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CORRELATION OF PHOSPHORUS SOIL TESTS AND FORMS OF
INORGANIC SOIL PHOSPHORUS WITH CROP RESPONSE
AND PHOSPHORUS UPTAKE FROM AIKEN SOILS

by

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CORRELATION OF PHOSPHORUS SOIL TESTS AND FORMS OF
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I. INTRODUCTION

The most important agricultural area of Oregon is the Willamette Valley from which 39% of the state's agricultural income is produced. One of the most extensive soil associations in this valley is the so-called "Red Hill" soils (97, p. 8) which occupies about one third of the total land in the valley. Aiken and Olympic soil series^{1/} are among the most extensive series that have been mapped in this group. From the early history, the soils were cropped chiefly to grain and later used for grass seeds and orchards, especially prunes and walnuts. Previous research (15, 88, 97, 107) has shown that the "Red Hill" soils of Western Oregon have a high total phosphorus content; Aiken and Olympic soils are the highest among all the soils in the Willamette Valley. However, the amount of phosphorus available to plants is frequently so small that profitable increases in crop yields are often observed when phosphate fertilizers are applied. The

^{1/} Soil survey work in progress is expected to result in redefinition of these soil series and assignment of different series names.

unavailability of the phosphorus has been attributed to the high content of Fe and Al of these soils which combines with phosphorus to form compounds of low solubility.

The increasing interest in the production of forage crops on the foothills surrounding the floor of the Willamette Valley made it desirable to consider this area for a cooperative Tennessee Valley Authority research program established with the objective of providing a basis for quantitative economic and agronomic prediction of the forage crops fertilizer recommendations on the Aiken soils.

The soil was selected as a representative of the residual "Red Hill" soils where there is a potential for forage production and where additional information was needed on the response from application of fertilizer and lime. Also, locations could be selected that would show a response from lime, phosphorus and potassium. A better relationship needed to be established between chemical analysis of the soil and response from fertilizers and lime to provide a basis for improving recommendations that are being made for farmers in the area. The calibrated soil analysis values will be needed in a regression equation which would describe the response surface and provide a basis for economic analysis of the costs and returns from application of lime and fertilizer.

Lime and phosphorus were thought to be the most important factors limiting the production of legumes on most of the "Red Hill" soils in the Willamette Valley.

The Oregon State University Soil Testing Laboratory has been estimating the phosphorus fertility of the soils in the state by determining soil phosphorus soluble in a NaHCO_3 solution. This method has been claimed to be applicable to calcareous, acid and neutral soils (86). In general, the NaHCO_3 method gives satisfactory prediction of the phosphorus status of most soils of Oregon. However, recent field and greenhouse experiments with many acid soils of Western Oregon and the Aiken soils in particular have shown the phosphorus fertility of the soils as indicated by this method to be very low while practically no response from phosphorus fertilization was obtained. This is probably due to the fact that NaHCO_3 solution is only capable of extracting phosphorus associated with calcium and some of the adsorbed forms which are present in rather small quantities in comparison to those forms of phosphorus associated with Fe and Al of the acid soils. Therefore, the amounts of phosphorus in these soils that are extractable by this method are usually very low and the sensitivity as a phosphorus fertility index becomes poor.

It has been shown in the literature that plants could utilize phosphorus from many Fe and Al phosphate compounds (127), and as a matter of fact certain forms of Al phosphate are as readily available to plants as mono-calcium phosphate. Some publications (109, 142) indicate that the extraction of phosphorus from Fe and Al phosphate of many acid lateritic soils gives the best prediction of the phosphorus fertility status of the soils. Therefore, it seems probable that a chemical phosphorus soil test method suitable for the Aiken soil should be the one that is able to extract phosphorus associated with calcium as well as Fe and Al compounds which are possibly available to plants.

The main objective of this thesis was an attempt to correlate the "available" phosphorus estimated by various phosphorus soil test methods with the crop responses and phosphorus uptake by plants from field and greenhouse experiments conducted on Aiken soils.

An attempt was also made to study the phosphorus fertility of Aiken soils as reflected by the distribution and relative availability to the plants of various forms of inorganic soil phosphorus. The influence of liming on the availability of the native and applied phosphorus and on the fate of the applied phosphorus in these soils were also studied.

II. LITERATURE REVIEW

(1) Forms of Inorganic Soil Phosphorus

Soil phosphorus can be divided into two general groups as follows: 1) organic combinations and 2) inorganic combinations. It is the scope of this review, however, to deal with only those which exist in the soils as inorganic compounds. Nevertheless, it does not mean that the organic forms of phosphorus in soils are not important. In some cases the bulk of the soil phosphorus in many agriculture soils is in the organic form (94). A more comprehensive review on this subject can be found in a paper by Black and Goring (12).

(1.1) Forms Occurring in Soils

Publications reporting studies of the forms of phosphorus in soils are numerous and frequently confusing. This is probably due to the fact that the phosphate ions can form a multitude of compounds of low solubility and variable composition when soluble phosphate is added to the soil.

According to Russell (105, p. 440), there are three groups of inorganic phosphorus compounds existing in the soils. Briefly, these groups are:

1) Inorganic minerals containing phosphates as an integral part of their structure. Apatite, $\text{Ca}(\text{OH})_2 \cdot 3\text{Ca}_3(\text{PO}_4)_2$ and fluorapatites, $\text{Ca}_{10}\text{F}_2(\text{PO}_4)_6$, are the most wide spread, but iron and aluminum phosphates also occur under some conditions (tropical conditions).

2) Insoluble calcium phosphates occurred when soluble phosphates are applied to the soils. It is still uncertain what these compounds are. Dicalcium phosphate, $\text{CaH}(\text{PO}_4)$, almost certainly occurs, the tricalcium phosphates, $\text{Ca}_3(\text{PO}_4)_2$, almost certainly does not, and a compound of composition $\text{Ca}_4\text{H}(\text{PO}_4)_3$, an octaphosphate, may also be present. The latter is believed to be the intermediate compound through which the dicalcium phosphate becomes converted back to apatite.

3) Phosphate is held on the surface of hydrated iron and possibly aluminum oxides. There is no sharp distinction between this group and the iron and aluminum phosphate minerals, for under some conditions these complexes probably crystallize to form new minerals. Phosphate may also be held on the surface of clay particles by mechanism other than these hydrated oxides.

In recent years, several investigators have studied the various forms of phosphorus resulting from the reactions of clay minerals and some cations in the soil solution (Ca, Mg, Fe, Al, etc.) with the added soluble

phosphates.

Cole and Jackson (25) have concluded that the aluminum phosphate precipitates contained variscite; that the iron phosphate precipitates contained strengite; and that these minerals of the variscite-barandite-strengite isomorphous series could occur as a result of phosphate fixation by the soils. This fixation is the precipitation reaction of the soluble phosphate to form crystals of the minerals of the variscite series. Haseman et al. (61) treated goethite, gibbsite, illite, kaolinite, and montmorillonite with phosphate solutions and different bases and were able to isolate and identify crystals of palmerite-like phosphate minerals with a formula

$(H,K,Na,NH_4)_3 (Al,Fe) PO_4 \cdot nH_2O$ in which Fe and Al could be present in widely varying proportions. If cations (H,K,Na,NH_4) were not present, an isomorphous series of variscite-barandite-strengite $[AlPO_4 \cdot 2H_2O - (Al,Fe)PO_4 \cdot 2H_2O - FePO_4 \cdot 2H_2O]$ was found and identified. These minerals resulted from the precipitation of soluble phosphates into a new discrete solid phase. They suggested that under some conditions the substitute palmerites and the variscite-barandite-strengite isomorphous series type of minerals might occur in soils. The escape of such crystalline products from detection in natural soils was attributed to the extremely small size of the crystals.

They stated further that the results of their phosphate fixation experiments showed two stages of phosphate fixation; a rapid initial reaction and a subsequent relatively slow reaction. This was in agreement with other workers (11, 76). It appeared to them that the palmerite-like and the variscite-barandite-strengite isomorphous series minerals might form in the acid soils during this initial rapid stage of fixation. The formations were believed to result from a combination of phosphate ions with ions of Al and Fe that are held in the extremities of the lattice. The exchange reactions of phosphate ions with both the clays and hydrous oxides of iron and aluminum might also be responsible for the rapid initial fixation. Phosphate ions adsorbed on the surface of clay minerals and hydrated oxides of Fe and Al may be considered as another form of phosphorus present in soils (106, 121, 131).

According to Lindsay and Stephenson (73), potassium taranakite $[H_6K_3Al_5(PO_4)_8 \cdot 18H_2O]$ could occur in the soils from the action of solutions derived from monocalcium phosphate. Kittrick and Jackson (68) also reported the formation of taranakite-like crystals by the action of $N NaH_2PO_4$ solution (pH 4.3) on kaolinite in one month at 90°C. Other compounds such as calcium ferric phosphate $[H_4CaFe_2(PO_4)_4 \cdot 5H_2O]$, potassium iron phosphate

$[H_8KFe_3(PO_4)_6 \cdot 6H_2O]$, potassium aluminum leucophosphate
 $[KAl_2(PO_4)_2 \cdot OH \cdot 2H_2O]$, potassium iron leucophosphate
 $[KFe_2(PO_4)_2 \cdot OH \cdot 2H_2O]$, colloidal aluminum phosphate, and
 colloidal ferric phosphate were also believed to be formed
 in the soils by the action of acid solutions of phosphate
 fertilizers with the soils (127).

Apatite has been identified by McCaughey and Fry (79)
 to be present in eleven of twenty-five soils from different
 parts of the United States. Other investigators (72, 96)
 also found that apatite and fluorapatite were present in
 some of the soils studied. These minerals were identified
 by means of microscopic examination of the sand and silt
 fraction of the soils. Other calcium phosphate compounds,
 namely, dicalcium phosphate dihydrate $[CaHPO_4 \cdot 2H_2O]$,
 octacalcium phosphate, $[Ca_8H(PO_4)_6 \cdot 3H_2O]$, and anhydrous
 calcium phosphate $[CaHPO_4]$ were believed to occur in
 soils and could persist in soils for periods longer than
 a few days after soluble phosphates had been applied to
 the soils (20, 73).

(1.2) Methods of Determining Various Forms of Soil P

The various forms of inorganic soil phosphorus have
 been reviewed. The realization that a knowledge of the
 chemical behavior of soil phosphorus is of agronomic

importance has made it important to devise analytical methods that could quantitatively differentiate these different forms.

The direct approach of determining and identifying forms of inorganic soil phosphorus through the use of microscopic examination technique has been tried by some investigators (72, 79, 96). This method is limited to those forms that are present in the sand and silt fraction of the soil, while most of the inorganic phosphorus, important to plants, occurs in association with the clay fraction which can not be separated by simple physical methods. Therefore, the direct methods are not very useful in this respect.

Various indirect means have been employed in the investigation of this problem. Stelly and Pierre (122), based on the studies of Fisher and Thomas (46), employed the soil phosphorus solubility versus pH curves to identify the forms of phosphorus in various soils. If the soils contain calcium forms of phosphorus, the solubility-pH curves of the soil will increase as the pH decreases from neutrality. The solubility-pH curve of soil containing Fe and Al phosphate forms, on the contrary, will rise as the pH rises from neutrality. They were able to show by this technique that alkaline soils usually display a P

solubility-pH curve similar to that of apatite, and acid soils usually display that of the iron and aluminum phosphates.

Other investigators, namely Aslyng (3), Clark and Peech (24) attempted to identify the inorganic phosphorus compounds of soils by means of the solubility-product concept. This technique bases its concept on the fact that a definite compound of constant composition of phosphorus occurs in the soils. These idealized compounds will have a definite solubility and maintain at equilibrium a certain concentration of phosphorus in solution as long as the solid phase of that particular compound is present. If the phosphates in a given soil are present as a series of insoluble compounds, the idealized situation will call for a stepwise decrease in solubility in a series of extractions. The solubility should be nearly constant until all of the most soluble compound dissolves, then the concentration of phosphorus in the solution will assume a level characteristic of the compound of the next-lower solubility. Unfortunately, the observed solubility of soil phosphorus showed no such stepwise change but decreased very gradually with repeated extractions or dilutions. Therefore, a sharp division between the postulated forms of soil phosphorus could not be made.

Holt et al. (65) studied calcium phosphate systems and found that solubility products were difficult to establish and varied in the presence of soluble salts and other conditions. The same situation may exist to a greater degree with phosphates of iron, aluminum and manganese, and the precipitation of single simple compounds of one of these ions in a diverse system like soil seems highly unrealistic. This may be the reason why the concept of solubility products can not be used readily in soil systems.

The approach used most commonly in the studies of various forms of phosphorus is successive extractions with different extractants. This is based on the selective solubility of different phosphate compounds in various extracting solvents. The technique of fractionating soil phosphorus has been investigated by Fraps (49) and Stoddart (123). They reported that freshly precipitated phosphates of Ca, Al, and Fe, as well as apatite, vivionite, and triplite were dissolved in 0.2N HNO₃ while Wavellite and dufrenite were only slowly soluble in acid at this concentration. Wavellite and dufrenite were, however, soluble in sodium hydroxide solution. Williams (142) also showed that the only phosphate forms definitely insoluble in sodium hydroxide are those of the apatite type.

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Dean (33) proposed a fractionation procedure which called for treatment of the soil with 0.25N NaOH to remove the iron and aluminum phosphates. The sample was then extracted with 0.5N H₂SO₄ to remove calcium forms. The portion not removed by these solutions was also determined by subtraction from the total. Later, different analytical schemes for fractionating soil phosphorus were proposed by many investigators (18, 51, 58, 95, 140). For instance, Williams (140), who modified the Ghani's method (58), used 2.5% acetic acid containing 1% 8-hydroxyquinoline to remove Ca-, Mg- and Mn-phosphates, preceding the extraction for Fe- and Al-phosphates by 0.1N NaOH. The insoluble phosphorus, not extracted by both solutions, is regarded as crystal-lattice phosphorus and phosphatic mineral. So far, most of the methods proposed could qualitatively separate calcium phosphate forms from those of Fe and Al forms to some degree but were not able to separate the Al-phosphate from Fe-phosphate, since both forms were soluble in the same alkaline solution. Until 1954 Turner and Rice (136) reported that neutral normal NH₄F could dissolve Al-phosphates but not Fe-phosphates. Subsequently Chang and Jackson (23) proposed a fractionation procedure with which Al-phosphate could be separated from Fe-phosphate by means of extracting the soil with neutral

0.5N NH_4F . According to this procedure soil phosphorus can be fractionated into Al-phosphate, Fe-phosphate, Ca-phosphate, reductant Fe-phosphate and occluded Al-phosphate respectively.

It should be mentioned at this point that the inorganic phosphate fractions extracted by various reagents should not be taken too literally. The phosphorus forms separated by these solutions are not as discrete as it sounds. It is only to be expected that clear cut boundaries between the different forms of inorganic soil phosphorus, applicable over a wide range of soils, simply do not exist. Nevertheless, the method of fractionating soil phosphorus can permit us to study certain phases of soil phosphorus fractions, their distribution in different soils, and how they are related to the performance of the crops. The attempt to fractionate soil phosphorus and to learn something about the chemical nature of the fractions have been and will continue to be the subjects of fruitful research.

(1.3) Availability of Various Phosphate Compounds

It is generally believed that the portion of soil phosphorus associated with calcium is more available to the plants than Fe and Al forms of phosphorus. Many

workers have placed emphasis on calcium forms as playing a dominant role in phosphorus nutrition of plants in most soils, even in soils with pH well below neutrality (133).

As early as 1907 Patterson (91) reported that Fe and Al phosphates were valuable sources of phosphorus for plants. The same conclusion was also reached by other investigators (42, 77). Peterson and Truog (93) and Truog (133) demonstrated that freshly precipitated and dried Fe-, Al-phosphates could serve as a good source of phosphorus for certain crops. Marais (77) showed that the phosphate minerals wavelite and vivianite were as available as Florida rock phosphate but were not as readily available as the chemically pure Al- and Fe-phosphates.

More recent work by Taylor et al. (127) indicated that some Fe- and Al-phosphate compounds, namely, calcium ferric phosphate, potassium taranakite, colloidal iron and aluminum phosphates, which were believed to be present in soils, were as available as mono-calcium phosphate to plants. Other phosphatic compounds like acid potassium iron phosphates and aluminum and iron leucophosphates were poor sources of available phosphorus for plants.

