatment levels, indicated that sorghum was an effective utilizer of P in the soil at low levels and treatments above 270 kg/ha would seem unnecessary.

Grain yields were also erratic in that yields for different P treatments the season immediately following P applications in October 1969 and July 1970, were not significantly different. In the second harvest season for each date of treatment, the yield differences

Table 4. May 1971 harvest data for sorghum stover yields, grain yields and total amount of P taken up by the seed as influenced by treatment dates and P treatments.

Treatment dates	P treatments (kg/Ha) 0	90	270	810	Mean
		Stover Yields, Kg/Ha			
October 1969	3596.01a*	5487.02ab	5580.02ab	6091.52b	5188.64a
July 1970	3596.01a	5456.02ab	5735.02ab	6882.02b	5417.27a
November 1970	3596.01a	6308.52bc	5192.52ab	7579.52c	5669.14a
Treatment Mean	3596.01a	5750.52bc	5502.52b	6851.02c	
		Grain Yields, Kg/Ha			
October 1969	2221.78a	3193.63ab	3377.77ab	3782.94b	3144.03a
July 1970	2221.78a	3226.18ab	3596.94b	4135.72b	3296.16a
November 1970	2221.78a	3643.44b	4072.17bc	4571.27c	3627.17a
Treatment Mean	2221.78a	3354.42b	3682.30bc	4163.[illegible]	
		P Uptake by grain, Kg/Ha			
October 1969	9.19a	12.84a	16.59ab	21.53b	15.03a
July 1970	9.19a	13.97ab	17.18b	20.25b	15.15a
November 1970	9.19a	15.91ab	20.84bc	24.85c	17.70a
Treatment Mean	9.19a	14.23ab	18.20bc	22.21c	

*Different letters indicate significant differences at the .05% level by Duncan's L.S.D. values. Yields may be compared between treatment levels within each treatment date, or between treatment means, or between treatment date means within a harvest date.

were significant. The November 1970 treatments caused highly significant differences in seed yields only on the harvest of May 1971.

Overall, grain yields were better than forage yields as indicators of differences in effects of individual P treatments, but by the final harvest in May 1971 the differences between treatment dates were not significant. Grain yields were more affected by P treatments than were stover yields at comparable harvest dates (Appendix Tables 10 and 11). Significant differences between treatment levels over all harvests as measured by grain yields indicated that a treatment of 90 or 270 kg/ha would be optimal for a single season application.

Plant yields for the February 1970 harvest were very low due to severe insect infestations and lack of consistent irrigation. Shoot-fly (Antherigona indica) damage caused the death of plants less than 3-4 weeks old and secondary tillering on plants up to six weeks of age. Shoot-fly damage on older plants was responsible for reduced yields resulting from smaller seed heads. In July and November 1970, Phorate applied to give systemic protection was moderately successful in preventing seedling damage. The crop did not receive irrigation since this was the monsoon season and adequate rainfall occurred.

Results for the May 1971 harvest for both stover and grain were selected as the prime data for treatment comparisons. The uniformity of the coefficient of variation values (C.V.) in Tables 7 and 8, indicate that the initial P treatments of October 1969 and July 1970 had come to an 'equilibrium' with the soil. From Table 4, the

effects of superphosphate treatments on plant growth after 21, 12, and 8 months can be observed. Application of Duncan's L.S.D. test to the means for all rates of P and dates of P applications showed that the means for treatment dates were not significantly different. Among means for treatment levels, grain yields and P uptake from a P treatment of 810 kg/ha was significantly greater than either 0 or 90 kg/ha, but were not significantly higher than those with 270 kg/ha treatments.

While the yields for the final harvest were high by Indian standards[1], they were only 60% of what have been reported for the same variety by the New Mexico Agricultural Experiment Station (39) and the Ohio Agricultural Research Center (45).

Soil chemical analyses

All soil samples were analyzed by the Pennsylvania State University Soil and Forage Testing Laboratory for K, Mg, Ca, O.M., NO_3-N and soluble salts (56). Subsamples were analyzed by the adsorption method developed by Baker (5) for K, Mg, Ca, and Na. All data were subjected to AOV to provide information on the effects of P treatments on the chemical properties, Appendix Table 18. In most cases, differences in data for K, Mg, Ca, O.M. and NO_3-N were not significant, or when significant, were not consistent over treatment

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[1] Personal communication from Prof. G. R. Tatwawadi, Millets Specialist Parbhani, Maharashtra State, India. March 11, 1969. Local varieties yielded 15-30 quintals/hectare, hybrid varieties 30-45 quintals/hectare.

or sampling dates. It was concluded that the data were of limited value in explaining variances in yield or soil P.

Differences in amounts of soluble salts were in all cases significant at the first sampling date after the initial treatment. This would indicate that the high amount of superphosphate applied to the plots was coming into solution. At the second sampling date for plots fertilized in July and November 1970, differences in soluble salts were not significant. At the July 1970 sampling of plots fertilized in October 1969 differences in soluble salts were significant, this may have been because no water had been applied to the plots since February 1970 and hence no salts had been leached.

Leaf and seed analyses

Flag leaf and grain samples were spectrographically analyzed at the Pennsylvania State University Horticulture Department (6). From the data obtained and through subsequent AOV's it was determined that uptake of elements other than P was not influenced substantially by P treatments, Appendix Table 19.

Data for P concentration in the grain and grain yield were used to compute total grain P, Table 4. Data for uptake of other elements were not consistent enough to be used in explaining yield differences. There was no relationship between concentrations of elements found in leaves and those in the seed.

Phosphorus uptake

The uptake of P by the plant has been a useful technique to

evaluate availability of P in the soil (4, 7, 51, 75, 78). Data presented in Table 4 were calculated by multiplying the grain yield times the fraction of P in the grain. The amounts in the grain when corrected for yield differences, agree closely with those reported by other investigators (77). Since only flag leaf samples were taken for tissue analyses it was not possible to calculate P taken up by the whole plant.

Concentrations of P in the grain were not significantly affected by P fertilizer treatments; however significant differences were noted (Table 4) in the total quantities of P harvested in the grain. Data presented for the May 1971 harvest did not show significant differences between treatment date means but did show highly signficant differences between P treatment levels both within treatments and pooled over all treatment dates. Subsequent correlations between soil P levels as measured by four procedures and total P in the grain gave higher, but not necessarily significantly different, correlations than those between stover and grain yields, Table 5.

Utility of hybrid sorghum in India

McNair 546 hybrid sorghum was chosen for this study because of its bird resistant characteristics and response to fertilizers. This variety has been used in the United States as a feed grain and yields very well under a wide variety of conditions (39, 45). It was initially thought to be a variety with potential for adaptive use in India; however, under field conditions this was not found to be true. Its short stature, a favorable characteristic with mechanized harvesting,

Table 5. Regression values (r) calculated for final stover yield, grain yield and P uptake by the grain (Y) against the logarithm of soil P (X) as determined by four test procedures. Where $Y = a + bx + cx^2$.