(2) Availability of Soil Inorganic Phosphorus

(2.1) Concept and Definition of Phosphorus Availability

The term available as used in connection with soil phosphorus in relation to the plants is sometimes very confusing. So far as the phosphorus in soils and plants is concerned the term implies the amount of phosphorus that can be utilized by the growing crop. The forms of phosphorus compounds in the soil and the mechanisms by which these forms are made available to plants are still not clear. The scientists know, however, that the amount of soil phosphorus that becomes available to growing plants in the same soil may vary for different crops, and from one season to the next. The availability of phosphorus to plants is influenced not only by the soil itself but also by the conditions under which a given crop is grown. Such factors as the soil pH (5, 128), moisture regime (60, 75), type of soil colloids (26, 139) and soil temperature (101) have an effect on the amounts of soil phosphorus available to plants.

The ability of different crops to utilize soil phosphorus is different. The character of the root system with regard to the properties of the root surfaces of the various species (36), the rate of growth, the total phosphorus requirement, and the metabolically produced CO₂ and

exchangeable H^+ of roots determine the ability of the plant to make use of the soil phosphorus.

For a long time, many scientists referred to the term available phosphorus as those fractions of phosphorus in the soil that were soluble in the extracting solutions which were devised to simulate the feeding capacity of the roots (40, 134). For instance, Truog (134) designated the term readily available for the fraction of soil phosphorus soluble in 0.002N H_2SO_4 buffered with $(NH_4)_2SO_4$ and consisting mostly of Ca and possible Mg-phosphates. He also introduced the term difficultly available to substitute for the term unavailable which referred to the fraction of phosphorus difficultly soluble in the extracting solution. The difficultly available phosphorus which consisted largely of Fe-, Al- and Ti-phosphates, could be made available by certain crops under certain climatic conditions. These terms have been adopted for general usage by many workers in the field of phosphorus fertility.

Other investigators (111, 126), on the other hand, viewed the concept of phosphate availability from the standpoint of a thermodynamic approach. They postulated that availability of soil phosphorus was mainly determined by the appropriate chemical potential, and suggested the measurement of the value $\frac{1}{2}pCa + pH_2PO_4$ as an index of the availability of the soil phosphorus. Thornton (130)

defined the available phosphorus in terms of the phosphorus fraction taken up by the rye plants in the Naubauer test.

These so-called fractions of available phosphorus determined by various chemical and biological methods are merely empirical and are not necessarily the same fractions of phosphorus actually available to the crops grown in the field. Nevertheless, this does not mean that the amount of phosphorus soluble in these conventional extractants are useless. With careful correlation and calibration of the values determined by any one of these methods with the actual crop performance under field conditions, such methods do furnish valuable information regarding the capacities of the soils to supply phosphorus to the plants.

To clarify the use of the term available phosphorus when referring to the actual form taken up by crops in the field, and that chemically or biologically extracted by conventional methods, some investigators resorted to the term "readily soluble" and "difficultly soluble". Quite often the term "available" within the quotation mark was used to represent the fractions of phosphorus extracted by the extracting solutions.

(2.2) Methods for Determining "Available" Soil P

(2.21) Concepts Considered in Developing Extracting Methods

The development of soil tests for "available" phosphorus has been under investigation since the middle 1800's. Daubney (32) was the first to study methods for extracting phosphorus from soils. It was not until the early 1900's that United States scientists investigated this problem. Since then a voluminous literature on this subject has been accumulated and not less than 40 different phosphorus soil test methods have been developed. Nevertheless, many problems relating to the testing of soils for available phosphorus remain unsolved and the application of using a phosphorus soil test to predict response from P is still limited. This is in part a result of our limited knowledge of the mechanism of phosphate absorption by plants and of the relative availability or unavailability of various forms of phosphorus compounds in the soil. The development of soil tests for "available" phosphorus is confronted with many difficulties, namely, the variability in ability of plants to obtain phosphorus, and still further complicated by many soil factors such as pH, amount of organic matter, and type of soil colloids.

The development of phosphorus soil test methods has proceeded in various directions depending on the individual theoretical concept as to how phosphorus compounds in the soil could be made available by the plants. In general, however, most of the proposed extracting procedures center around at least one of these general concepts:

1. Simulation of root action
2. Soil solution concept
3. Anion exchange concept
4. Quantitative or proportionate measure of the significant forms.

Simulation of root action. It has been considered that plant roots absorbed mineral nutrients from the soil by excreting organic acids which dissolve soil phosphorus and other mineral substances. The soluble nutrients are then passed into the roots by osmosis. Dyer of England (40) was probably the first to adopt this concept for practical application. In 1894 he proposed the use of 1% citric acid as an extracting solution for "available" phosphorus from soil. The 1% citric acid had approximately the same degree of acidity as cell sap and he argued that it must therefore exert approximately the same solvent action on the soil phosphates as the plant excretions, and would give the truest picture of the phosphatic materials

available for plant nutrition. The idea that plants dissolve nutrients through the acid their roots exude is no longer fully supported since no satisfactory evidence can be obtained that any acid other than H_2CO_3 is excreted. Consequently, the theoretical basis underlying the selection of 1% citric acid is gone and the method becomes purely empirical.

Since the time of Dyer, regardless of the invalidity of the concept of this mechanism of plant feeding, many different extraction methods employing different kinds of organic acid have been developed. Some of the organic acid extraction, besides the citric acid method of Dyer, proposed and still widely used are:

a) the acetic acid method of Hibbard (64) with various modification by Fyn (55), Ghani (59), Morgan (84) and Peech and English (92).

b) the lactic acid method of Egner (41).

Since there was evidence indicating that plant roots respire and that CO_2 gas was evolved from the roots, it was logical to assume that the H_2CO_3 formed tends to make the soil phosphorus more soluble and thus more available for plants (89). Truog (134) indicated that the solvent operating at the point of contact between root hair and soil particles was a saturated solution of carbonic acid.

This solution is approximately 0.04N with a pH near 3.7, and the plant can absorb phosphorus from the soil by means of the dissolution of phosphates in this acid solution. This has been the basis for many workers for selecting weak or dilute acid as a phosphorus extractant. In an attempt to approximate this solvent in a practical and convenient way, Truog selected 0.002N H_2SO_4 solution buffered with $(NH_4)_2SO_4$ to a pH of 3.0. He believed that the phosphorus existing as calcium phosphate went into solution in this extractant very rapidly and consisted of the large part of the phosphorus measured. The solubility and availability of calcium phosphates are strikingly greater than for those tied up as iron and aluminum phosphates. He thus was convinced that this method was suitable to measure the "readily available" phosphorus of soils.

Other workers, namely Fraps and Fudge (50), White et al. (138) and Rubin and Dean (103) have likewise reported the method satisfactory. However, Olsen et al. (86), Richer and White (102), Thompson and Pratt (129) found that other methods gave higher correlation coefficient when the soil test values were correlated with crop yields. Some other dilute mineral acid extractants which were designed to extract the readily available phosphorus were 0.01N H_2SO_4 by Kerr and Stieglitz (67), N/21 H_2SO_4

buffered with sodium borate at pH 1.5 by Beater (7).

The use of CO₂-saturated water has been advocated for soil testing on the basis that plant roots produce CO₂. McGeorge (80) and Fuller and McGeorge (54) found that the solubility of phosphorus in alkaline soils increased with increasing concentration of CO₂ in water, they found a distinct relationship between the amount of carbonic acid soluble phosphorus and availability of soil phosphorus to plants. Ensminger and Larson (43) stated that the CO₂ charged water method was reliable in differentiating between the soils of low and high crop response but did not differentiate between soils of low and medium or medium and high response categories. According to the soil test work group of the National Soil Research Committee (119), the CO₂ solution was influenced by the type of soil and, in general, gave better correlation with the soils neutral to slightly alkaline in reaction.

Soil solution concept. There is good evidence to indicate that most, if not all, of the phosphorus absorbed by plants from the soil solution is in the form of inorganic orthophosphate (105, p. 450). Since the soil reaction in the immediate vicinity of active plant roots is usually in the neighborhood of pH 5 as a result of the excretion of metabolic CO₂ at the root surface, the

dominant ion of phosphorus in this immediate root zone must be H_2PO_4^- . With this evidence, some investigators suggested that an estimate of water soluble phosphorus in the soil should give a good measure of the level of phosphorus available to the plants (9, 13, 21, 112). The water extracting method was found to give satisfactory prediction of crop response to phosphorus fertilization in California (9) and in the citrus fruit area and organic Everglades soils of Florida (48). However, under many soil conditions water extract failed to give good correlation between soil test results and crop response.

With a view towards evaluating the rate of replenishment of soil solution phosphorus caused by the removal of phosphate ions from the soil by plants, it was considered that phosphate ions could be removed by a cation exchange resin as rapidly as they were released by the soil to the soil solution. Moller and Morgensen (83) employed sodium zeolites (NaZ) to decrease the Ca^{++} and other cation activities and thus cause a shift of equilibrium reaction to the right in the following equation:



More phosphate ions, which were tied up in the sparingly soluble compounds like $\text{Ca}_3(\text{PO}_4)_2$, would then come into solution.

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Amer (1) employed 1 gm of the Cl-form of the strong base anion exchange resin Dowex 2, shaking for 2 hours with 1 gm soil. The amounts of phosphate adsorbed by the resin were correlated with the "A" value of Fried and Dean (52) and the amount of phosphate extracted by Bray No. 1 solution. The correlation coefficients obtained were 0.95 and 0.91 respectively.

The anion exchange resin technique for measuring the phosphorus supplying power of the soil is based on the hypothesis that phosphate ions moving from the soil particles to solution can be adsorbed by the resin particles. The resin continually removes any phosphate ions which may come into solution, thus preventing the equilibrium to be established between the phosphate ions in the solution phase and in the solid phase, in the same manner as the plant roots do. Sheard and Caldwell (114) also found that the amount of phosphate adsorbed by the anion exchange resin Dowex 2 gave a correlation coefficient of 0.87 with the "A" value from 24 Ontario soils. Lathwell et al. (70) used Amberlite IRA 410 in the chloride form and reported good correlations between the amount of phosphate adsorbed by the resin and the phosphorus uptake by crops, and also the P extracted by the rapid chemical soil test of Peech and English (92). However, the necessity for the separation of the resin from the soil and the subsequent

replacement of H_2PO_4^- from the resin, render these methods too cumbersome for rapid soil test work.

Anion exchange concept. Suggestions concerning anion exchange in soils and clays have been mentioned by Prescott (98) and the matter was further discussed by Mattson (78). A number of studies have been made since then to determine the nature and extent of anion exchange in soil (27, 34, 35, 104). Mechanisms of anion adsorption in soils have been postulated by many investigators (78, 99, 110, 132), but the exact mechanism is still not clear. There were some indications that phosphates adsorbed by gel of iron and aluminum could be excellent sources of phosphorus (139). Also, some available evidence indicated that barley, corns and oats could readily utilize the phosphate adsorbed on kaolinitic and montmorillonitic clays. Burd and Murphy (21) suggested an extraction of soils with sodium hydroxide in order to replace adsorbed phosphate and took into account this fraction and the anion adsorption capacity along with the usual easily acid soluble fraction to predict phosphate deficiency in soils. Kurtz et al. (69) studied a number of anions to replace phosphate from soils and found that the order of replacing ability to be fluoride > oxalate > citrate > bicarbonate > borate > acetate > thiocyanate > sulfate > chloride. Dickman and Bray

(37) proposed the use of 0.1N neutral ammonium fluoride for the determination of adsorbed phosphate. Bray and Dickman (17) showed that the adsorbed phosphate as determined by 0.1N NH_4F at pH 7 was the most effective source of soil phosphorus for crop growth.

Bray and Kurtz (18) proposed other methods for determining soil phosphorus. The methods that are well known and widely used are Bray No. 1 and Bray No. 2. The Bray No. 1 method was designed primarily to determine the adsorbed phosphorus where as Bray No. 2 was designed to extract both adsorbed and acid soluble forms. Bray was of the opinion that the adsorbed form of phosphorus was more readily available than the acid soluble form.

Both of Bray's methods are widely employed by many laboratories, especially those of the Midwestern states, namely, Ohio, Iowa, Minnesota, Kansas, Nebraska, South Dakota, Arkansas, Illinois, Missouri, North Dakota and Montana.

Anions other than fluoride have been used to replace adsorbed phosphorus. Schollenberger (113) and Dean and Rubin (34, 35) suggested the use of arsenate ions for replacing phosphorus from soils. Sodium hydroxide which furnished the OH group was proposed by Burd and Murphy (21) for replacing the adsorbed phosphate from soils.

Quantitative or proportionate measure of the significant forms of phosphorus. According to Bray (16, 19) the idea that a soil test must simulate plant feeding and remove the available nutrients in amounts corresponding to those removed by crops is no longer fundamentally sound. He suggested that the soil test method to be developed should either quantitatively or proportionately measure the significant form or forms of nutrients from which plant roots meet their requirements during a growing season.

A number of chemical phosphorus soil test methods including acid, base, and buffered solutions have been developed with the objectives of evaluating these forms of phosphorus. Also, Bray and Kurtz (18) designed various combination of concentrations of HCl and NH_4F to extract the "adsorbed", "acid soluble and adsorbed", "total adsorbed" and "total acid soluble and adsorbed" forms of phosphorus which eventually, as they believed, could be made available to plants in various degree.

An extractant consisting of a mixture of 0.05N HCl and 0.025N H_2SO_4 was introduced for advisory work in North Carolina (85, 120). The method was used to evaluate the phosphorus fertility of the high phosphate fixing capacity soils of the Piedmont and mountain regions. The method

was designed primarily to extract the aluminum and especially iron phosphates which constituted the major source in these soils. Besides phosphorus, calcium, magnesium, and potassium are also determined in this single extract. The method has been used successfully in North Carolina, Alabama, Georgia and Virginia. Miller and Axley (82) proposed an extracting solution consisting of 0.03N H_2SO_4 and 0.03N NH_4F for assessing the phosphorus fertility of acid soils. The theoretical basis of this solution is the same as that of Bray No. 1. The 0.03N H_2SO_4 was used instead of 0.025N HCl because H_2SO_4 is more effective than HCl for removing the difficultly available phosphorus especially for soil high in phosphorus fixing capacity and high in sesquioxides.

Fraps (49) was among the early workers to study the solubility of different phosphate minerals in dilute acid. He reported that freshly precipitated phosphate of calcium, aluminum and iron as well as apatite, vivianite and triplite were dissolved in 0.2N HNO_3 or HCl. Consequently, 0.2N HNO_3 was proposed by Fraps (49), Stoddard (123) and Shedd (115).

In some of the red soils or soils high in fixing capacity and sesquioxides, the iron and aluminum forms of phosphate seem to reflect the phosphorus status of soils better than dilute acid soluble forms of phosphorus. Iron

and aluminum phosphates were reported to be easily soluble in sodium hydroxide solution while calcium phosphates such as those of the apatite type were not. Jones (66) recommended 0.5N NaOH solution for use in the acid red soils of Kenya. Williams (141) suggested that the phosphorus forms soluble in 0.1N NaOH solution were the best index of phosphorus fertility of the South Australian soils.

Saunders (109) suggested hot 0.1N NaOH for determination of available phosphorus in Southern Rhodesia soils. The method was found to be superior to 0.1N HCL + 0.5N NH_4F , 0.5N NaHCO_3 and 0.2N K_2CO_3 . Friend and Birch (53) compared 11 different phosphorus soil test methods with the phosphorus response of wheat in a number of soils in East Africa. They reported that only total organic phosphorus and inorganic phosphorus extracted with hot 0.1N NaOH were significantly related to phosphorus response of the crops; the former at the 1% level and the latter at the 5% level.

Some milder base or alkaline solutions have been developed by many workers. There is some evidence to believe that phosphorus compounds present in the alkaline soils are largely associated with calcium and magnesium which contribute to the greatest portion of the total phosphorus made available by plants. Several methods

designed to extract forms of Ca-phosphate, have been developed for evaluation of the phosphorus fertility of alkaline soils. Das (30) proposed a 1% K_2CO_3 solution while Rhoades (100) employed a 0.01N Na_2CO_3 solution buffered with enough H_3BO_3 to give the solution the same pH as the soil. Recently Olsen et al. (86) proposed a 0.5N $NaHCO_3$ for the extraction of alkaline soils. The mechanism of the bicarbonate method is based on the increased solubility of Ca-Phosphate as a result of decreasing the Ca ion activity in solution. Also, the $NaHCO_3$, probably through ionic competition of bicarbonate, carbonate, and hydroxyl ions, extracts about one half of the amount of phosphorus on the surface of soil particles which is readily exchangeable with P^{32} in the soil solution. They also claimed that the method could be applied to acid and neutral soils as well as alkaline soils. Thompson and Pratt (129) and Datta and Kamath (31) also provided positive evidence of the satisfactory use of the $NaHCO_3$ method for both acid and alkaline soils.

In the case where $NaHCO_3$ solution at pH 8.5 has been used successfully in some of the acid soils, this extractant might have brought about enough hydrolysis of the more significant forms of Fe- and Al-phosphates. Also, there may exist competition between the OH^- and the phosphate ions for attachment to the hydrous oxides of Fe and

Al in the soil. The use of an alkaline extractant may increase the OH^- concentration, which in turn may cause the balance to move towards OH^- retention, and thereby increase the equilibrium concentration of phosphate ions in solution. On the contrary, many investigators have reported the failure of the NaHCO_3 method for use with the acid soils (82, 109).

(2.22) Classification of the Chemical P Soil Test Methods

An attempt is made here to summarize the chemical phosphorus soil test methods developed in the past. They are grouped into 4 general categories as 1) water extractants, 2) base and alkaline extractants, 3) acid extractants, and 4) cation and anion exchangers. Some of these procedures are very similar, although differing in detail, but others are extreme in variation. These methods, including the references are summarized in Figure 1.

(2.23) Evaluation of Different P Soil Test Methods

According to Bray (19) the extracting solution of a successful chemical soil test should meet the following requirements:

"1. It must extract the total amount (or proportionate amount) of the available form of the nutrient from soil

Phosphorus Extracting Solutions

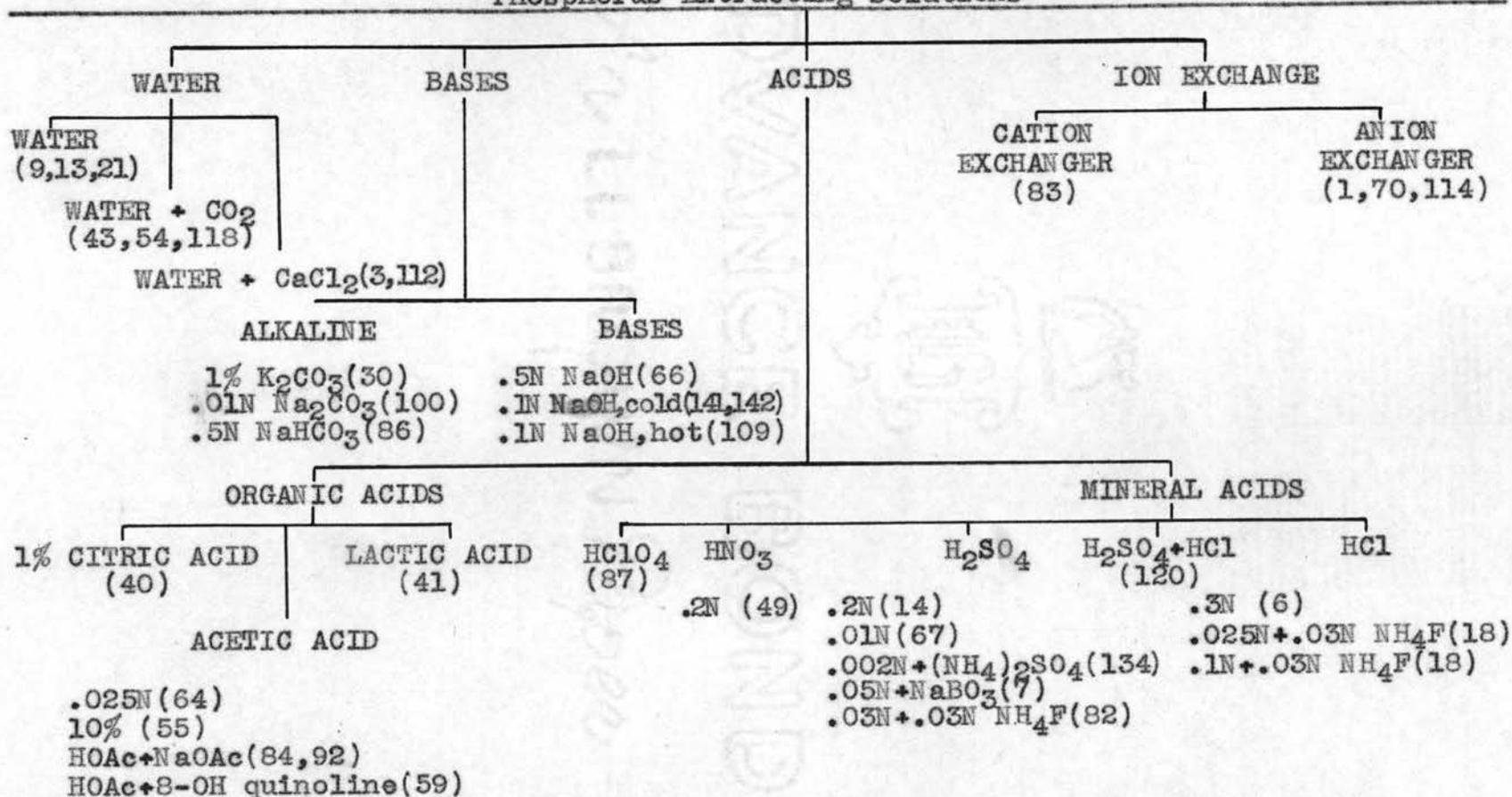


Figure 1. Classification of the commonly known chemical methods of P soil test.

with variable properties.

2. It must measure with reasonable accuracy the amount of nutrient in the extract.

3. Its action must be fairly rapid,..... however, it must meet requirements 1 and 2.....".

It is apparent that no single chemical extractant is regarded as best adapted for the soils and crops in all parts of the country. It is generally agreed, however, that practically all phosphorus extracting methods proposed could be used satisfactorily under a limited group of crops growing on soils which have a relatively narrow range in those properties affecting plant growth.

The response of a crop to phosphorus fertilization can be expressed either as percentage yield of maximum or as percentage increase in yield due to added phosphorus. The amount of phosphorus extracted by various soil tests has been commonly expressed as either ppm or pounds per acre of P or P_2O_5 . Recently the introduction of the "A" value concept by Fried and Dean (52) has been widely adopted by many investigators (86, 114) for correlation work, especially in evaluating different chemical soil tests. The "A" value is defined as the amount of soil phosphorus that is as available to the plants as the phosphorus in a standard phosphate fertilizer which has been mixed with the soil. Therefore, if a chemical soil test

method gives a better correlation with the "A" value than other methods, it is considered to be superior to the other methods compared. Some workers evaluate different phosphorus soil tests by means of associating the extractable phosphorus with the phosphorus content of the crop, per cent of the crop, and total yield from both field and greenhouse experiments.

The statistical correlation of linear regression analysis is the most widely used method for comparison of different soil test methods. The magnitude of the correlation coefficients, r , which varies between $+1$ to -1 are compared. The closer the r value to $+1$ or -1 as the case may be, the better the method in predicting the variation of the values on the coordinate.

Sometimes when the relationship between the extractable phosphorus and per cent yield or other variable is not linear, some workers suggest the transformation of one or both variables to a scale in which the relationship is linear. This makes it possible for the correlation coefficient to express a greater portion of the relationship not just for a linear part. Other investigators employ Bray's method of correlation and calibration (190) and use a somewhat qualitative evaluation through the comparison of the c_1 values. The less the variability of c_1 values from soil to soil the better is the method to

provide a reliable index of the phosphorus status of the soils.

(2.24) Correlation and Calibration of P Soil Test Methods

The main objective of soil tests for available phosphorus is to estimate the phosphorus fertility level of soils and be able to furnish the individual farmer dependable information as to the fertilizer needs of his field. Since the soil test method does not quantitatively measure any definite fraction of the soil phosphorus directly available to plants, a great deal of calibration is necessary before any method can be successfully used for fertilizer recommendations.

In an attempt to correlate the chemical phosphorus soil tests with crop response to phosphorus fertilization, a number of approaches have been used by various workers. Both field and greenhouse experiments are normally employed for this purpose. In order to correlate the crop response to added phosphate fertilizer, Bray (19) suggested the use of two treatments. One treatment should provide the essential nutrients in such amounts that there is neither a deficiency nor harmful excess of any nutrient. The second treatment is the same except phosphorus is omitted.

Control of water, insects, diseases, weeds, etc., should be such as to assure the most favorable growth conditions. If the yield produced by the first treatment is significantly higher than that produced by the second, the crop is said to respond to phosphorus on that soil. When yields on plots without added phosphorus are calculated in terms of the percentage of the yields from the complete treatment, and then plotted against the soil test values, a curve closely following the Mitcherlich's growth curve is obtained. Because this curve closely coincided with a typical curve of the law of diminishing returns, the Mitcherlich's equation for the curve was modified to fit this situation as follows:

$$\log(A-y) = \log A - c_1 b_1 \text{ -----(1)}$$

Where A = yield on the completely treated plot, y = yield on the plot without added phosphorus, b_1 = the phosphorus test value on the plot without added phosphorus, and c_1 = the proportionality constant. By solving for c_1 on each field and averaging the values, a mean c_1 value was obtained for the crop in question. This was used to construct the continuous curve which has been drawn through the dotted curve.

Bray found that the expression of crop response to added phosphate fertilizer in terms of the percentage yield was very useful.

$$\text{percentage yield} = \frac{\text{yield without added P}}{\text{yield with added P}} \times 100$$

The response of a crop to added phosphate fertilizer can be visualized from the percentage yield, the lower the percentage yield value, the greater will be the response of the soil to added phosphorus.

In order to determine the amount of phosphorus fertilizer required by the soil, another term, cx , was added to the equation (1) as follows:

$$\text{Log (A-y)} = \text{Log } 100 - (c_1 b_1 + cx)$$

where c = second proportionality constant expressing the efficiency per unit of the added fertilizer,
 x = the increment of the fertilizer added,
 y = percentage yield obtained with any combination of b plus x .

Bray stated further that in the case where two nutrients are both deficient in the soil at the same time, his percentage yield concept can also be used, in the same manner as the Baule's percentage yield concept, to predict the per cent combined sufficiency of the soil to grow a certain crop. When the per cent combined sufficiency was subtracted from 98%, which is the percentage in yield that can be expected as a result of making both nutrients (e.g. P and K) adequate, the value obtained would serve as a

basis for estimating whether or not the treatment will be worth while. To do this, one must also know how much phosphate and potash fertilizer was needed.

Several workers have approached the problem of correlation by determining the levels of available phosphorus in soils which are known to give a crop response to added phosphorus fertilizer and the level of phosphorus of the soils giving no response (43, 118). It is expected that the soil test results for the phosphorus responsive soils will all fall below some critical value and those for the unresponsive soils will be above this value. An example of this type of correlation was that conducted by Ensminger and Larson (43) who used the percentage increase in yield as an indicator of the degree of responsiveness to the added phosphate fertilizer. Four response categories, none, low, medium and high, were arbitrarily established so that the per cent increase in yield to phosphate fertilizer of each soil could be categorized. The phosphorus soil test values of the soils in the same response class were averaged and used as the representative phosphorus test for that class.

Olsen et al. (86) attacked the problem of calibrating the phosphorus soil test with crop response data by establishing the relationship between the percentage of soils

showing a significant (5% level) crop yield increase due to applied phosphorus from both field and greenhouse experiment and the amount of P_2O_5 extractable by the $NaHCO_3$ method so that a range of soil test values could be established in each class of the expected crop response. The responses of the crop were measured from the percentage of maximum yield, or of the yield from the largest P_2O_5 rate used. The quantitative relationship between the phosphorus soil test values and the number of soils showing significant increase in yield from phosphate fertilization can be obtained through correlation analysis. From their calibration curve based on field experiments on wheat, oats and alfalfa the expected yield response to applied phosphate and the level of $NaHCO_3$ -soluble phosphorus was as follows: below 25 pounds P_2O_5/A , a response; 25-50 pounds, a probable response; above 50 pounds, a response unlikely. The authors also mentioned that this same scale of calibration may be expected to apply also for crops with similar phosphorus requirement, but the values may need to be lower for corn and higher for potatoes.

Another method for correlating soil tests and crop data was that presented by Attoe and Truog (4). The actual yields of a crop, in this case tons of hay per acre,

are correlated directly with level of "available" phosphorus and potassium in the soils. The levels of phosphorus and potassium were expressed in terms of logarithms because their effectiveness is more precisely stated in this form. The general equation which best fitted to the correlation curve was expressed as follows:

$$\text{Tons of hay per acre} = a. \log \text{ lbs. avail. P} + b. \log \text{ lbs. exch. K} + c.$$

Where the values of a, b, and c vary with weather conditions and with the types of soils, the predicted yields can be calculated by substituting the values of "available" phosphorus and exchangeable potassium as determined by the soil test into the equation.

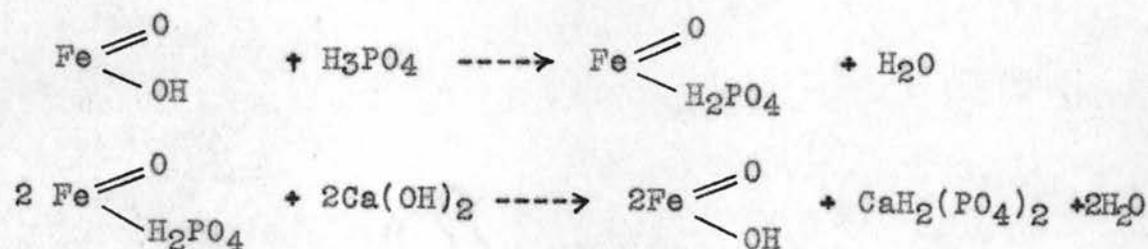
(3) Effect of Liming on Phosphate Availability to Plants

Numerous investigations have established that the low efficiency of soil phosphorus associated with acid soils is largely due to the presence of phosphorus as iron and aluminum phosphates. Liming acid soils is commonly recommended by soil scientists to amend the acid condition, and to promote the formation of calcium phosphates as well as increasing the availability of Fe- and Al-phosphates that are already present or that are subsequently formed in soils (28, 39, 90).

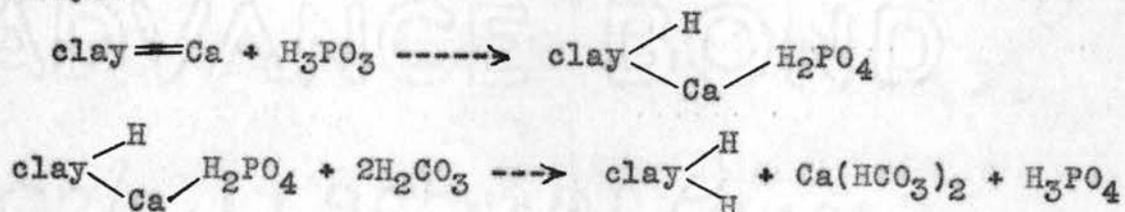
Birch (10) studied the relationship between base saturation and crop response to phosphate on acid soils. He reported that exchangeable bases, notably Ca, could retain appreciable amount of P in readily accessible forms for plant use. The author considered this phosphorus to be in what he termed the saloid-bound forms. As the degree of base saturation of acid soils increased the conditions become more favorable for the formation of saloid-bound form, he concluded that the percentage base saturation was directly reflected to phosphorus availability and inversely to phosphorus response.

Perhaps the most extensive field plot investigations regarding the influence of liming over a period of years have been carried by workers at the Ohio Agricultural Experiment Station. The results of these experiments were summarized by Salter and Barness (108). The experiments were conducted for a period of 40 years on the field consisting of acid Wooster and Confield soils. The influence of liming on the yields of corn, oats, wheat, clover and timothy during the 40 year period (1894-1933) has been observed. So far as the effect of liming on phosphate availability was concerned the data indicated that liming these acid soils had liberated sufficient native phosphorus for crop use.