Soil Test	a	b	c	r
		Stover Yield		
Bray No. 1	40.81	27.72		.415 *
Bray No. 2	25.04	34.65		.448 **
Olsen	11.29	44.42		.573 **
Adsorption	30.10	58.42		.500 **
		Grain Yield		
Bray No. 1	49.91	34.49		.556 **
Bray No. 2	-86.53	252.06	-87.45	.671 **
Olsen	-59.84	173.05	-54.94	.777 **
Adsorption	33.91	77.58		.715 **
		P Uptake by the Grain		
Bray No. 1	6.80	11.95		.634 **
Bray No. 2	-28.25	65.35	-21.04	.747 **
Olsen	-5.30	18.61		.852 **
Adsorption	2.50	24.60		.747 **

* = significance at the .05% level; ** = significance at the .01% level; Second degree equations are given only for those found to give a significantly better fit than a first degree equation.

meant less forage than obtained with local varieties. Because the thick, tough stalk made this variety unpalatable to cattle, it appeared that the best use of the stover was as fuel for cooking. The grain of this sorghum variety was hard to grind for bread; therefore it was viewed less favorably by the people than the commonly grown Indian varieties.

The variety was susceptible to attack by most insects, particularly shoot-fly, and needed close and expensive management to be grown successfully. The bird resistance was found to be a relative factor. As long as alternative food sources were available, McNair 546 was not eaten. In 1971 no other food sources were available and total loss to birds was prevented only by bagging the seed heads in the rows selected for harvest.

The plant reaches 50% bloom in about 60 days and is between 115 and 125 cm. (46-50 in.) tall at maturity, which is attained in 109 to 140 days. The seed coat has a dark red-brown color and, because of the presence of organic compounds, gives the grain a bitter taste which is objectionable to birds. The compounds decompose at maturity and after drying, the grain may be fed to animals.

Bray No. 1 extractant

The use of Bray No. 1 extractant under calcareous conditions has met with limited success, but because of its wide acceptance on other soils, it has been used as a standard against which new procedures are measured (7, 21, 55). The inclusion of acid in the extractant brings

the more active calcium phosphates into solution and prevents their precipitation (29). However in soil with very hich calcium contents, the dilute acid is neutralized by free carbonate or the Ca^{++} ion is complexed with the F^{-} ion and negates P complexing (11, 29). This may explain the low P levels reported in Table 6. When stover and grain yields were correlated with P levels in May 1971, Bray No. 1 extractant was significant in only three cases, Tables 7 and 8. These results support the conclusion that this extractant is not suitable for measurement of P levels in calcareous soils.

Bray No. 2 extractant

Bray No. 2 extractant was included in this study to test the hypothesis that a more concentrated acid might overcome the objections listed above for the Bray No. 1 method. This extractant has not been used widely since on acid soils Bray No. 1 has proven superior (7) and on calcareous soils, Olsen's extractant has been widely accepted (47, 54, 73, 85).

Data for the final sampling date, Table 6, show Bray No. 2 to be better than the Bray No. 1 but not as consistent as Olsen's or the adsorption method. Perhaps even the 0.1 N HCl acid was not concentrated enough to overcome the effects of the high Ca content of the soil used in this study. Some investigators (60, 72) feel that by increasing the solution to soil ratio, acid extracts are more valuable. This was not tried in this study but may warrant further investigation.

The consistency, high correlations and the number of discrete

Table 6. Soil phosphorus levels in samples collected in June 1971 as determined by four tests procedures and in influenced by treatment dates and P treatments

Treatment dates	P treatments (kg/Ha)				Mean
	0	90	270	810	
		Bray No. 1, as Parts/Million			
October 1969	3.33a*	4.67ab	7.00ab	10.33b	6.33a
July 1970	3.33a	3.00a	4.67ab	24.33b	5.33a
November 1970	3.33a	7.33a	11.33a	24.33b	11.58b
Treatment Mean	3.33a	5.00ab	7.67b	15.00c	
		Bray No. 2, as Parts/Million			
October 1969	6.00a	7.40a	11.40b	15.8[illegible]	10.15a
July 1970	6.00a	7.60a	13.60b	33.40c	15.15b
November 1970	6.00a	9.40ab	20.20b	38.46c	18.52b
Treatment Mean	6.00a	8.13a	15.07b	29.22c	
		Olsen's $NaHCO_3$, as Parts/Million			
October 1969	6.7a	8.0a	14.3b	19.7c	12.2a
July 1970	6.7a	10.0ab	15.0b	34.7c	16.6b
November 1970	6.7a	18.0b	23.3b	40.7c	22.2c
Treatment Mean	6.7a	12.0b	17.6c	31.7d	

Table 6. (Continued)

Treatment dates	P treatments (Kg/Ha)				Mean
	0	90	270	810	
	Adsorption Method, as μM in solution				
October 1969	2.20a	3.73b	3.73b	4.30c	3.49a
July 1970	2.20a	2.66a	2.70a	5.73b	3.33a
November 1970	2.20a	4.73b	4.47b	7.77c	4.74b
Treatment Mean	2.20a	3.64b	3.63b	5.93c	

*Different letters indicate significant differences at the .05% level by Duncan's L.S.D. values. P levels may be compared between treatment levels within each treatment date, or between treatment means, or between treatment date means.

Table 7. Correlation coefficients (r) relating sorghum stover yield in May 1971 harvest, to the logarithm of soil P levels as measured by four test procedures before (B) planting and after (A) harvest. Each coefficient included results for a sampling date over P treatments and harvest dates.

Treatment Date	Soil Sample Date	P Test Procedure	Linear Corr. Coefficient	P Level† Sig.	Yield† Sig.	Yield C.V.
October 1969	November 1970 (B)	Bray No. 1	0.224 NS	**	NS	37.0
		Bray No. 2	0.214 NS	**	NS	37.0
		Olsen	0.378 NS	**	NS	37.0
		Adsorption	0.219 NS	**	NS	37.0
October 1969	June 1971	Bray No. 1	0.204 NS	NS	NS	37 0
		Bray No. 2	0.384 NS	**	NS	37.0
		Olsen	0.588 *	**	NS	37.0
		Adsorption	0.362 NS	*	NS	37.0
July 1970	November 1970 (B)	Bray No. 1	0.483 NS	**	NS	31.2
		Bray No. 2	0.668 *	**	NS	31.2
		Olsen	0.457 NS	**	NS	31.2
		Adsorption	0.664 *	**	NS	31.2
July 1970	June 1971 (A)	Bray No. 1	0.687 *	NS	NS	31.2
		Bray No. 2	0.605 *	**	NS	31.2
		Olsen	0.713 **	**	NS	31.2
		Adsorption	0.613 *	**	NS	31.2
November 1970	June 1971 (A)	Bray No. 1	0.566 NS	*	*	38.2
		Bray No. 2	0.375 NS	**	*	38.2
		Olsen	0.549 NS	**	*	38.2
		Adsorption	0.599 *	**	*	38.2

† Significant differences where indicated in stover yield and phosphorus test levels by AOV of P treatment levels, where * = .05%; ** = .01%; NS = no significant differences at the .05% level.

Table 8. Correlation coefficients (r) relating sorghum grain yields in May 1971 harvest, to the logarithm of soil P levels as measured by four test procedures before (B) planting and after (A) harvest. Each coefficient included results for a sampling date over P treatments and harvest dates.