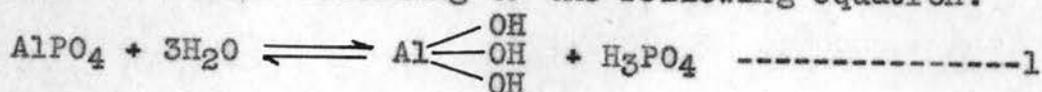
Attoe and Truog (4) reported yield data from experiments on acid podzolic soils (Spencer) of Wisconsin which furnish evidence to show that a decrease in effectiveness of established phosphorus levels was due to a decided increase in the availability of the native soil phosphorus as a result of liming. However, they did not find any accumulation of "available" phosphorus in the soils as measured by extraction with 0.002N H_2SO_4 and indicated the belief that rapid crop absorption of this fraction allowed little or no accumulation of the "available" phosphorus supply as indicated by the soil test. The increase in the native supply of soil phosphorus due to liming was explained through the fact that lime increased the OH ions in the soil solution which could replace the phosphate ions held or fixed by Fe- and Al-oxides and consequently increased the solubility or availability of the native soil phosphorus. Truog (135) postulated possible reactions that might take place when goethite adsorbed soluble phosphate under acid condition and a consequent release of the phosphate ions to be as follows:



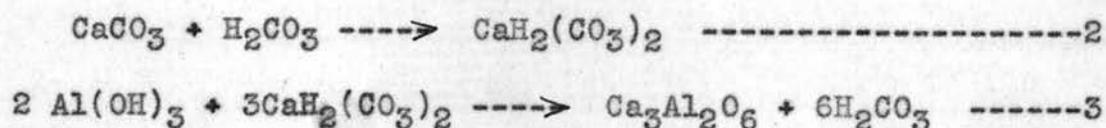
Similar reactions were also postulated for phosphates adsorbed by and released from montmorillonite type of clays:



Liming also has been reported by many investigators to increase the availability of the difficultly available iron and aluminum phosphate minerals (77, 90, 137). Marais (77) showed that the mineral phosphates of iron and aluminum were effective sources of phosphorus to plants, especially when used in conjunction with lime. He explained that the basic type of aluminum phosphates, namely wavelite, could undergo hydrolysis in neutral or nearly neutral solutions according to the following equation:



When such a reaction took place in the presence of plant roots there would be a tendency for the phosphoric acid to be removed and the aluminum hydrate to remain in the soil. The beneficial action of lime was to remove the aluminum hydrate from the reaction by precipitating it as insoluble calcium aluminate.



The continued removal of aluminum hydrate would prevent the first reaction from reaching an equilibrium. Thus the reaction would be shifted to the right and the plant would be supplied steadily with soluble phosphorus.

Other investigators stated that the effect of liming on phosphorus availability to plants was more indirect than direct. They suggested that liming created favorable reaction conditions in soils that promoted microbiological activities. The break down of soil organic matter consequently resulted in available phosphorus being released to the plants (56, 57). Some evidence also indicates that during periods of microorganism activity, promoted by liming of acid soils, certain organic anions derived from organic matter decomposition could form complexes with Fe and Al and consequently could bring about the reduction of fixation of added phosphate ions, and the dissolution of native iron and aluminum phosphates (29, 125). It seems possible that during the period of active decomposition of organic matter by microorganism the production of CO_2 is increased and consequently the dissolution of calcium and magnesium phosphates may increase, especially in the soils containing rock phosphate or having pH

around neutrality.

The indirect influence of liming on increased phosphorus uptake also can be attributed to the favorable soil conditions for rapid root growth and proliferation, consequently phosphorus can be exploited from a larger volume of soil and more phosphorus in the soil becomes available to the plants.

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III. EXPERIMENTAL METHODS AND MATERIALS

(1) Chemical Methods

(1.1) Chemical P Soil Test Methods for Preliminary Evaluation

At the present time a large number of chemical phosphorus soil test methods have been proposed and used in various parts of the country. Only the more commonly known and widely used methods will be evaluated in this study. These methods including the constituents of the extracting solutions and soil to solution ratios are listed in Table 1.

The Modified Olsen No. 1, 2 and 3 were developed by adding NH_4F to the NaHCO_3 solution in order to increase the ability of the solution to extract more phosphorus associated with Al and Fe, which is abundant and may be readily available to plants in the acid Aiken soils.

For preliminary evaluation, the concentrations of NH_4F at 0.03N, 0.1N and 0.5N in combination with 0.5M NaHCO_3 were selected and designated as Modified Olsen No. 1, 2 and 3 respectively. The soil to solution ratio of 1:20 instead of 1:10 was used. The determination of phosphorus in the extract was the same as the original method except 7.5 ml of 0.8M HBO_3 was added to the 25 ml

Table 1
 Chemical Phosphorus Soil Test Methods Including the Constituents of the Extracting Solution and Soil to Solution Ratios

Method	Extracting Solution	Soil:Solution Ratio
Bray No. I(18)	0.025N HCl+0.03N NH ₄ F	1:20
Bray No. II(18)	0.1N HCl+0.03N NH ₄ F	1:20
Olsen's (86)	0.5N NaHCO ₃ , pH 8.5	1:10
Truog's (134)	0.002N H ₂ SO ₄ +(NH ₄) ₂ SO ₄	1:100
Mehlich's(120)	0.05N HCl+0.025N H ₂ SO ₄	1:4
Morgan's (84)	0.73N NaOAc+0.52N HOAc	1:20
Miller & Axley (82)	0.03N H ₂ SO ₄ +0.03N NH ₄ F	1:20
Lancaster's ^{1/}	20 ml HOAc+10 ml lactic acid +1.11g NH ₄ F+6.7g(NH ₄) ₂ SO ₄ + 8.5NaOH in one liter, pH 4.25	1:4
Mod. Olsen 1	0.5N NaHCO ₃ +0.03N NH ₄ F, pH 8.5	1:20
Mod. Olsen 2	0.5N NaHCO ₃ +0.1N NH ₄ F, pH 8.5	1:20
Mod. Olsen 3	0.5N NaHCO ₃ +0.05N NH ₄ F, pH 8.5	1:20

^{1/} Personal communication through Dr. L. A. Alban, Soils Department, Oregon State University.

volumetric flask before developing the molybdenum blue color. The HBO_3 was added in order to prevent the interference of fluoride ion in the determination of phosphorus.

(1.2) Preparation of Soils for Recovery Tests

Soils employed in this test were phosphated with different phosphorus levels under both laboratory and field conditions.

Under laboratory conditions, 300 gm of soil were spread in a petri dish (6" in diameter and 4" high) into 5 to 6 layers of approximately equal thickness. A dilute KH_2PO_4 solution of the required concentration was added to each successive layer until the soil was saturated. The soils were then kept in the oven and maintained at 60°C for 24 hours, after which the soils were almost dried. The soils were pulverized to pass 2 mm sieve and air dried for 2 days before being used. Aiken soils from Langdon and Riches locations were used. The following rates of phosphorus were added:

Langdon 0, 30, 60, 120 and 240 lbs $\text{P}_2\text{O}_5/\text{A}$

Riches 0, 90, 180, 360 and 720 lbs $\text{P}_2\text{O}_5/\text{A}$

The fixation reaction between the phosphorus and soils at 60°C for the period of 24 hours was thought to be sufficient to approach equilibrium. The original phosphorus in the soil subjected to the same condition did

not seem to be altered so far as the amount soluble in the Bray No. 2 solution was concerned.

Under field conditions, soils were fertilized with concentrated super phosphate at the rate of 0, 60 and 120 lbs P_2O_5/A annually for 5 years. A legume crop was grown each year.

The soils pretreated with phosphate from both laboratory and field were extracted for phosphorus by 11 methods as described in the previous section. The amounts of extractable phosphorus and recovery efficiency of these methods were compared.

(1.3) Inorganic P Fractionation

The procedure for fractionating inorganic soil phosphorus of Chang and Jackson (23) was followed with some modifications as suggested by Hsu.^{2/} The changes consisted of extracting Al-phosphate by 0.5N NH_4F solution adjusted at pH 8.5 instead of pH 7.0. The extraction with 1N NH_4Cl prior to Al-phosphate extraction was omitted because phosphate soluble in NH_4Cl could be refixed by Fe and Al. The extraction of Ca-phosphate was made after the reduction of Fe and removal of occluded Fe- and Al-phosphates. The reason for this reversion of the extraction order of

^{2/} Personal communication through Dr. T. T. Chao, Soil Department, Oregon State University.

the original method was because certain amounts of occluded Fe- and Al-phosphates could dissolve in 0.5N H_2SO_4 . The outline of the procedure followed is shown in Figure 2.

(1.4) Determination of P in Plant Tissue

The plant samples from both field and greenhouse experiments were wet digested and analyzed for phosphorus. The samples were predigested with concentrated HNO_3 until the brown nitric oxide fumes disappeared. The mixture was further digested with perchloric acid on the hot plate until the solution was clear and fumes of $HClO_4$ persisted. The solution was cooled, filtered and diluted with water to 50 ml.

Phosphorus in the solution was determined by ammonium molybdate-1,2,4 aminonaphthol sulfonic acid. Perchloric acid was employed to acidify the system. The transmittancy of the developed blue colored solution was measured on a Klett-Summerson colorimeter using a red No. 66 filter.

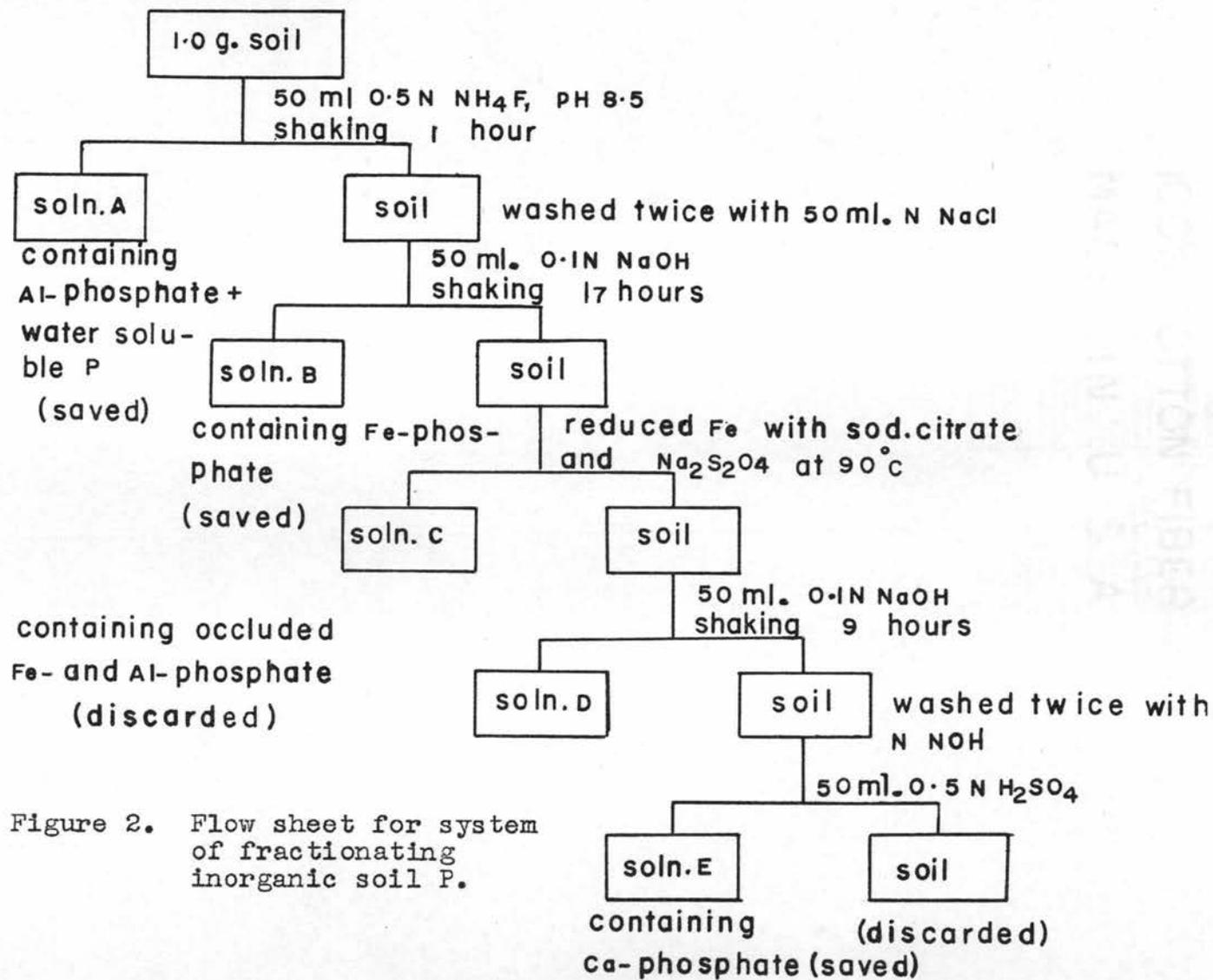


Figure 2. Flow sheet for system of fractionating inorganic soil P.

(2) Field Experiments

(2.1) Experimental Locations and Characterization of Soils

The study included 10 field experiments which were located in different counties in the Willamette Valley. Eight of these locations were part of the O.S.C. TVA cooperative research project No. 331. Three of these eight locations were established in 1958 while the rest were initiated in the spring of the following year. The other two field experiments were from the O.S.C. research project No. 73. The experimental locations were chosen with the following objectives in mind: 1) that they were representative of the Aiken soils of the region; 2) that they cover as wide a range of exchangeable K, NaHCO_3 -soluble phosphorus, pH and lime requirement as possible; and 3) that the owners of the farms would be good cooperators. The locations, names of the cooperators, year of establishment and the fertility level of these experimental sites are shown in Table 2.

The soils at the experimental locations were described and identified by E. G. Knox, Soils Department, Oregon State University. These soils are currently considered to be Aiken. However, there is a possibility that studies in progress may lead to redefinition of the series. The soils in these locations, except those in Douglas and

Table 2
Locations, and Chemical Analyses of Aiken and Olympic Soils Used in the Various
Phases of Phosphorus Studies

Field expt. No.	Names of Farms	County	Year estab- lished	pH	L.R. ^{1/} T/A	P ppm	K me/100	Ca me/100	Mg me/100	C.E.C. me/100	% O.M.
502	Langdon	Douglas	1958	5.8	3.0	2.0	0.54	5.2	2.8	21.0	6.6
506	Miotke	Marion	1958	5.7	3.5	12.5	0.51	7.5	1.3	23.0	7.6
508	Riches	Polk	1958	5.0	5.0	11.0	0.50	3.1	0.9	21.5	6.7
510	Adam	Yamhill	1959	5.6	2.5	6.9	0.74	6.8	1.7	19.2	4.0
512	McDougal	Marion	1959	5.5	3.0	8.8	0.89	5.7	1.8	18.4	3.6
514	Johnson	Linn	1959	5.2	4.0	4.7	0.50	3.2	1.3	22.6	6.4
516	Bonkovski	Linn	1959	5.4	3.5	13.6	0.47	6.9	2.4	25.9	6.1
518	Ashton	Clackamas	1959	5.4	3.5	7.0	0.23	5.5	2.7	26.6	6.8
108	Anderson	Clackamas	1959	5.7	2.0	2.8	0.26	3.3	1.5	28.0	4.7
105	Red Soils Exp. Sta.	Bra. Clackamas	1957	5.3	3.0	4.5	0.26	2.6	0.6	16.0	5.0
103	Red Soils Exp. Sta.	Bra. Clackamas	1955	5.4	3.5	7.8	0.14	3.1	2.0	15.5	--

^{1/} Lime requirement determined by Woodruff method and expressed as tons of CaCO₃/A.

Clackamas counties may be assigned to a different series. The soils are well drained Reddish Brown Latosols developed from residuum derived from basalt rock or basalt-like material.

A typical profile description of the Aiken soils employed in this study is shown in Appendix 1. The chemical and physical analysis of the soil profile of some of the locations are also shown in Appendix 2. The chemical analysis of the profiles sampled indicated that the bicarbonate soluble phosphorus decreased and then increased with depth at most locations. The content of exchangeable bases also decreased with depth.

Identification of the kinds of clay minerals present in these soils have been made. In general, slight amounts of kaolin, vermiculite or vermiculite-chlorite integrate silicate clays were identified as being present in the coarse clay fractions throughout the soil profile. Small amounts of kaolin were found to be the only crystalline materials present in the fine clay fractions. In these soils, the fine clay fraction accounts for approximately 80% of the total clay. Since these soils contain quite high percentages of clay, and since only small to moderate quantities of layer silicate minerals are present in the fine clay fractions, these soils apparently contain relatively large amounts of amorphous material. The amorphous

materials may be largely allophane and residual Al and Fe oxides. Further work is needed, however, to verify this.

(2.2) Experimental Design and Treatments

The experimental design for the experiments from the TVA project (Exp. No. 502 to 518) and experiment No. 108 was a modified composite design which allowed the calculation of a response surface without the use of a complete factorial. The experiments consisted of 27 treatments replicated 3 times from which phosphorus, lime, potassium, molybdenum, boron and sulfur were studied as variables. DuPuits variety of alfalfa was used as the indicator crop. The first 10 treatment combinations from each location were used to evaluate the lime x phosphorus interaction. They are the factorial combination of 4 levels of lime and 4 levels of phosphorus; these treatments received an optimum rate of potassium, boron and sulfur. The lime and fertilizer application rates at the different locations varied with the soil analyses and results from previous greenhouse experiments.

The ten treatment combinations are shown in Table 3.

Lime was applied as finely ground agricultural lime stone. The source of phosphorus was sulfur-free concentrated superphosphate. Potassium was applied as muriate of potash, boron was applied as borax, and sulfur was

Table 3
Treatment Level Combinations and Fertilizer Rates for
Expt. No. 502 to 518 and Expt. 108

Treatment Number	Treatment Combinations Levels of the Elements				
	Lime	P	K	B	S
1	0	0	2	1	1
2	0	2	2	1	1
3	1	1	2	1	1
4	1	2	2	1	1
5	1	3	2	1	1
6	2	0	2	1	1
7	2	1	2	1	1
8	2	2	2	1	1
9	3	1	2	1	1
10	3	3	2	1	1

Locations	Elements	Fertilizer Rates			
		0	1	2	3
Adam (Exp. 510)	Lime	0	1.5	3	4.5
Riches (Exp. 508)	(Tons of lime/Acre)	0	3	6	9
Others	" " " "	0	2	4	6
All	P ₂ O ₅ , lbs/Acre	0	45	90	180
Riches (Exp. 508)	K ₂ O, lbs/Acre	-	-	100	-
Others		-	-	150	-
All	B, lbs/Acre	-	4	-	-
All	S, lbs/Acre	-	40	-	-

ADVANCE BOND

applied as gypsum. Lime was broadcast and disced into the upper 6 inches of soil in a single application prior to establishment. The other fertilizer treatments were applied according to the treatments listed in Table 3. Plots with phosphorus treatments received the first 30 lbs of P_2O_5/A banded underneath the seeds to insure establishment of alfalfa and the remainder was broadcast. Four pounds of boron was applied at the time of establishment and 2 lbs of boron/A was applied annually. All fertilizers, with the exception of the banded application of phosphorus, were disced in prior to establishment. The annual application of fertilizer was surface applied in the fall of the year. The plot size was 9x30 feet.

Another experiment (Exp. No. 105) located at the Red Soils Branch Exp. Sta. was a lime x phosphorus placement and rate experiment. The experiment consisted of a complete randomized block design with 3 replications. Some of the treatment combinations employed are listed in Table 4. Every treatment combination had a constant application of Mg, S and K. Lime was applied as a single application and incorporated with the upper 6 inches of the surface soil prior to planting alfalfa. A wide range of phosphorus levels was established since rates of 0, 120, 180 and 360 lbs P_2O_5/A were applied the first year.

The first harvest was done between May 10 and 20, 1960

Table 4
Treatment Level Combinations and Fertilizer
Rates for Exp. No. 105

Level of the elements		Application of P
Lime	P	
1	0	single
1	3	single
1	1	annually for 3 years
1	2	annually for 3 years
2	0	single
2	6	single
2	1	annually for 3 years
2	2	annually for 3 years

Fertilizer Rates

Lime 1 = 2 tons of lime/A, 2 = 6 tons of lime/A

P 1 = 60 lbs P_2O_5/A , 2 = 120 lbs P_2O_5/A

3 = 180 lbs P_2O_5/A , 6 = 360 lbs P_2O_5/A

and the second cutting in early July. An area 3.5x22 feet was harvested from the center of each plot and moisture samples taken. Yields were reported as pounds of oven dried alfalfa per acre. Plant samples were taken from the upper half of the plant at the first cutting for chemical analysis.

(3) Greenhouse Methods

(3.1) Preliminary Study for the Suitability of the Indicator Crops to be Used - Oats vs. Barley

Oats and barley have been employed by many investigators for phosphorus uptake studies in the greenhouse. They grow fast and seed germination is fairly uniform. The roots are fibrous so that a thick mat of roots develops in a fairly short time. The plant itself does not grow very tall and can be handled easily.

The objective of this preliminary study was to examine the relative performances of oats and barley for short term phosphorus absorption under the confined conditions in the greenhouse. The two plants differ primarily in tolerance to soil acidity, with barley being more sensitive to low pH. The experiment was carried out to evaluate both the optimum rate of nitrogen and growing period required for maximum phosphorus absorption.

In order to determine the optimum rate of nitrogen, 200 gm of Aiken soil from Riches location was weighed out into round waxed cardboard cartons of 12-ounce capacity whose bottoms were punched with a small nail to serve as a drainage hole. The surface of the soil was covered with a layer of fiber glass. Fifty seeds of either oats or barley were placed over the fiber glass and then covered with acid washed sand. Prior to seeding, nitrogen was applied with half of the rate in the form of NH_4NO_3 and the other as $(\text{NH}_4)_2\text{SO}_4$. The rates were 0, 250, 500, 1000, 2000 and 3000 pounds of N per acre. All treatments received 110 lbs P_2O_5 and 70 lbs K_2O per acre and each treatment was duplicated. The soils were kept moist by watering at least once a day. The seeds germinated after 4 to 5 days. The plants were cut at the ground level 10 days after the seeds germinated. The plant samples were dried in the oven at 70°C for 48 hours, weighed and analyzed for phosphorus.

Soils and plants were prepared in the same manner as above to evaluate the best period of growth. Growing periods of 8, 12, 16, 24 and 32 days were duplicated. Each treatment received 500 lbs N, 110 lbs P_2O_5 and 70 lbs K_2O per acre. Plant samples were treated in the same way as above.

The results obtained are shown in Tables 5 and 6 and can be summarized as follows:

Nitrogen rate experiment: 1) The best growth and maximum yield of oats was obtained at 500 lbs of N/A. 2) The higher rates of nitrogen (above 1000 lbs of N/A for oats and 500 lbs of N/A for barley) caused burning of the leaves and the plants began to die about 6 days after germination. 3) Both plants showed maximum P content at maximum yield. 4) It was suggested from this experiment that oats tolerated higher concentrations of nitrogen and the nitrogen should not be applied in a concentration greater than 1000 lbs of N/A as a single application.

Growing period experiment: 1) During the first 12 days after germination barley seedlings grew much faster than oats, the plants then became yellow and stopped growing. Oats, on the contrary, grew slower but were still growing steadily at 32 days (Figure 3). 2) Phosphorus content of barley reached maximum at 12 days old and then declined. The P content of oats followed the same trend as its yield curve and became greater than that of barley after 16 days and tended to level off slightly at 32 days (Figure 3).

From these preliminary experiments it was concluded that oats were more suitable than barley for the study of short term phosphorus absorption under the micropot

Table 5
 Dry Weight and Phosphorus Content of the Tops of 10 Day
 Old Barley and Oats at Various Rates of Applied Nitrogen

Treatment lbs/A	Yield dried weight ^{1/} mg/plant		P content of tops ^{1/} ug P/plant	
	oats	barley	oats	barley
0	10.3	14.9	46.6	59.5
250	13.0	16.8	48.4	61.5
500	14.1	22.8	52.6	68.8
1000	15.2	16.6	53.9	53.4
2000	13.1	13.4	44.5	53.1
3000	10.0	9.9	33.9	49.8

^{1/} Average of duplicate

Table 6
 Dry Weight Yield and Phosphorus Content of the Tops of
 Barley and Oats at Various Growth Periods

Growth period, days	Yield dried weight ^{1/} mg/plant		P content of tops ^{1/} ug P/plant	
	oats	barley	oats	barley
8	8.5	11.0	41.8	45.3
12	12.7	20.9	47.2	56.9
16	23.9	26.6	57.1	52.9
24	38.2	29.5	69.4	39.6
32	55.0	30.0	77.2	40.8

^{1/} Average of duplicate

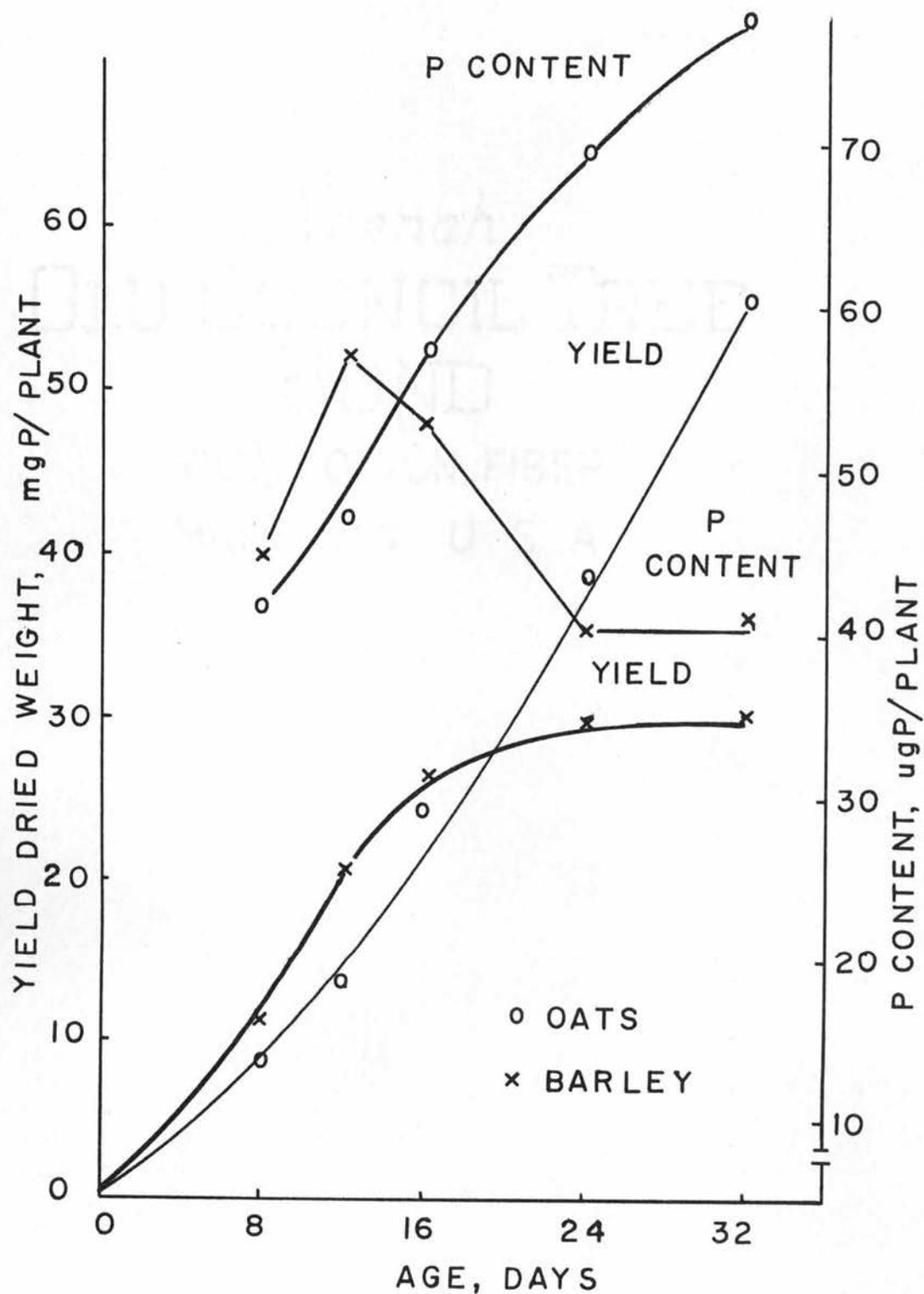


Figure 3. Yields and P contents of barley and oats at various stages of growth.

technique conditions used. The oats could also be grown under these confined conditions with 500-1000 lbs of N/A as long as 32 days to yield maximum phosphorus uptake. A technique to obtain uniform germination was developed and will be described later.

It was decided that a legume crop should be used as an indicator plant since the amount of phosphorus taken up and the correlation between the amount of P uptake versus P soil test values would be different.

Subterranean clover was chosen as an indicator crop since it has been demonstrated that this legume could grow on acid soils that were well supplied with P. The inoculated seeds were planted under the micropot technique as previously done for oats and barley in order to test for uniform germination and to evaluate the growth under confined conditions. The plants grew well even though the initial growth was slow. As many as 50 plants could be grown in a pot. A technique for uniform germination was also developed and will be described in detail in the next section.

(3.2) Soils Used in the Greenhouse Study

The soils from the 8 TVA locations plus experiment 108 were sampled for greenhouse experiments. In each

location a sample of 700 to 1000 gms of surface soil (0-6"), was taken from the 10 treatments listed in Table 3. Three replications were sampled separately. Soil samples were taken in the fall at least 6 weeks after the fertilizers had been applied and the fall rains had started.

The soil from experiment 105 is not Aiken but is closely related to it and has been mapped as Olympic. The experiment was a lime x phosphorus placement x phosphorus rate study. Samples were taken from 8 treatments shown in Table 4, the three replications were sampled separately.

The soil represented by experiment 103 has also been mapped as the Olympic series. This experiment was a complete 3 x 3 lime x phosphorus factorial with 3 replications. The phosphorus rates were 0, 60, and 120 lbs of P_2O_5/A each year and the lime rates were 0, 3 and 6 tons/A of lime prior to establishment.

Soil samples were taken in the fall from all the plots with a total of 27 samples. Since the samples were taken on the fifth year of this experiment the phosphorus application rates totaled 0, 300, and 600 lbs of P_2O_5/A .

(3.3) Preparation of Soils and Seeds

Surface soil samples were taken from field plots prior to treatment with various levels of lime and phosphorus, air dried and ground to pass 2 mm sieve. Two hundred grams of soil were weighed out into 16-ounce waxed cardboard cartons whose bottoms were punched with a nail to serve as a drainage hole. The hole was lined with fiber glass to prevent the loss of the soil through this opening. The surface of the soils in the pots was leveled and then covered with a thin layer of fiber glass.

In order to obtain oat seeds of a uniform size, the oat seeds were sieved to pass a No. 6/64 screen and be held on a No. 5/64 screen. The seeds retained by the latter sieve were collected and poured into water. The floated seeds were discarded and heavier submerged seeds were saved. The seeds were dried with a fan at room temperature and were then ready for planting.

The clover seeds were sieved with a 2 mm mesh screen and the retained seeds were saved. The thickness of the clover seed coat and the speed with which water is absorbed is quite variable. In order to obtain uniform germination, the seeds were soaked in water for 10-15 hours and only the swollen seeds were used for planting in the experiment.

Immediately prior to seeding, the clover seeds were adequately inoculated with appropriate symbiotic bacteria. The seeds were planted immediately after inoculation.

(3.4) Method of Planting Oats and Subterranean Clover

Seventy five oat seeds were soaked for 24 hours and were placed evenly over the surface of the soil which was previously lined with fiber glass. Nitrogen solution at the rate of 500 lbs of N/A was added prior to seeding. The nitrogen solution consisted of half NH_4NO_3 and half $(\text{NH}_4)_2\text{SO}_4$. The seeds were then covered with about 100 grams of acid washed quartz sand. The pots were watered with 100 ml of distilled water and transferred to the constant-temperature room at 20°C . The sand in the pots was kept moist by covering with moist cheese cloth. After 3 days the seeds germinated and the coleoptiles emerged about 1 cm above the sand. The plants were moved to the greenhouse at this stage. The ages of the plants were counted from the date they were transferred to the greenhouse.