Treatment Date	Soil Sample Date	P Test Procedure	Linear Corr. Coefficient	P Level† Sig.	Yield† Sig.	Yield C.V.
October 1969	November 1970 (B)	Bray No. 1	0.543 NS	**	NS	26.7
		Bray No. 2	0.376 NS	**	NS	26.7
		Olsen	0.511 *	**	NS	26.7
		Adsorption	0.556 NS	**	NS	26.7
October 1969	June 1971 (A)	Bray No. 1	0.569 NS	**	*	26.7
		Bray No. 2	0.569 NS	**	*	26.7
		Olsen	0.735 **	**	*	26.7
		Adsorption	0.646 *	**	*	26.7
July 1970	November 1970 (B)	Bray No. 1	0.577 *	**	*	26.4
		Bray No. 2	0.714 **	**	*	26.4
		Olsen	0.571 NS	**	*	26.4
		Adsorption	0.669 *	**	*	26.4
July 1970	June 1971 (A)	Bray No. 1	0.552 NS	**	*	26.4
		Bray No. 2	0.682 *	*	*	26.4
		Olsen	0.745 **	**	*	26.4
		Adsorption	0.672 *	*	*	26.4
November 1970	June 1971 (A)	Bray No. 1	0.600 *	*	**	27.3
		Bray No. 2	0.671 *	*	**	27.3
		Olsen	0.839 **	**	**	27.3
		Adsorption	0.828 **	**	**	27.3

† Significant differences were indicated in grain yield and phosphorus test levels by AOV of P treatment levels, where * = .05%; ** = .01%; NS = no significant differences at the .05% level.

treatment level distinctions obtained indicated that the Bray No. 2 method compared favorably with Olsen's and the adsorption technique when all sample dates were compared, Appendix Table 13.

Olsen's $NaHCO_3$ extractant

This extraction procedure is designed to decrease and hold constant the ionic activity of Ca. The solubility product of $CaCO_3$ (0.87×10^{-8}) is so low that in the presence of the concentration of carbonate ion in 0.5 M $NaHCO_3$, calcium phosphates are dissolved, thereby increasing phosphate activity and the amount of extractable P (29, 48).

As shown in Table 6 values for extractable P are somewhat higher than for Bray No. 2. There were more significant differences in levels of P measured by the Olsen technique than by either the Bray No. 1 or No. 2 procedures. Values for P extracted by Olsen's extractant from soils receiving P at 270 or 810 kg/ha were significantly greater, for each application date, than those for soils receiving P at 0 or 90 kg/ha. This was not unexpected since in the field small nodules of presumably nearly pure superphosphate were formed in the soil. Since superphosphate is water soluble, this could result in high P levels in solution.

For each treatment date, assuming that the P fertilizer applied was confined to the upper 15 cm. (6 in.) of soil and neglecting indigenous P, the levels of P extracted from soil treated with P at

810 kg/ha approached the amount applied. With the same assumptions, about 70 per cent of the applied P was extracted from the soil treated with P at 270 kg/ha.

From the June 1971 data, the greatest number of differences between treatment levels or treatment dates were made by P levels measured with Olsen's extractant. These data would also confirm the optimum P levels by the Olsen method to be 18 to 25 ppm as reported in the literature (48).

Baker adsorption method

Water soluble P most closely approximates the conditions under which plants must grow (10, 75, 81, 82). The range of P levels in natural soil solutions necessary for adequate plant growth have been reported to be between 0.1 and 2.5 ppm, with the availability of P and the uptake by the plant being governed by soil properties and the type of plant (10, 22, 50).

With the Baker adsorption method the concentrations of several cations and phosphorus are held at levels and ratios which would be considered near optimum for plant growth. For calcareous soils, this solution would tend to hold the activities of calcium and magnesium constant and the availability of P should then be a direct function of the relative partial molar free energy of P in solution (5):

$$(\overline{F} - \overline{F}^{\circ})_P = RT \ln \overline{\gamma}_P C = RT \ln \overline{A}_P \qquad (1)$$

where; $(\overline{F} - \overline{F}^{\circ})_P$ is the relative partial molar free energy of P, R is

the universal gas constant, T is the absolute temperature, $\overline{\gamma}_p$ is the average activity coefficient, $\overline{C}_p$ is the concentration of P in the substrate, and $\overline{A}_p$ is the average activity of P. The P in a soil exists primarily as $HPO_4^{=}$ and $H_2PO_4^{-}$ ions depending upon pH. Thus for the adsorption method to be equally applicable on different soils the pH and temperature should be held constant. For calcareous soils these conditions are easily attainable as the pH is maintained constant by the presence of free calcium carbonates in the soil and labor-tory temperature fluccuations are relatively small.

The concentrations of other ions are maintained at nearly uniform levels in the testing solution for all samples being tested; therefore, the concentration of P remaining in the testing solution, after equilibration with the soil, provides a direct measure of P activity ($\overline{A}_p$) of the samples. If the uptake of P by plants is more a function of $\overline{A}_p$ than $\overline{C}_p$, as several investigators have concluded (5, 8, 10, 22, 52, 53, 78, 81), then the Baker adsorption method (5) should provide a more reliable measurement of P availability when soils having different adsorption of fixation characteristics ($\overline{\gamma}_p$) are tested. For soils of a given area where $\overline{\gamma}_p$ of equation (1) remains the same for all samples being tested, the Baker adsorption method and the Olsen sodium bicarbonate method should be nearly equal for evaluating the P availability of soils. The Olsen method was design to extract the available P [$\overline{C}_p$ of equation (1)] while the Baker method strives to measure P availability [$\overline{A}_p$ of equation (1)] (4, 21). The Baker testing solution supplies enough P to the soil to grow a crop;

therefore, initially $\overline{C}_p$ should not be limiting. Thus the adsorption method attempts to differentiate soils by evaluating the P adsorption or P fixation characteristics of soil as reflected by $\overline{A}_p$ after equilibrium. With this approach the availability of P to plants is determined from the effects that a soil has on an ion in solution rather than the effect of a solution on the soil (5).

After the addition of 100 ml equilibrating solution to 10g of soil, the sample was shaken for one hour and allowed to stand overnight to insure equilibration between soil and solution P (22, 75). Samples were then filtered and P determined colorimetrically following procecures outlined by Murphy and Riley (43).

The test solution supplies 31 ppm of P to the soil being tested. Beckwith (10) working with acid soils of Australia found it necessary to add 50 to 500 ppm of P as sodium phosphate to obtain P concentrations between 0.1 and 2.0 ppm in equilibrium solutions. Conversion of solution concentrations reported in Table 5 show values for this study to range from 0.68 to 2.41 ppm.

With the addition of 3.1 ppm P to the adsorption solution (31 ppm soil P), a level approaching an optimum return for a single season application is approximated. If the soil is able to fix most of the P added to the solution then the same reaction will occur under field conditions. In that case plant response is related to the P fixing capacity of the soil rather than the availability of P based on the application rate or water solubility of the fertilizer material (42).

Soil P data are presented in Table 6 and Appendix Table 15. The values are in agreement with those in the literature and show

significant differences between treatment levels and treatment dates. As was experienced with all four testing procedures, the extreme treatments, 0 and 810 kg/ha were better defined than 90 or 270 kg/ha treatments.