The temperature in the greenhouse was kept at $75 - 80^\circ\text{F}$ during day and $55 - 60^\circ\text{F}$ during the night time through the use of a thermostatically controlled cooler and heater. The plants were also

furnished with supplemental lighting which provided a minimum of 500 foot candles light intensity for 13 hours. The supplemental lighting consisted of an alternating series of 40 watt cool and warm white daylight type fluorescent tubes spaced 6 inches apart. The warm white tubes were included to supply light in the longer wavelength region.

The soil moisture was depleted rapidly due to high evapotranspiration. Therefore the moisture content of the soil had to be watched very closely. The pots were watered slightly twice a day with distilled water. Yellowing of plants at 20 days indicated nitrogen deficiency. Nitrogen was then added to each pot at the rate of 250 lbs of N/A.

The plants were harvested after 30 days of growth in the greenhouse. The oats were cut as close to the seed as possible and the plants counted so that the dry weight yield of the oat tops could be adjusted upon the basis of 75 plants. The harvested oat tops were oven dried at 70°C for 3 days. The dried plant material was weighed and ground with an electric blender to the fineness suitable for wet digestion in HClO₄-HNO₃ system. The ground samples were saved for phosphorus analysis.

In order to study the reduction of different forms of soil phosphorus, some of the soils grown under the first

crop of oats were again grown to oats. The soils with L_0P_0 and L_3P_3 from 7 locations were selected in order that the fairly wide range of phosphorus availability would be obtained. As soon as the first crop of oats was cut, the soils were air dried and pulverized to pass 2 mm sieve. As many roots as possible were removed. One hundred grams of soil were weighed out into 12 ounce waxed cardboard cartons (the cartons used for the first crop were 16 ounces). The planting procedure was essentially the same as previously described for the first crop with the exception that 100 oat seeds were planted and 1000 lbs of N/A and 400 lbs of K_2O/A were added prior to seeding. Again 1000 lbs of N/A and 400 lbs of K_2O/A were added when the plants were 15 days old. The plants were cut at 35 days of age. The plants were analyzed for phosphorus uptake and the soils were air dried and kept for analysis.

Fifty inoculated clover seeds were placed as evenly as possible over the surface of the soil formerly lined with fiber glass. Prior to seeding the soil was treated with ammonium molybdate solution at the rate of 1 pound Mo per acre. The seeds were then covered with about 100 gm of acid washed sand and watered with 100 ml of distilled water. The seeds were allowed to germinate and then transferred to the greenhouse in the same manner as oats. At 20 days, the plants were fertilized with

potassium sulfate at the rate of 100 lbs of K_2O/A .

After 45 days of growth the plants were cut as close to the soil surface as possible. The slower initial growth of the clover required a longer growing period to yield adequate plant samples (3-4 gm dry weight) to determine yield and phosphorus uptake from the soils. The plant samples were treated in the same manner as those of oats.

IV. RESULTS AND DISCUSSION

(1) Laboratory Studies

(1.1) Preliminary Evaluation of Different Extractants for Soil P

Various rates of soluble phosphates were added to two Aiken soils, one from Riches farm and the other from Langdon farm. These soils were then extracted for "available" phosphorus by 11 common phosphorus soil test methods. The amounts of phosphorus extracted by these extracting solutions are shown in Table 7. The time of shaking and the ratio of soil to extracting solution are also shown. The data showed that the amounts of phosphorus extracted by these methods vary widely. For instance, the amount extracted from the soil from Riches farm, treated with 0 rate of P_2O_5 varied from 5.0 ppm by Mehlich method to 179.5 ppm by Modified Olsen No. 3. This same variation was also obtained from soils from Langdon farm. Morgan solution extracted a large amount of phosphorus but had no relation to the level of phosphorus added to the soils and therefore has been omitted from further discussion.

The efficiency of recovering added phosphorus from the soils was used as a criterion to evaluate these extracting solutions. The amount of phosphorus recovered

Table 7

Amounts of Phosphorus Extracted by Different Chemical Phosphorus Soil Test Methods

Amount of P ₂ O ₅ added lbs/A	Amounts phosphorus extracted, ppm P										
	Bray No. 1	Bray No. 2	Miller & Olsen Axley	Modified Olsen			Lan- caster	Truog	Meh- lich	Morgan	
shaking ratio	1 min.	40 sec.	1 min.	30 min.	30 min.	30 min.	30 min.	10 min.	30 min.	5 min.	30 min.
	1:20	1:20	1:20	1:10	1:20	1:20	1:20	1:4	1:100	1:4	1:20
Aiken Soil from Langdon Location											
0 ^{1/}	8.0	8.0	8.2	3.2	7.8	19.0	30.9	1.0	3.5	1.5	68.0
30	10.0	10.5	10.5	3.8	8.9	21.8	35.4	1.3	4.2	1.9	61.0
60	11.0	10.5	11.2	4.7	9.3	21.8	40.2	1.5	4.6	2.3	72.0
120	15.0	14.0	15.0	5.2	10.5	24.2	47.6	2.3	6.0	3.0	85.0
240	18.0	25.5	21.6	7.3	17.0	38.4	55.7	3.3	10.2	4.6	76.0
Aiken Soil from Riches Location											
0 ^{1/}	74.7	103.5	103.6	19.0	40.3	132.0	179.5	9.3	24.8	5.0	60.0
90	86.0	106.0	111.6	22.0	47.0	139.0	191.0	10.2	25.6	5.8	62.5
180	91.2	118.0	121.0	26.0	48.4	148.0	203.5	11.1	27.5	6.8	57.5
360	114.0	143.0	144.0	30.0	68.0	164.0	226.0	14.2	36.0	8.6	65.0
720	154.0	184.0	182.6	42.0	83.3	222.0	303.5	20.4	53.8	12.4	62.5
Olympic Soil from Red Hill Exp. Sta. (Rep. 2)											
0 ^{2/}	41.5	57.5	52.3	22.8	16.0	38.4	76.5	13.0	14.6	5.0	23.5
300	58.3	85.0	72.0	28.0	24.4	59.0	106.0	18.5	20.2	7.3	20.0
600	70.0	86.0	83.7	33.1	25.8	62.5	111.7	23.3	29.5	10.4	21.5

^{1/} Phosphorus was applied under laboratory conditions.

^{2/} Phosphorus was applied in the field as concentrated Super phosphate.

was determined by subtracting the amount extracted from the untreated soil from the amount extracted from the various phosphorus treated soils. The recoverable phosphorus, obtained for different methods, plotted against the actual amounts applied to Aiken soil from Riches farm are shown in Figure 4. The amount of phosphorus recovered was very low for Mehlich, Lancaster, Olsen and Truog methods. The Modified Olsen No. 1 method extracted appreciably more than the above four methods but not nearly as much as the Miller and Axley, Bray No. 2, Bray No. 1 and Modified Olsen No. 2 methods. These last four extracting solutions have almost essentially the same recovery curves. The Modified Olsen No. 3 showed the greatest recovery of all. The same results were obtained for the soil from the Langdom farm.

The efficiency of the phosphorus soil test methods were also evaluated in terms of the percentage of the recovery. These values were obtained by dividing the absolute amounts of phosphorus recovered by the corresponding amounts of phosphorus applied, multiplied by 100. The percentage of recovery for any extracting solution does not vary widely for the different soil phosphorus levels. The average per cent of recovery varied widely among the different extracting solutions. These are

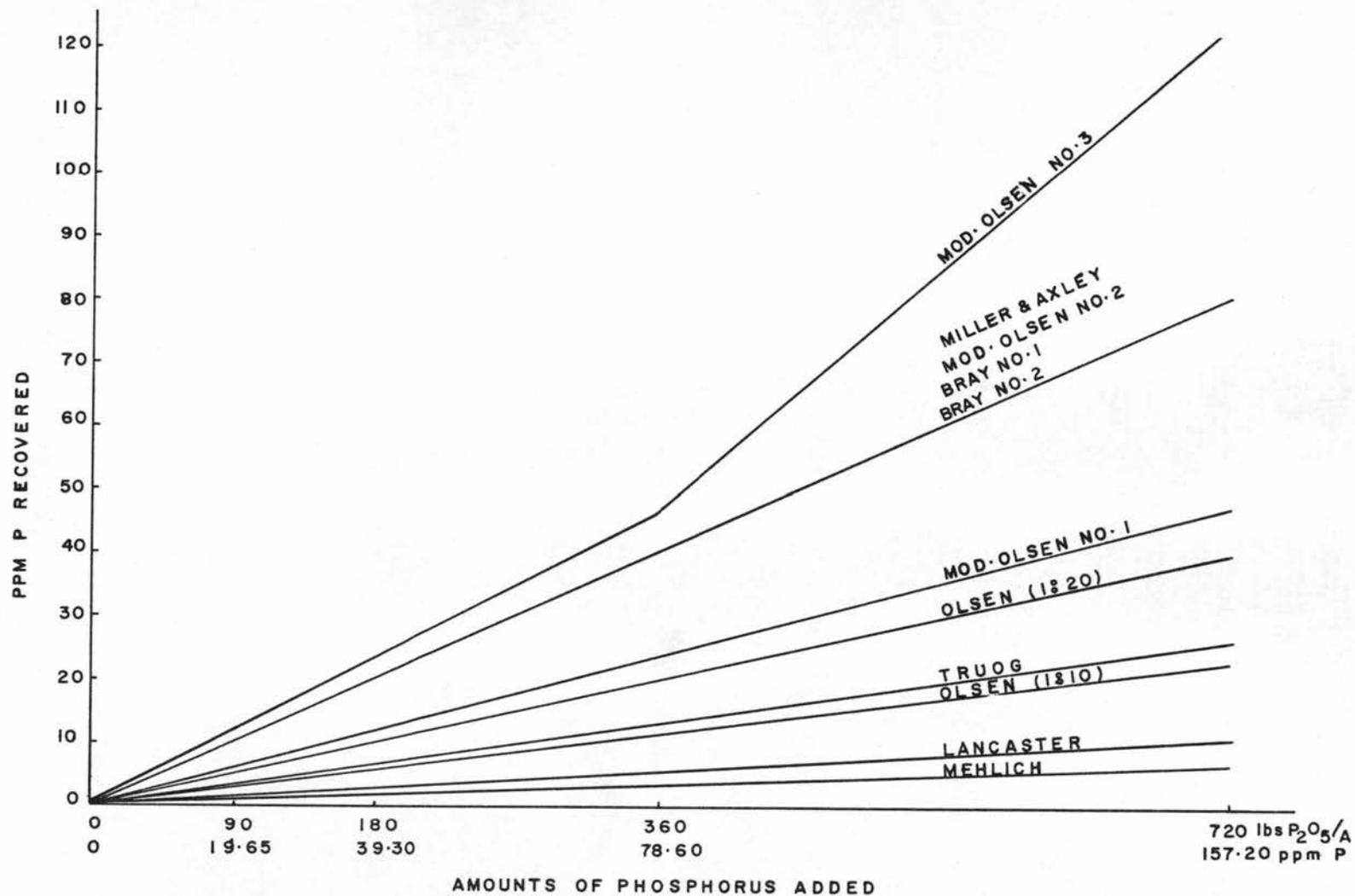


Figure 4. Added phosphorus recovered by different extracting solutions (Aiken soil from Riches farm).

shown in Figure 5 for the two Aiken soils. The values varied from 5.05% (Lancaster) to 62.7% (Modified Olsen No. 3) for soil from Langdon farm and from 4.42% (Mehlich) to 64.4% (Modified Olsen No. 3) for soil from Riches farm. The Modified Olsen No. 3 showed the highest percentage recovery which was over 60% for both soils. Both of Bray's methods, Miller and Axley and Modified Olsen No. 2 gave about the same per cent recovery which was over 20% for Langdon's and over 35% for Riches'. Lower per cent recovery was obtained for Truog, Olsen, Mehlich and Lancaster methods.

It was decided that three extracting methods would be used for the correlation studies with the field and greenhouse experiments. According to the results obtained, there were 5 methods that showed some promise of giving a good prediction of the phosphorus status of Aiken soils. These methods were Bray No. 1 and 2, Miller and Axley, Modified Olsen No. 2 and No. 3. From these five methods only two, Bray No. 1 and Modified Olsen No. 2 were selected. Bray No. 1 was preferred to Bray No. 2 and Miller and Axley methods because of the fact that it contained lower concentration of acid but still had about the same efficiency in extracting the soil phosphorus. According to the literature, Bray No. 1 appeared to be more

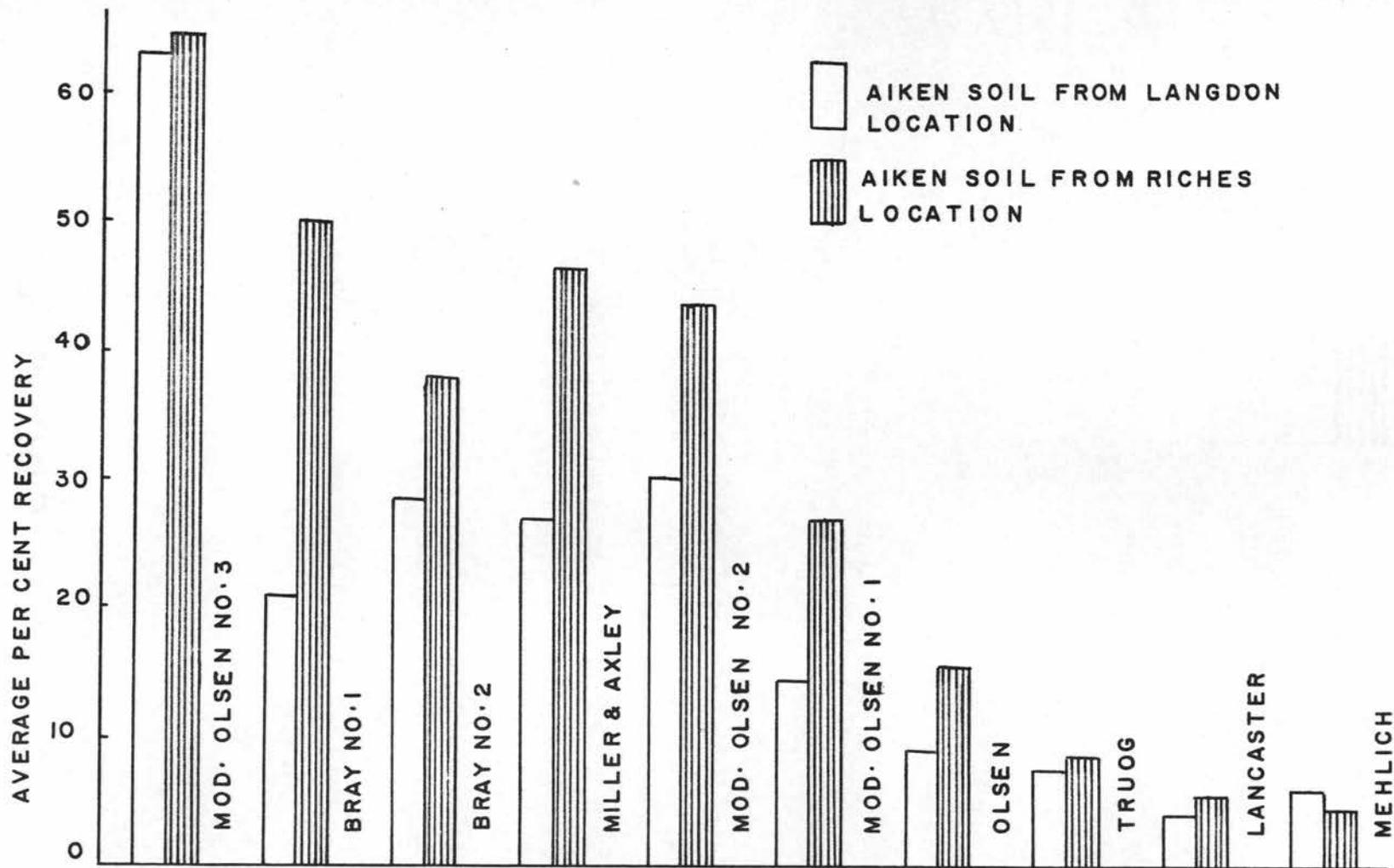


Figure 5. Average per cent recovery of added phosphorus from Aiken soils by different extracting solutions.

widely employed by many states and results from various investigators showed that this method, in most cases, gave good correlation with the crop responses to added phosphorus fertilizer. Since the modification of the Olsen method was intended to improve the extracting power of the original method, the Modified Olsen method No. 2 was selected. This method was preferred to No. 3 because it yielded about the same sensitivity and magnitude of extractable phosphorus from the soils tested as did Bray No. 1. Also, the Modified Olsen No. 3 was essentially an ammonium fluoride extracting reagent and it was thought desirable to maintain NaHCO_3 as an important component of the extracting solution. Since the Modified Olsen No. 2 was the only one selected for further studies, this method will be referred to merely as Modified Olsen in later discussion.

The third method chosen was the original Olsen method since it is the one presently employed by the Oregon State University Soil Testing Laboratory for routine soil testing.

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(1.2) Influence of the Addition of NH_4F with 0.5M NaHCO_3 on the Extractable Soil P

The efficiency of the Olsen method in recovering phosphorus added to the soils was shown to be about doubled (Figure 4) by widening the ratio of soil to extracting solution from 1:10 to 1:20. The addition of NH_4F to the 0.5M NaHCO_3 solution could also result in increasing the extracting power of the solution. The greater the concentration of NH_4F added to the solution the greater the amount of phosphorus extracted.

The increase in the amounts of phosphorus extracted probably resulted from the ability of NH_4F to dissolve phosphates associated with aluminum (23, 44, 45). Since the extracting solutions were alkaline, certain quantities of Fe-phosphates might have been extracted also. It is the writer's opinion that Fe-phosphates and particularly Al-phosphates are the major sources of available phosphorus in the Aiken soils.

(1.3) Influence of Liming on the Amounts of P Extracted by Various Concentrations of NH_4F Alone and in Mixture with 0.5M NaHCO_3 Solution

It was found that liming increased yields and phosphorus uptake from acid Aiken soils, therefore

additional studies were made to determine the effect of liming on the amounts of phosphorus extracted.

Limed and unlimed soils from Riches and McDougal farms were extracted with various concentrations of NH_4F . The ratio of soil to extracting solution used was 1:20. The phosphorus extracted was determined according to the method described by Chang and Jackson (23) for Al-phosphate. The unlimed soils had a pH of 4.8 and 5.2 for soils from Riches and McDougal farms respectively. After liming the soil from Riches location with 6 tons per acre and soil from McDougal location with 4 tons per acre, the pH was raised to 6.5 and 6.2, respectively. The amounts of phosphorus extracted by various concentrations of NH_4F from these unlimed soils has been presented in a bar diagram in Figure 6. As the concentration of NH_4F increased the amount of phosphorus extracted from both limed and unlimed soils increased accordingly and at approximately the same rate. At a lower concentration of NH_4F the amounts of soluble phosphorus obtained from the unlimed soils appeared to be greater than those from the limed soils. However, the differences in the amounts of phosphorus extracted from limed and unlimed soils diminished when the concentration of NH_4F increased, especially when approaching 0.5N.

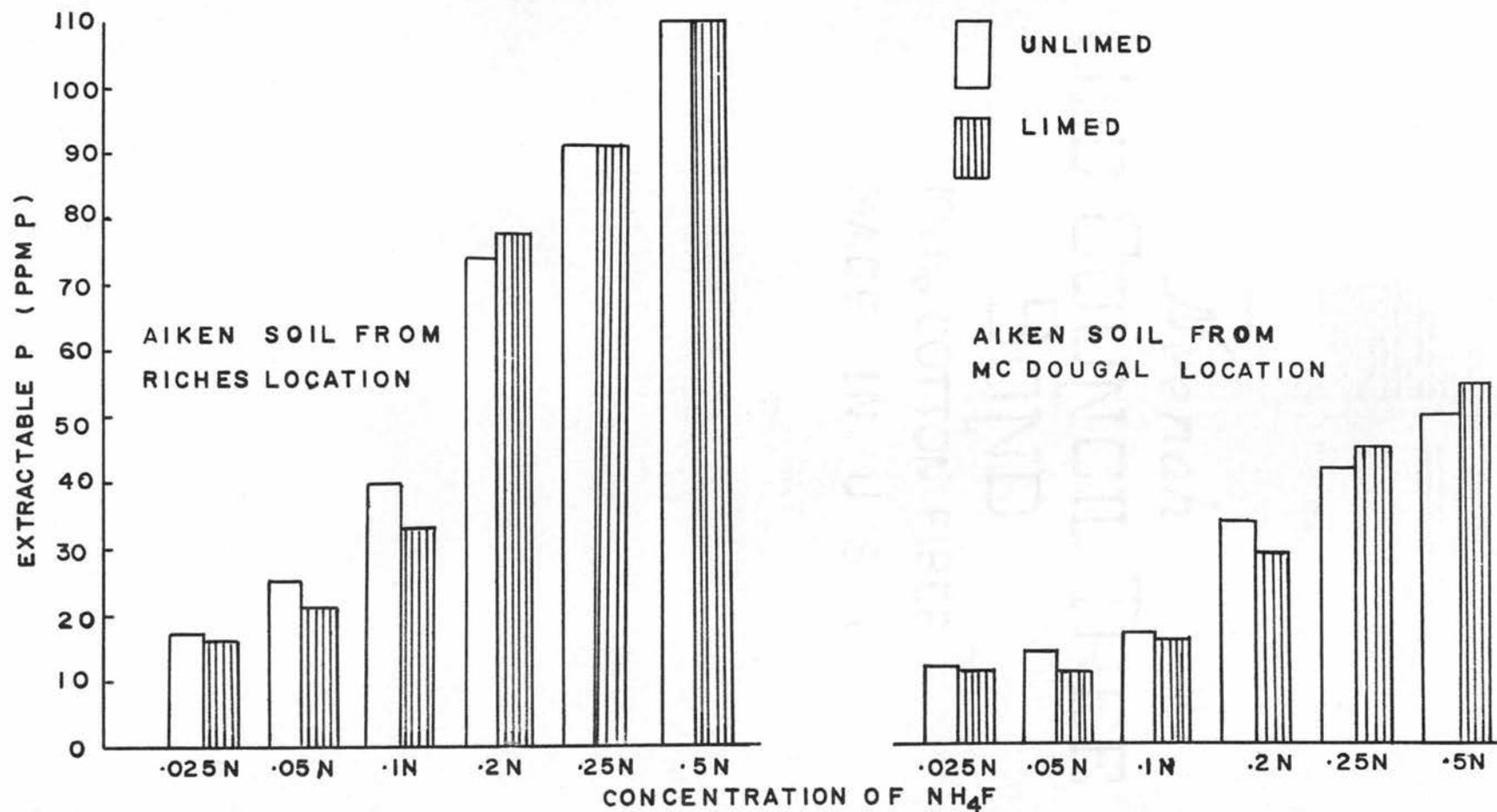


Figure 6. P extracted by various concentrations of NH_4F from Aiken soils which were limed and unlimed under field condition.

The same results were obtained when both limed and unlimed soils were phosphated under laboratory conditions, prior to extraction with various concentrations of NH_4F (Table 8).

An attempt was also made to determine the effect of lime on the amount of phosphorus extracted by the mixture of 0.5M NaHCO_3 and various concentrations of NH_4F solutions. The limed and unlimed soils from different field locations were extracted and the results shown in Table 9. The phosphated limed and unlimed soils from Riches location (under laboratory conditions) were also extracted with the mixture of 0.5M NaHCO_3 and various concentrations of NH_4F ; the results are shown in Table 8. Both results indicate the same repressive effect of lime on the amount of phosphorus extracted by the NH_4F solution alone except that the amounts extracted were much greater with the mixture solution. The repressive effect of lime on the amount of phosphorus extracted was diminished when the concentrations of the NH_4F in the mixture were increased up to 0.5N.

Smith et al. (117) have also reported the repressive effect of NH_4F (0.03N) on the soluble phosphorus in a dilute acid solution (0.025N HCl) when used with alkaline soils. The depression of extractable phosphorus was

Table 8

Phosphorus Extracted by 0.5N NaHCO₃ in Mixture With Various Concentrations of NH₄F
From Limed and Unlimed Aiken Soils^{1/}

Location	Lime Treat. T/A	Exch. Ca + Mg me/100g	Soil pH	ppm P extracted by 0.5N NaHCO ₃ mixed with following conc. NH ₄ F					
				0.025N	0.05N	0.1N	0.2N	0.25N	0.5N
McDougal	0	7.6	5.2	29.8	36.1	48.1	67.5	75.5	88.5
	4	10.1	6.3	29.7	27.3	40.0	63.5	78.0	89.5
Riches	0	5.0	4.8	35.3	45.2	105.5	130.0	144.0	168.0
	6	10.4	6.5	33.7	40.0	89.0	127.5	137.5	176.0
Adam	0	6.2	5.4	20.2	23.5	30.8	45.0	47.4	54.3
	3	9.9	6.1	20.6	22.7	28.4	42.2	46.6	58.8
Bonkovski	0	5.8	5.0	47.6	54.6	101.0	136.8	142.0	164.0
	4	11.0	5.8	47.6	50.6	91.0	121.0	137.0	163.0
Anderson	0	8.6	5.9	12.2	10.1	21.0	36.4	39.2	47.4
	4	10.4	6.2	9.7	7.3	15.0	27.6	31.6	44.6
Langdon	0	6.2	5.3	5.15			10.6	12.3	
	4	17.8	5.8	5.15			11.1	12.3	

^{1/} The soils were previously treated in the field prior to sampling for analysis.

Table 9
Influence of Liming on the Extraction
of the Applied Phosphorus^{1/} Using 0.5N NaHCO₃ and Various
Concentrations of NH₄F Alone and in Combination at pH 8.5-
Aiken Soil From Riches Farm

Lime applied T/A	pH	ppm P extracted by						
		0.5N NaHCO ₃	.05N NH ₄ F	.1N NH ₄ F	.5N NH ₄ F	NaHCO ₃ + .05N NH ₄ F	NaHCO ₃ + .1N NH ₄ F	NaHCO ₃ + .5N NH ₄ F
0	5.45	27.8	29.8	45.6	117.8	59.5	128.0	194.2
2	5.85	25.0	21.6	32.8	103.8	45.6	111.0	192.0
4	6.10	25.4	19.0	30.5	119.0	41.2	97.0	189.0
6	6.50	27.0	17.8	28.9	121.5	39.6	90.5	185.0
10	7.20	30.6	16.5	32.7	126.0	38.2	69.7	172.0
Check ^{2/}	5.45	21.4	24.2	38.0	109.0	45.6	112.5	181.0

^{1/} Phosphorus is applied as KH₂PO₄ at the rate of
180 lbs of P₂O₅/A.

^{2/} Soil from the same location but without added lime and
phosphorus.

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attributed to the repressive effect of fluoride ions upon the solubility of certain forms of Ca-phosphates such as tribasic calcium phosphate and apatite, which were more soluble in the acid-fluoride mixture. In this study it was not apparent why liming an acid soil caused the repression in the amounts of phosphorus extracted, especially at the low concentration of NH_4F . However, it could be hypothesized that this was probably due to some of the active fluoride ions being precipitated by the exchangeable calcium forming difficultly soluble CaF_2 , thus resulting in the reduction of the extracting power of the solution. When the concentration of NH_4F was increased the reduction of fluoride ions by precipitation with calcium becomes negligible, thus resulting in no differences in the amounts of phosphorus extracted from limed and unlimed soils.

(1.4) Forms of Inorganic P in Aiken Soils

(1.41) Relative Distribution of Various Forms

Aiken soils from 9 locations and Olympic soil from experiment 103 were fractionated into aluminum phosphate (soluble in 0.5N NH_4F); iron phosphate (soluble in 0.1N NaOH) and calcium phosphate (soluble in 0.5N H_2SO_4). The method employed was that of Chang and Jackson (23) with

certain modification as previously described. The amount of the three different forms of inorganic phosphorus from three check plots (without added lime and phosphorus) in each location were determined. The results, which were the averages of the three replications, are presented in Table 10. It was observed that the amount of Al-phosphate varied from 18.2 ppm phosphorus for Langdon location to 153.1 ppm phosphorus for Riches location. The amounts of the Fe-phosphates varied from 99.5 ppm phosphate in Langdon to 608.0 ppm phosphate in Bonkowski location. The amounts of Ca-phosphates in all locations were considerably lower than the other two fractions. The lowest amounts were 16.6 ppm phosphorus in Langdon. The three phosphorus fractions were distributed as follows among these soils: Fe-phosphate comprised the greatest portion- 63-80% of the total, Al-phosphate ranked second 13.6-28.2%, and Ca-phosphate ranked third. Nine locations contained from 4.8 to 8.6% Ca-phosphate, while the Langdon location had 12.4%. The amounts of Al-phosphate and Fe-phosphate varied greatly from soil to soil. The Al-phosphate fraction varied more than the Fe-phosphate fraction. It was also observed that high amounts of Al-phosphate were not necessarily accompanied by high amounts of Fe-phosphate and vice versa.

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Table 10
Distribution of Different Forms of
Inorganic Phosphorus in Aiken and Olympic Soils

Locations	Amounts in ppm P ^{1/} L ₀ P ₀ ^{2/} plots			Total 3 Fractns.	Per cent of the total 3 fractions		
	AlP	FeP	CaP		AlP	FeP	CaP
Miotke	131.2	295.0	39.1	465.3	28.2	63.5	8.3
Riches	153.1	411.6	30.2	594.9	25.7	69.0	5.3
Exp. 103	66.8	189.6	23.1	279.5	24.0	67.8	8.2
McDougal	90.5	308.5	26.0	425.0	21.3	72.5	6.2
Anderson	56.3	212.8	18.4	287.5	19.5	74.1	6.4
Bonkovski	149.1	608.0	37.2	794.3	18.7	76.6	4.7
Johnson	86.4	368.1	26.4	480.9	17.9	76.6	5.5
Adem	57.5	273.5	31.1	362.1	15.9	75.5	8.6
Ashton	99.5	522.5	31.5	653.5	15.2	80.0	4.8
Langdon	18.2	99.5	16.6	134.3	13.6	74.0	12.4

^{1/} Averages of three replications.

^{2/} L₀P₀ no lime and phosphorus were added.

(1.42) Distribution of the Added P into Various Forms

An attempt was made to determine the fate of soluble phosphorus which was added to the limed and unlimed Aiken soils. The same modified method of Chang and Jackson (23) as used in the previous section was employed to determine the extent of the three forms of phosphates.

Aiken soils from two locations, Riches and Langdon, were limed with $\text{Ca}(\text{OH})_2$ and phosphated with KH_2PO_4 under laboratory conditions at rates of 0 and 10 tons CaCO_3/A and 0 and 180 lbs $\text{P}_2\text{O}_5/\text{A}$ respectively. The results are shown in Table 11. Both Al- and Fe-phosphate fractions increased with the addition of soluble phosphorus. Why the Ca-phosphate fraction tended to decrease when soluble phosphate was added to the soils was not quite certain. It is possible, since the magnitude of the decrease in the amounts of the Ca-phosphate form were small, the change was due to sampling or determination error. All of the added phosphorus probably reacted with Fe and Al. Some Ca-phosphates might have formed, especially in the case of the lime-treated soils, but compounds such as mono- and di-calcium phosphates are soluble in NH_4F and therefore can not be detected by H_2SO_4 which is the last extraction. However, it should be observed that the addition of lime tended to increase the Ca-phosphate fraction especially

Table 11

Distribution of Various Forms of Phosphorus Before and After the Addition of Lime and Phosphorus to Aiken Soils from Langdon and Riches Locations under Laboratory Conditions

Treat- ^{1/} ment	Amounts, ppm P ^{2/}			Increase of Soil Phosphorus fraction due to						
	ALP	FeP	CaP	added P at the same level of lime			added lime at the same level of P			
				ALP	FeP	CaP	ALP	FeP	CaP	
L a n g d o n	L ₀ P ₀	15.8	129.0	20.9				1.3	-11.5	-0.3
	L ₀ P ₂	27.9	197.0	14.7	12.1	68.0	-5.2	(L ₂ P ₀ - L ₀ P ₀)		
	L ₂ P ₀	14.5	117.5	20.6	(P ₂ L ₀ - P ₀ L ₀)			2.3	-32.0	2.8
	L ₂ P ₂	30.2	165.0	17.5	15.7	47.5	-3.1	(L ₂ P ₂ - L ₀ P ₂)		
R i c h e s	L ₀ P ₀	90.0	465.0	31.9				0.8	0.0	0.8
	L ₀ P ₂	144.2	506.0	30.2	54.2	41.0	-1.7	(L ₂ P ₀ - L ₀ P ₀)		
	L ₂ P ₀	89.2	465.0	32.7	(P ₂ L ₀ - P ₀ L ₀)			25.3	-16.0	2.2
	L ₂ P ₂	169.5	490.0	32.4	80.3	25.0	-0.3	(L ₂ P ₂ - L ₀ P ₂)		

^{1/} L₀, P₀ = no lime and phosphorus are applied.