In the final sampling, P levels measured by Olsen's method were significantly different more often than P levels measured by the adsorption technique, correlations between stover yields, grain yields or P uptake by the plant were not significantly higher, Tables 5, 7, 8. When all sample dates were compared, Appendix Table 15, adsorption P levels were significantly different nearly as often as Olsen's extraction P levels. Similar relationships between water soluble P extraction and Olsen's extraction were noted by Pack and Gomez (54). The effect of the chlorides of Ca, Mg, and K in the equilibrating solution to maintain a constant ionic strength and calcium activity was considered important. Other investigators (3, 81) have used calcium salts of similar concentrations to increase the amount of P coming into solution.

As presented in Table 6, for the June 1971 data, there was 3.5 times as much P in solution on the soils receiving the highest rate of P as on the untreated soils. The ranges were even greater from data in Appendix Table 15. A comparison of the soil sampled in February 1970, for the October 1969 treatments, indicated that 725 times as much P came into solution with the highest P treatment compared with untreated plots. These values were related closely to those for Olsen's extraction and may have been high for the reasons

mentioned before. With the initial samples for the July and November 1970 treatments the ratio of P levels on the P-treated to untreated plots were 100 and 13 times, respectively. The ratios of P-treated to untreated plots for October 1969, June 1970 and November 1970 were 2.0, 2.2, and 3.5 respectively, at the June 1971 sampling date. While the fixation capacity of the soil did not seem to have been satisfied, the positive benefits of residual phosphorus were measured.

The use of the adsorption method has many advantages. It requires only two reagents, one for equilibration and one for color development. In addition, the need for activated charcoal is eliminated. The filtered solutions are clear and the color developed is intense with good stability. Free energy relationships can be conveniently calculated with changes in ion concentration. Simple apparatus can be constructed for multiple sampling and standard laboratory equipment can be used to measure P concentrations in solution.

Correlations

Regression equations and correlation coefficients were calculated for the relationshops between stover yield, grain yield and total P in grain at the May 1971 harvest and values for P obtained by testing samples obtained in June 1971, Table 5. All correlation coefficients were highly significant (P = 0.01) or significant. Total P in grain was more highly correlated with soil P than were grain or stover yields. In the case of each of the variables, the correlation

coefficients relating the soil P, were highest for the Olsen procedure followed by the Baker adsorption, Bray No. 2 and Bray No. 1 procedures.

Data in Tables 7 and 8, and Appendix Tables 16 and 17, were categorized so that P levels in the soil as measured before the crop was planted and after harvest could be compared to stover yields and grain yields. Stover yields, when compared with P levels measured before planting, were significantly correlated only once with Bray No. 2 and the adsorption technique. Measuring P after the harvest showed Olsen's to be the best measure with four significant correlations followed by the adsorption method and Bray No. 2 with three each and Bray No. 1 with two. When grain yields were used to measure P response a greater number of significant values were calculated. Sampling before planting showed all soil P test procedures to have two significant values. After harvests, the adsorption method and Olsen's could be correlated to yield six times, followed by Bray No. 2 with four and Bray No. 1 with three.

Other investigators (11, 54, 85) have measured P response by means of yields and P contents of crops and found the data from field investigations to be erratic. For the most part, P uptake and yield data have been collected in greenhouse studies on immature plants. While field studies may result in lower measurements or correlation values, they are still the best measure of management. Extrapolation of greenhouse or laboratory data may be useful in understanding many fundamental soil-plant interactions but information so gained is not always directly applicable to field conditions (10).

Evaluation of the Adsorption Method

From the data presented in Tables 5, 7, and 8, the adsorption method of testing for soil P compared quite well with the Bray No. 2 and Olsen's $NaHCO_3$ extraction procedures. Pack and Gomez (54) noted water soluble P was correlated significantly with both Olsen's and Bray's extracted P and uptake of P by cotton and alfalfa on calcareous soils.

The values in Table 6 are reported as moles per liter x 10^{-6} (μM) of P in solution after equilibration with the soil rather than concentrations in the soil. Soil properties such as cation exchange capacity, organic matter and texture have been reported (75) not to influence P levels in an equilibrium solution. These soil characteristics would have to be assigned coefficient values in order to relate solution P directly to soil P. From the range of P concentrations reported by Beckwith (10), it would appear that each soil has its own definite characteristics and a single coefficient could not be applied to all soils or to soils seemingly of similar nature. A standard solution could be used to characterize the relative P availability and possibly P fixation properties. In this study P fixation characteristics were taken into account when P levels were evaluated.

In order to evaluate the adsorption technique as a possible basis for field recommendations, the per cent of the maximum yield within the May 1971 harvest date was plotted against the logarithm of P concentration, Figure 1. By using the per cent of maximum yield

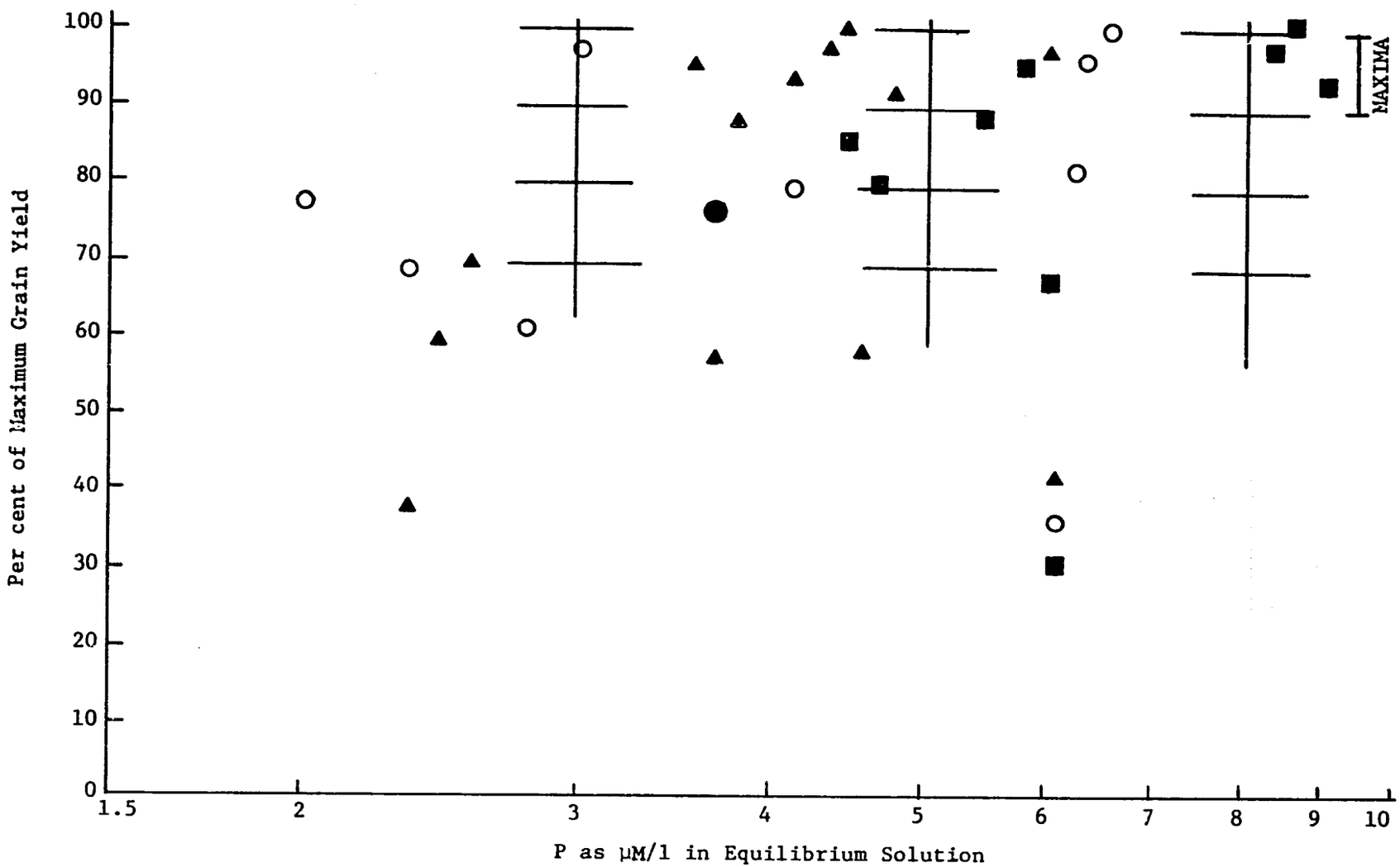

Figure 1. Scatter diagram relating per cent of maximum sorghum grain yield for the May 1971 harvest with the logarithm of the P concentration in equilibrium solution measured by Baker's procedure.

value, management problems related to field conditions could be eliminated without losing a measure of response to residual P from the October 1969 and June 1970 fertilizer applications. The use of logarithmic values for P concentrations is in keeping with the use of equation (1).

As Figure 1 illustrates, the data group themselves into two distinct areas, those below 70% maximum yield and those above. Further, a clear grouping below 3.0 μM appears to be a logical point to differentiate low soil test values. In the range of 3.0 - 5.0 μM values are scattered between 75 and 100% maximum yield, indicating some response to low treatment levels or residual effects of earlier applications. Between 5.0 and 8.0 μM yields were high and indicated that the levels of P in the soil for plant growth was near optimum. In an attempt to find the highest level of P in the soil measured with an equilibrium solution at which a sorghum grain yield increase would result from application of P, the first derivative of the second degree equation for all yield and soil P test values was calculated. The maxima value was found to be 8.48 μM and this value was arbitratily defined as "high" to indicate that any values found above this level indicate soil P is adequate and no remedial measures are necessary (Table 9).

Table 9. Phosphorus evaluation levels for the four test procedures used in this study, shown as ppm in the soil for Bray No. 1, Bray No. 2 and Olsen's $NaHCO_3$ and as μM in equilibrium solution for the adsorption method.

	By Cited Literature	P.S.U. Laboratory
Bray No. 1	< 3 = very low	< 15 = very low
	3 - 7 = low	15 - 30 = low
	7 - 20 = medium	30 - 50 = medium
	> 20 = high	50 - 80 = high
		> 80 = very high

	By Missouri Laboratory	
Bray No. 2	< 5 = low	P needed in excess of 115 ppm
	5 - 20 = low	P needed; 75 - 110 ppm
	20 - 40 = medium	P needed; 10 - 75 ppm
	> 40 = high	P not needed

Olsen $NaHCO_3$

< 5 = low
5 - 10 = medium
10 - 18 = adequate
18 - 25 = high
> 25 = very high

Adsorption method

< 3.0 = very low
3.0 - 5.0 = low
5.0 - 8.0 = adequate
8.0 - 10.0 = high
> 10.0 = high

SUMMARY

A two-part study was undertaken to evaluate P fixation on a calcareous soil in India in an attempt to refine the management practices and soil tests associated with phosphorus fertilization. Field plots were established in Maharashtra State, India, and 0, 90, 270, and 810 kg/ha of P as superphosphate was applied on three separate dates during 1969 and 1970. Plots were harvested for stover yields four times, grain yields three times and soil samples were taken on five dates over a 23 month period.

Grain and leaf samples from each harvest were spectrographically analyzed at the Pennsylvania State University for uptake of P, K, Ca, Mg, Mn, Fe, Cu, B, Al, Zn, and Na. Soil samples were analyzed by the Pennsylvania State University Soil and Forage Testing Laboratory for pH, exchangeable K, Mg, and Ca; organic matter, nitrate-N, and soluble salts.

Soil subsamples were analyzed for P by four techniques to obtain correlations among available P, plant yield, and P uptake by the plants. The four soil tests for P included: Bray No. 1 extractant (0.03 N NH_4F + 0.025 N HCl); Bray No. 2 (0.03 N NH_4F + 0.1 N HCl); Olsen's extractant (0.5 M $NaHCO_3$ buffered to pH 8.5); and an adsorption method developed by Baker in which the equilibrating solution contained 100 μM of P as KH_2PO_4, 0.005 M $CaCl_2$, 0.001 M $MgCl_2$ and 0.00025 M KCl. Phosphorus concentrations in the solution after equilibrium were used to estimate optimum P levels in the soil.

From the data collected after three grain harvests, four stover harvests and five soil sampling dates on 30 plots, the results were summarized as follows:

1. In comparing the number of significant differences as indicated by Duncan's L.S.D. values, the levels of P measured by Baker's adsorption method and Olsen's method were the most consistent. The regression (r) values relating total grain P to soil test values were 0.85, 0.75, 0.74, and 0.63 for the Olsen, Baker, Bray No. 2 and Bray No. 1 methods, respectively.
2. Highest linear correlation coefficients and best graphic displays were obtained when the total uptake of P by the grain (Y) was plotted against the logarithm of P levels in solution (X) regardless of the soil P test procedure.
3. Stover yields were the poorest data for indicating responses to P treatments over time
4. Grain yield data were slightly better than stover yields for differentiating between P treatments.
5. Grain uptake of P gave a better measure of P treatment effects than either stover or grain yields.
6. Leaf analysis to measure elemental concentrations and interactions involving P, K, Ca, Mg, Mn, Fe, Cu, B, Zn, Na and Al did not explain yield differences.

CONCLUSIONS

As was theorized from the chemistry in soil of the Baker equilibrating solution and the Olsen extracting solution, the two methods were about equal for predicting the availability of P in a calcareous soil. It was concluded that for future work involving different soils containing free calcium carbonate, both tests should be used in order to determine if the adsorption method of Baker is equal to or superior to the Olsen method. The ease with which P concentrations could be measured by the Baker adsorption technique makes it promising for use in India.

As a guide to P evaluation in the soil by Baker's adsorption technique for comparison against soil P by the Olsen method, the following P levels are suggested.

Phosphorus Availability	Baker's Adsorption Technique (μM/l in solution)	Olsen's Method (ppm in soil)
Very Low	< 3.0	< 5.0
Low	3.0- 5.0	5.0-10.0
Adequate	5.0- 8.0	10.0-18.0
High	8.0-10.0	18.0-25.0
Very High	> 10.0	> 25.0

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APPENDIX

Table 10. The effects of harvest dates, treatment dates and P treatments on sorghum stover shown as percent of maximum yield on a dry weight basis

Harvest dates	Treatment dates	P Treatments (Kg/Ha) 0	90	270	810	Treatment date means
		Stover Yields (%)				
February 1970	October 1969	69.99a*	72.39a	69.76a	83.73b	73.96
October 1970	October 1969	69.46a	90.82a	78.06a	71.27a	72.78a
" "	July 1970	51.63a	54.55a	74.70ab	92.08b	68.17a
Treatment Means		58.36a	69.98a	74.05a	79.55a	
February 1971	October 1969	8.77a	35.20a	47.32a	57.40a	52.17a
" "	July 1970	9.31a	55.23b	57.21b	75.69c	49.36a
" "	November 1970	9.37a	70.97b	76.93b	93.93c	62.58b
Treatment Means		9.30a	43.58b	46.76b	59.02c	
May 1971	October 1969	44.70a	68.21a	69.34a	75.73a	55.51a
" "	July 1970	40.49a	61.43ab	64.57ab	77.48b	57.96a
" "	November 1970	38.47a	67.49bc	55.55ab	81.09c	60.65a
Treatment Means		38.47a	61.53bc	58.87b	73.30c	

* Different letters indicate significant differences at the .05% level by Duncan's L.S.D. values. Yields may be compared between treatment levels within each treatment date, or between treatment means, or between treatment dates within a harvest date.

Table 11. The effects of harvest dates, treatment dates and P treatments on sorghum grain shown as percent of maximum yield on a dry weight basis.

Harvest dates	Treatment dates	P Treatments (Kg/Ha) 0	90	270	810	Treatment date means
		Stover Yields (%)				
February 1970	October 1969	56.44ab*	44.41a	64.21ab	80.12b	61.29
October 1970	October 1969	49.61a	35.36a	46.21a	86.71b	46.31a
" "	July 1970	42.18a	51.95ab	82.29bc	91.34c	66.94b
Treatment Means		42.17a	41.011a	60.78a	82.53b	
May 1971	October 1969	55.38a	79.60ab	84.19ab	94.29b	66.80a
" "	July 1970	49.63a	72.06ab	80.34b	92.38b	70.01a
" "	November 1970	47.20a	77.41b	86.52bc	97.12c	77.06a
Treatment Means		47.20a	71.27b	78.23bc	88.45c	

*Different letters indicate significant differences at the .05% level by Duncan's L.S.D. values. Yields may be compared between treatment levels within each treatment date, or between treatment means, or between dates within a harvest date.

Table 12. Phosphorus levels in soil samples measured by Bray No. 1 extraction method as influenced by sampling dates, treatment dates, and P treatments

Sampling dates	Treatment dates	P Treatments (Kg/Ha) 0	90	270	810	Treatment date means
February 1970	October 1969	3.67a*	16.67ab	46.00b	157.00c	55.83
June 1970	October 1969	2.33a	7.33a	20.00b	54.33c	21.00
November 1970	October 1969	1.33a	1.00a	3.00b	5.50c	2.71a
" "	July 1970	2.67a	4.33a	4.67a	54.67b	16.58b
Treatment Means		2.00a	2.67a	3.83a	30.08b	
February 1971	October 1969	2.67ab	1.33a	3.33ab	4.00b	2.83a
" "	July 1970	1.33a	2.33a	4.00a	18.50b	6.54a
" "	November 1970	2.67a	8.00a	13.00a	60.00b	20.92b
Treatment Means		2.22a	3.89a	6.78	27.50b	
June 1971	October 1969	3.33a	4.67ab	7.00ab	10.33b	6.33a
" "	July 1970	3.33a	3.00a	4.67ab	10.33b	5.33a
" "	November 1970	3.33a	7.33a	11.33a	24.33b	11.58b

*Different letters indicate significant differences at the .05% level by Duncan's L.S.D. values. Phosphorus levels may be compared between treatment levels within each treatment date, or between treatment means, or between treatment dates within a harvest date.

Table 13. Phosphorus levels in soil samples measured by Bray No. 2 extraction method as influenced by sampling dates, treatment dates, and P treatments.

Sampling dates	Treatment dates	P Treatments kg/ha 0	90	270	810	Treatment date means
		Soil P (ppm)				
February 1970	October 1969	22.80a*	26.80a	69.27b	87.60c	51.62
June 1970	October 1969	17.00a	15.80a	17.00a	41.60b	22.85
November 1970	October 1969	10.40ab	9.80a	14.00b	26.40c	15.50a
November 1970	July 1970	10.40a	20.40ab	29.60b	70.80c	32.30b
Treatment Means		10.40a	15.10ab	21.80b	48.60c	
February 1971	October 1969	10.40a	12.20a	12.80a	25.87b	15.32a
February 1971	July 1970	10.40a	12.60a	26.00b	59.20c	27.05b
February 1971	November 1970	10.40a	17.40a	37.40b	73.40c	34.65c
Treatment Means		10.40a	14.07a	25.40b	52.82c	
June 1971	October 1969	6.00a	7.40a	11.40b	15.80c	10.15a
June 1971	July 1970	6.00a	7.60a	13.60	33.40c	18.52b
June 1971	November 1970	6.00a	9.40ab	20.20b	38.46c	18.52b
Treatment Means		6.00a	8.13a	15.07b	29.22c	

* Different letters indicate significant differences at the .05% level by Duncan's L.S.D. values. Phosphorus levels may be compared between treatment levels within each treatment date, or between treatment means, or between treatment dates within a harvest date.

Table 14. Phosphorus levels in soil samples measured by Olsen's $NaHCO_3$ extraction method as influenced by sampling dates, treatment dates, and P treatments.

Sampling dates	Treatment dates	P Treatments kg/ha 0	90	270	810	Treatment date means
		Soil P (ppm)				
February 1970	October 1969	8.0a*	20.0a	69.3a	250.7b	87.0
June 1970	October 1969	6.7a	8.0a	16.0a	65.3b	24.0
November 1970	October 1969	8.0a	12.0a	29.3a	56.0b	26.3a
November 1970	July 1970	8.0a	32.0a	65.3a	220.0b	81.3b
Treatment Means		8.0a	22.0a	47.3b	138.0c	
February 1971	October 1969	14.7a	14.7a	16.0a	37.3b	20.7a
February 1971	July 1970	14.7a	28.0a	33.3a	214.0b	72.5b
February 1971	November 1970	14.7a	80.0a	78.7a	289.7b	115.8b
Treatment Means		14.7a	40.9a	42.7a	180.3b	
June 1971	October 1969	6.7a	8.0a	14.3b	19.7c	12.2a
June 1971	July 1970	6.7a	10.0ab	15.0b	34.7c	16.6b
June 1971	November 1970	6.7a	18.0b	23.3b	40.7c	22.2c
Treatment Means		6.7a	12.0b	17.6c	31.7d	

* Diffent letters indicate significant differences at the .05% level by Duncan's L.S.D. values. P levels may be compared between treatment levels within each treatment date, or between treatment means, or between treatment dates within a harvest date.

Table 15. Phosphorus levels for soil samples measured by Baker's adsorption method as influenced by sampling dates, treatment dates, and P treatments.

Sampling dates	Treatment dates	P Treatments kg/ha 0	90	270	810	Treatment date means
		Solution P (μM)				
February 1970	October 1969	0.30a*	1.10a	72.50b	217.33c	72.80
June 1970	October 1969	2.20a	3.37a	5.19a	30.50b	10.31
November 1970	October 1969	0.20a	1.07b	1.10b	4.00c	1.59a
November 1970	July 1970	0.20a	2.43a	5.20a	20.10b	6.98b
Treatment Means		0.20a	1.75ab	3.15b	12.05c	
February 1971	October 1969	2.57a	2.40a	3.47a	5.47b	3.48a
February 1971	July 1970	2.57a	2.50a	4.20a	15.00b	6.07a
February 1971	November 1970	2.57a	6.69a	12.64a	33.50b	13.85b
Treatment Means		2.57a	5.85b	4.79ab	17.99c	
June 1971	October 1969	2.20a	3.73b	3.73b	4.30c	3.49a
June 1971	July 1970	2.20a	2.70a	2.70a	5.73b	3.33a
June 1971	November 1970	2.20a	4.73b	4.47b	7.77c	4.74b
Treatment Means		2.20a	3.64b	3.63b	5.93c	

* Different letters indicate significant differences at the .05% level by Duncan's L.S.D. values Phosphorus levels may be compared between treatment levels within each treatment date, or between treatment means, or between treatment dates within a harvest date.

Table 16. Correlation coefficients (r) relating sorghum stover yields to the logarithm of soil P levels as measured by four methods. Each coefficient included results for a sampling date over P treatments and harvest dates.

Treatment Dates	Harvest Dates	Soil sample Dates	P test Method	Linear corr. Coefficient (r)	P Level† Sig.	Yield† Sig.	Yield C.V.
Oct. 1969	Feb. 1970	Feb. 1970	Bray No. 1	0.589 *	**	*	14.2
			Bray No. 2	0.323 NS	**	*	14.2
			Olsen	0.626 *	**	*	14.2
			Adsorption	0.501 NS	**	*	14.2
Oct. 1969	Oct. 1970	June 1970	Bray No. 1	-0.170 NS	**	NS	25.9
			Bray No. 2	-0.182 NS	**	NS	25.9
			Olsen	-0.109 NS	**	NS	25.9
			Adsorption	-0.189 NS	**	NS	25.9
Oct. 1969	Oct. 1970	Nov. 1970	Bray No. 1	-0.135 NS	**	NS	25.9
			Bray No. 2	-0.278 NS	**	NS	25.9
			Olsen	-0.254 NS	**	NS	25.9
			Adsorption	-0.055 NS	**	NS	25.9
Oct. 1969	Feb. 1971	Nov. 1970	Bray No. 1	0.094 NS	**	NS	42.5
			Bray No. 2	0.246 NS	**	NS	42.5
			Olsen	0.029 NS	**	NS	42.5
			Adsorption	0.061 NS	**	NS	42.5
Oct. 1969	Feb. 1971	Feb. 1971	Bray No. 1	-0.064 NS	**	NS	42.5
			Bray No. 2	0.057 NS	**	NS	42.5
			Olsen	0.123 NS	**	NS	42.5
			Adsorption	0.284 NS	**	NS	42.5

Table 16. (Continued)

Treatment Dates	Harvest Dates	Soil sample Dates	P test Method	Linear corr. Coefficient (r)	P Level† Sig.	Yield† Sig.	Yield C.V.
Oct. 1969	May 1971	Nov. 1970	Bray No. 1	0.224 NS	**	NS	37.0
			Bray No. 2	0.214 NS	**	NS	37.0
			Olsen	0.378 NS	**	NS	37.0
			Adsorption	0.219 NS	**	NS	37.0
Oct. 1969	May 1971	Feb. 1971	Bray No. 1	0.284 NS	NS	NS	37.0
			Bray No. 2	0.461 NS	**	NS	37.0
			Olsen	0.462 NS	**	NS	37.0
			Adsorption	0.252 NS	**	NS	37.0
Oct. 1969	May 1971	June 1971	Bray No. 1	0.204 NS	NS	NS	37.0
			Bray No. 2	0.384 NS	**	NS	37.0
			Olsen	0.588 *	**	NS	37.0
			Adsorption	0.362 NS	*	NS	37.0
July 1970	Oct. 1970	Nov. 1970	Bray No. 1	0.650 *	**	*	30.7
			Bray No. 2	0.710 **	**	*	30.7
			Olsen	0.793 **	**	*	30.7
			Adsorption	0.794 **	**	*	30.7
July 1970	Feb. 1971	Nov. 1970	Bray No. 1	0.520 NS	**	**	55.8
			Bray No. 2	0.713 **	**	**	55.8
			Olsen	0.684 *	**	**	55.8
			Adsorption	0.776 **	**	**	55.8
July 1970	Feb. 1971	Feb. 1971	Bray No. 1	0.683 *	**	**	55.8
			Bray No. 2	0.676 *	**	**	55.8
			Olsen	0.386 NS	*	**	55.8
			Adsorption	0.550 NS	**	**	55.8

Table 16. (Continued)

Treatment Dates	Harvest Dates	Soil sample Dates	P test Method	Linear corr. Coefficient (r)	P Level† Sig.	Yield† Sig.	Yield C.V.
July 1970	May 1971	Nov. 1970	Bray No. 1	0.483 NS	**	NS	31.2
			Bray No. 2	0.668 *	**	NS	31.2
			Olsen	0.457 NS	**	NS	31.2
			Adsorption	0.644 *	**	NS	31.2
July 1970	May 1971	Feb. 1971	Bray No. 1	0.564 NS	**	NS	31.2
			Bray No. 2	0.711 **	**	NS	31.2
			Olsen	0.442 NS	*	NS	31.2
			Adsorption	0.413 NS	**	NS	31.2
July 1970	May 1971	June 1971	Bray No. 1	0.687 *	NS	NS	31.2
			Bray No. 2	0.605 *	**	NS	31.2
			Olsen	0.713 **	**	NS	31.2
			Adsorption	0.613 *	**	NS	31.2
Nov. 1970	Feb. 1971	Feb. 1971	Bray No. 1	0.503 NS	**	**	54.4
			Bray No. 2	0.728 **	**	**	54.4
			Olsen	0.648 *	**	**	54.4
			Adsorption	0.612 *	**	**	54.4
Nov. 1970	May 1971	June 1971	Bray No. 1	0.422 NS	**	*	38.2
			Bray No. 2	0.514 NS	**	*	38.2
			Olsen	0.524 NS	**	*	38.2
			Adsorption	0.396 NS	**	*	38.2

Table 16. (Continued)

Treatment Dates	Harvest Dates	Soil sample Dates	P test Method	Linear corr. Coefficient (r)	P Level† Sig.	Yield† Sig.	Yield C.V.
Nov. 1970	May 1971	June 1971	Bray No. 1	0.566 NS	*	*	38.2
			Bray No. 2	0.375 NS	**	*	38.2
			Olsen	0.549 NS	**	*	38.2
			Adsorption	0.599 *	**	*	38.2

† Significant differences were indicated in plant yield and phosphorus test levels by AOV of P treatment levels, where * = .05%; ** = .01%; NS = no significant differences at the .05% level.

Table 17. Correlation coefficients (r) relating sorghum grain yields to the logarithm of soil P levels as measured by four methods. Each coefficient included results for a sampling date over P treatments and harvest dates.

Treatment Dates	Harvest Dates	Soil sample Dates	P test Method	Linear corr. Coefficient (r)	P Level† Sig.	Yield† Sig.	Yield C.V.
Oct. 1969	Feb. 1970	Feb. 1970	Bray No. 1	0.622 *	**	NS	30.6
			Bray No. 2	0.570 NS	**	NS	30.6
			Olsen	0.633 *	**	NS	30.6
			Adsorption	0.672 *	**	NS	30.6
Oct. 1969	Oct. 1970	June 1970	Bray No. 1	0.680 *	**	**	50.2
			Bray No. 2	0.599 *	**	**	50.2
			Olsen	0.592 *	**	**	50.2
			Adsorption	0.628 *	**	**	50.2
Oct. 1969	Oct. 1970	Nov. 1970	Bray No. 1	0.640 *	**	**	50.2
			Bray No. 2	0.604 *	**	**	50.2
			Olsen	0.615 *	**	**	50.2
			Adsorption	0.552 *	**	**	50.2
Oct. 1969	May 1971	Nov. 1970	Bray No. 1	0.543 NS	**	NS	26.7
			Bray No. 2	0.376 NS	**	NS	26.7
			Olsen	0.584 *	**	NS	26.7
			Adsorption	0.527 NS	**	NS	26.7
Oct. 1969	May 1971	Feb. 1971	Bray No. 1	0.293 NS	NS	NS	26.7
			Bray No. 2	0.578 *	**	NS	26.7
			Olsen	0.511 NS	**	NS	26.7
			Adsorption	0.556 NS	**	NS	26.7

Table 17. (Continued)

Treatment Dates	Harvest Dates	Soil sample Dates	P test Method	Linear corr. Coefficient (r)	P Level† Sig.	Yield† Sig.	Yield C.V.
Oct. 1969	May 1971	June 1971	Bray No. 1	0.569 NS	**	NS	26.7
			Bray No. 2	0.569 NS	**	NS	26.7
			Olsen	0.735 **	**	NS	26.7
			Adsorption	0.646 *	*	NS	26.7
July 1970	Oct. 1970	Nov. 1970	Bray No. 1	0.524 NS	**	NS	39.6
			Bray No. 2	0.655 *	**	NS	39.6
			Olsen	0.695 *	**	NS	39.6
			Adsorption	0.694 *	**	NS	39.6
July 1970	May 1971	Nov. 1970	Bray No. 1	0.577 *	**	*	26.4
			Bray No. 2	0.714 **	**	*	26.4
			Olsen	0.571 NS	**	*	26.4
			Adsorption	0.669 *	**	*	26.4
July 1970	May 1971	Feb. 1971	Bray No. 1	0.581 *	**	*	26.4
			Bray No. 2	0.723 **	**	*	26.4
			Olsen	0.543 NS	*	*	26.4
			Adsorption	0.580 *	**	*	26.4
July 1970	May 1971	June 1971	Bray No. 1	0.550 NS	**	*	26.4
			Bray No. 2	0.682 *	*	*	26.4
			Olsen	0.745 **	**	*	26.4
			Adsorption	0.672 *	*	*	26.4
Nov. 1970	May 1971	Feb. 1971	Bray No. 1	0.511 NS	**	**	27.3
			Bray No. 2	0.720 **	**	**	27.3
			Olsen	0.641 *	**	**	27.3
			Adsorption	0.605 *	**	**	27.3

Table 17. (Continued)

Treatment Dates	Harvest Dates	Soil sample Dates	P test Method	Linear corr. Coefficient (r)	P Level† Sig.	Yield† Sig.	Yield C.V.
Nov. 1970	May 1971	June 1971	Bray No. 1	0.600 *	*	**	27.3
			Bray No. 2	0.671 *	**	**	27.3
			Olsen	0.839 **	**	**	27.3
			Adsorption	0.828 **	**	**	27.3

† Significant differences were indicated in plant yield and phosphorus test levels by AOV of P treatment levels, where * = .05%; ** = .01%; NS = no significant differences at the .05% level.

Table 18. Effect of P treatments on the soil test levels of other soil components within sampling dates and treatment dates. Results from the Pennsylvania State University Soil and Forage Testing Laboratory and by Baker's modified equilibration solution.

Treatment Date	Sampling Date	P.S.U. Soil Test Lab Results						Equilibrated Solution			
		K	Mg	Ca	O.M.	NO_3	Salt	K	Mg	Ca	Na
October 1969	February 1970	NS†	*	*	NS	NS	**	NS	NS	*	**
October 1969	July 1970	*	*	NS	NS	NS	**	*	NS	NS	NS
October 1969	November 1970	NS	NS	*	NS	NS	NS	NS	*	NS	NS
October 1969	February 1971	NS	*	NS	NS	NS	NS	NS	NS	NS	NS
October 1969	June 1971	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
July 1970	November 1970	NS	NS	NS	NS	NS	**	*	NS	NS	NS
July 1970	February 1971	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
July 1970	June 1971	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
November 1970	February 1971	NS	NS	NS	NS	NS	*	NS	NS	NS	*
November 1970	June 1971	*	*	**	NS	NS	NS	NS	NS	NS	NS

† * = significance at the .05% level; ** = significance at the .01% level: NS = not significant at .05%.

Table 19. Effect of P treatments on the uptake of certain elements by sorghum leaf and grain, within sampling dates and treatment dates. Results from the Pennsylvania State University Horticulture Department.†

Treatment Date	Sampling Date	P	K	Ca	Mg	Mn	Fe	Cu	B	Al	Zn	Na
						Leaf Analysis						
October 1969	February 1970	**††	NS	NS	NS	NS	*	NS	*	NS	*	NS
October 1969	October 1970	*	NS	*	*	NS	NS	NS	*	NS	**	NS
October 1969	February 1971	*	NA	*	NS	*	NS	*	**	**	**	*
October 1969	May 1971	NS	*	NS	*	NS	NS	NS	NS	NS	NS	NS
July 1970	October 1970	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS
July 1970	February 1971	*	*	*	NS	NS	NS	NS	NS	**	*	*
July 1970	May 1971	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
November 1970	February 1971	*	NS	NS	NS	NS	NS	NS	NS	**	*	*
November 1970	May 1971	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
						Grain Analysis						
October 1969	February 1970	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
October 1969	October 1970	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
October 1969	May 1971	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
July 1970	October 1970	**	NS	NS	*	**	NS	NS	NS	NS	*	NS
July 1970	May 1971	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
November 1970	May 1971	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† Dr. C. B. Smith in charge.

†† * = significance at the .05% level: ** = significance at the .01% level; NS = not significant at the .05% level.

VITA

Michael Colegrove was born in Ventura, California on July 31, 1941 of Marshall and Birdie Colegrove. He grew up and was educated in Bellflower, California where he graduated from high school in 1959. After one year at Cerritos College in Norwalk, California, Mr. Colegrove transferred to the California State Polytechnic College at San Luis Obispo. He received his B.S. degree in Agriculture in June of 1964 with a major in soil science. From the fall of 1964 through the summer of 1966, he served as a Peace Corps Volunteer in the Ministry of Agriculture and Training at Tengeru, Tanzania, East Africa. He returned to the United States and graduate studies in September of 1966 and received his M.S. degree in Agronomy from The Pennsylvania State University in 1969. Since 1968 Mr. Colegrove has been a recipient of Department of State, Agency for International Development, funds for work toward his Ph.D. degree.

Mr. Colegrove is married to the former Elisabeth Lawson of Binghamton, New York and they have one son, Peter.