L₂, P₂ = 10 T CaCO₃/A and 180 lbs P₂O₅/A (39.3 ppm P) are applied respectively.

^{2/} Average of a duplicate.

in the case of added phosphorus. The same increase was also observed for the Al-phosphate fraction. On the contrary, a depression in the formation of Fe-phosphate was observed.

The amounts of phosphorus added were completely recovered in the Al- and Fe-phosphate fractions. Evidently greater amounts of phosphorus were recovered than the actual amounts of phosphorus added. This could have been due to large determination errors, especially in the case of Fe-phosphate, or to the effect of applied phosphate on the extractability of some other phosphate fractions (occluded Fe- and Al-phosphates). Similar results were reported by Laverty and McLean (71). They also found that soils with a high phosphate fixing capacity (fixation against the extraction with Bray No. 1) retained more phosphorus in the form of Fe-phosphate than Al-phosphate. The reverse situation was true for soils lower in phosphorus fixing capacity. Comparable results were obtained from this study. The soil from Langdon location which fixed about 80% of the applied phosphorus against the extraction by Bray No. 1 (Figure 5) retained a large portion of added phosphorus in Fe-phosphate form. The reverse situation was observed for soil from Riches location. The soil fixed about 50% of the added

phosphorus and retained it largely in the form of Al-phosphate.

Aiken soils from nine field experimental locations were also studied. Only the soil samples from the plots treated with L_0P_0 and L_3P_3 were fractionated in the same manner as described in the previous sections. The results of the analysis (average of three replications) are shown in Table 12. It should be noted that three of these locations (Langdon, Miotke and Riches) received 360 lbs of P_2O_5/A , half of which was applied a year before and the other half was applied a few months before taking soil samples. The rest of the locations received 180 lbs of P_2O_5/A which was applied a few months prior to sampling. It was observed that both Al- and Ca-phosphates increased with the application of phosphate fertilizer on the limed soils. The Fe-phosphate, however, tended to decrease or did not change except for the Langdon location where an increase was observed when phosphate fertilizer was applied to the limed soils.

(1.5) Forms of Inorganic Soil P Removed by Different Chemical P Soil Tests

This experiment was carried out in order to study the various forms of soil phosphorus removed by different

Table 12
The Effect of the Application of Lime in Combination With Phosphate Fertilizer
on the Distribution of Various Forms of Phosphorus in Aiken Soils

Locations	Treatment		pH	Amounts, ppm P ^{1/}			Forms of P increased		
	Lime	P ₂ /		ALP	FeP	CaP	ppm P		
	T/A	lbs. P ₂ O ₅ /A					ALP	FeP	CaP
Langdon	0	0	5.6	18.2	99.5	16.6	25.7	30.7	5.7
	6	360	6.0	43.9	130.2	22.3			
Miotke	0	0	5.3	131.2	295.0	39.1	52.3	-29.2	7.2
	6	360	6.1	183.5	265.8	46.3			
Riches	0	0	4.8	153.1	411.6	30.2	44.0	-35.9	10.3
	9	360	6.1	197.1	375.7	40.5			
Bonkowski	0	0	5.2	149.1	608.0	37.2	24.5	-29.2	5.2
	6	180	6.2	173.6	578.8	42.6			
Adam	0	0	5.5	57.5	273.5	31.1	17.6	- 7.8	12.1
	4.5	180	6.4	75.1	265.7	43.2			
McDougal	0	0	5.2	90.5	308.5	26.0	26.2	-35.8	5.6
	6	180	6.6	116.7	272.7	31.6			
Ashton	0	0	5.2	99.5	522.5	31.5	40.9	- 0.5	6.7
	6	180	6.1	140.0	522.0	38.2			
Anderson	0	0	5.7	56.3	212.8	18.4	20.2	-10.9	6.2
	6	180	6.6	76.5	201.9	24.6			
Johnson	0	0	5.0	86.4	368.1	26.4	11.1	-56.1	1.0
	6	180	5.8	97.5	312.0	25.4			
^{1/} Average of 3 replications			^{2/}	360 lbs P ₂ O ₅ /A = 78.6 ppm P					
				180 lbs P ₂ O ₅ /A = 39.3 ppm P					

chemical phosphorus soil test methods. Aiken soil from Riches location which was treated with soluble phosphorus at the rate of 0 and 180 lbs of P_2O_5/A , was used for this purpose.

Duplicate 1 gm samples of soil were fractionated at the same time. One sample was fractionated according to the modified Chang and Jackson method while the other was extracted for "available" phosphorus by Bray No. 1, Olsen and Modified Olsen prior to fractionation. The extraction for "available" phosphorus was done in a 50 ml polyethylene centrifuge tube. The ratio of soil to solution was 1:20 for Bray No. 1 and Modified Olsen and 1:10 for Olsen. The soils were extracted for 30 minutes for Olsen and Modified Olsen and 1 minute for Bray No. 1. A clear extract was obtained by centrifugation. Prior to fractionation, the soils were washed twice with 1N NaCl.

The results of the analysis are shown on Table 13. From the data obtained it was observed that in all cases the Al- and Fe-phosphate forms decreased consistently following the removal of the "available" phosphorus. Calcium phosphate fractions, however, showed some increases. The author does not have an explanation for this difference. Since the Ca-phosphate form was the last fraction determined it was subjected to considerable error

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Table 13

Amounts of Various Forms of Inorganic Soil Phosphorus Removed by Different Chemical Phosphorus Extracting Solutions - Aiken Soil from Riches Location

Treatment lbs P ₂ O ₅ /A	P Soil test	Phosphorus fractions (ppm P)								
		Al-phosphate			Fe-phosphate			Ca-phosphate		
		before ^{1/}	after ^{2/}	diff.	before ^{1/}	after ^{2/}	diff.	before ^{1/}	after ^{2/}	diff.
0.025N HCl + 0.03N NH ₄ F										
0	79.6	137.0	92.5	44.5	420.0	370.0	50.0	30.8	34.0	-3.2
180	88.4	156.0	106.0	50.0	440.0	381.0	59.0	32.6	41.0	-8.4
0.5M NaHCO ₃ (pH 8.5)										
0	12.0	137.0	122.3	14.7	420.0	381.0	39.0	30.8	32.6	-1.8
180	15.2	156.0	138.0	18.0	440.0	408.0	32.0	32.6	34.4	-1.8
0.5M NaHCO ₃ + 0.1N NH ₄ F (pH 8.5)										
0	102.0	137.0	76.0	61.0	420.0	332.5	87.5	30.8	39.0	-8.2
180	120.0	156.0	82.7	73.3	440.0	340.0	100.0	32.6	35.8	-3.2

^{1/} Soil samples were fractionated without prior extraction for "available" phosphorus.

^{2/} Soil samples were fractionated after extraction for "available" phosphorus.

in the determination. These errors may have been large enough to mask real differences in this form of phosphorus. Consequently it was concluded that small amounts if any of the Ca-phosphate forms were removed by the three phosphorus soil test methods. Insufficient observations and lack of statistical analyses limit the quantitative conclusion that can be drawn. Nevertheless, the following observations were noted: first the "available" phosphorus removed by the three phosphorus soil test methods could be accounted for by the losses in the Al- and Fe-phosphate forms, second the NaHCO_3 extracting solution removed considerable amounts of Al- and Fe-phosphate forms from the soil as compared to the amounts of the "available" phosphorus removed.

(2) Greenhouse Studies

(2.1) Correlation of P Soil Test Values with Greenhouse Data

Correlation between the soil test values from various methods and the phosphorus content and per cent of phosphorus of the plants were performed.^{3/} The scheme of the

^{3/} The IBM cards were processed at the O.S.U. Statistic Service and the data were analyzed by the Western Data Processing Center at the Univ. of California. The author is very grateful to Dr. R. G. Petersen, Assoc. Prof. of Statistics, Oregon State University, for statistical analysis and helpful consultation.

correlation analysis was as follows:

Independent variables

- | | |
|--------------------------------------|---------------------|
| 1. Exch. Ca + Mg
(me/100 gm soil) | 3. soil test values |
| | a) Olsen |
| 2. soil pH | b) Modified Olsen |
| | c) Bray No. 1 |

Dependent variables

- | Oats | Clover |
|-----------------------|-----------------------|
| 1. mg P/75 plants | 4. mg P/40 plants |
| 2. mg P/pot | 5. mg P/pot |
| 3. per cent P content | 6. per cent P content |

These correlations totaled 18 analyses between soil test methods and the greenhouse data. Soil pH and Exch. Ca + Mg were included in the analysis because, from the observation of the data, they seemed to affect both the soil test values as well as the amount of phosphorus taken up by the plants. Therefore 12 more correlation analyses were obtained between soil pH and exch. Ca + Mg and that of the greenhouse data. In the correlation analysis the soil pH values were handled as a regular number.

The correlation coefficients for the relationship between the phosphorus soil test values, as determined by different methods, and the phosphorus content of oats and clover are shown in Table 14.

The phosphorus contents of oats and clover were

Table 14

Simple, Partial and Multiple Correlation Coefficients
Between Different Chemical Phosphorus Soil Tests, Soil pH
and Exch. Ca+Mg with Phosphorus Content and Per Cent P of
Oats and Clover

Chemical Soil Tests	Correlation Coefficients					
	Oats			Clover		
	mgP/75 plants	% P	mgP/ pot	mgP/40 plants	% P	mgP/ pot
Simple Correlation						
Olsen	.748	.723	.657	.860	.853	.856
Mod. Olsen	.502	.561	.446	.743	.755	.715
Bray No. 1	.578	.651	.510	.813	.805	.786
Exch. Ca+Mg	.293	.252	.222	.192	.155	.198
Soil pH	.135	-.020	.085	-.099	-.102	-.105
Partial Correlation						
Olsen	.744	.670	.643	.832	+.826	.827
Exch. Ca+Mg	.009	.231	-.014	.212	.097	.247
Soil pH	.179	-.151	.126	.197	-.106	-.233
Mod. Olsen	.597	.560	.506	.756	.772	.716
Exch. Ca+Mg	.128	.390	.087	.296	.197	.332
Soil pH	.214	-.041	.160	.024	.114	-.035
Bray No. 1	.629	.614	.537	.795	.792	.755
Exch. Ca+Mg	.012	.191	-.006	.132	.026	.178
Soil pH	.255	.011	.194	.089	.163	.021
Multiple Correlation						
Olsen	.703	.741	.673	.867	.855	.866
Mod. Olsen	.652	.662	.554	.809	.810	.784
Bray No. 1	.679	.700	.581	.839	.826	.812

Significant at 5% level $r > .113$
1% level $r > .148$

expressed in both mg phosphorus per 75 plants for oats and 40 plants for clover, and mg phosphorus per pot. This was done because not all the seeds (75 seeds for oats and 50 seeds for clover) germinated; so, at the end of the growing period the number of plants varied from pot to pot. There was a possibility that the phosphorus content of the seeds might overshadow the differences between the amounts of phosphorus taken up by plants from different treatments. Consequently, the number of plants in each pot was counted and the phosphorus contents expressed on a per plant basis. It was also recognized that fewer plants in the pot could grow faster and might take up as much total phosphorus as a pot with a few more plants. Therefore, the phosphorus contents of the plants were also expressed as total per pot regardless of the number of the plants in the pot. Both methods of expressing phosphorus content were used in the correlation with phosphorus soil test results. From Table 14 it was observed that, in all cases, the correlation coefficients for the relationships between the phosphorus content as mg phosphorus per the same number of plants and the soil test values were higher than mg phosphorus per pot vs. soil test values. This probably indicated that the former method of expressing phosphorus content of the plant was subjected to less error than the latter method.

The correlation coefficients for the relationship between phosphorus soil test values for all methods vs. phosphorus content of clover were much higher than those of oats. All the methods were significantly correlated at the 1% level with all of the greenhouse data, and did not show a marked difference among the methods studied. Of these methods, the Olsen gave the highest correlation coefficients for both oats and clover. The order of the magnitude of the correlation coefficients for different phosphorus soil test methods and phosphorus content of both oats and clover, from high to low, was Olsen, Bray No. 1 and Modified Olsen.

The results of this experiment indicated that the per cent phosphorus in both oats and clover increase with the increase in phosphorus soil test values, which in turn means that the per cent phosphorus content of 30 day old oats and 45 day old clover increase with the increase phosphorus fertility of the soils.

The relationship between the phosphorus content and per cent phosphorus in the plants vs. the exch. Ca + Mg and soil pH were very low for both oats and clover. Lower correlation coefficients were obtained with subclover than with oats. Even though the greenhouse data^{4/} were not

^{4/} Greenhouse data, as used in this thesis, refers to the results obtained from the greenhouse experiment, namely per cent and total phosphorus content of oats and clover.

greatly influenced by either soil pH or $\text{exch. Ca} + \text{Mg}$, the soil test values were depressed to some degree by soil pH which will be shown in the later section.

In order to see whether the relationship between phosphorus soil test values and greenhouse data could be improved, partial correlation analysis was used. That is, the phosphorus soil test values were related to greenhouse data while maintaining the soil pH and $\text{exch. Ca} + \text{Mg}$ constant. The partial correlation coefficients are shown in Table 14. The partial correlation coefficients for soil pH vs. the greenhouse data - while phosphorus soil test values and $\text{exch. Ca} + \text{Mg}$ were constant - and those of $\text{exch. Ca} + \text{Mg}$ vs. the greenhouse data while keeping the other two factors constant are shown in the same table. The data obtained revealed that the correlation coefficients for the Modified Olsen were improved slightly while the correlation coefficients for the rest of the methods were not improved or were slightly decreased.

When the phosphorus soil test values, soil pH and $\text{exch. Ca} + \text{Mg}$, were related to the greenhouse data simultaneously, multiple correlation coefficients were obtained (Table 14). Again, the degree of the relationships for clover was much higher than for oats. The multiple correlation coefficients for both oats and clover were only slightly greater than those obtained through simple and

partial correlation analyses. These results thus indicate that the reliability of using the phosphorus soil test values in predicting the phosphorus status of the soil under greenhouse condition is only slightly improved if the soil pH and exch. Ca + Mg are also taken into consideration.

The relationships of the soil test methods with the greenhouse data were improved by stratifying the soil test values into two groups according to the soil pH. The pH ranges employed were from 5.8 to 6.8 and from 4.7 to 5.7. In this stratified correlation analysis 27 observations from experiment 103 were also used, 19 were classified into the pH 5.8-6.8 group and the rest of the observations were added to the pH 4.7-5.7 group. The total number of observations in the first group was 185 and a total of 136 belonged to the second group. The stratified correlation coefficients for the relationship between phosphorus contents as mg P/same number of plants vs. the phosphorus soil test values of the various methods are shown in Table 15. All methods showed an increase in the correlation coefficients for the pH 5.8-6.8 group but a decrease for the pH 4.7-5.7 group, with the exception of Bray No. 1 for oats where the reverse situation was true. The results obtained thus indicated that the methods tended to give a

Table 15

Correlation Coefficients and Linear Regression Equations for the Relationship Between the "Available" P, Determined by Different Chemical Soil Test Methods, vs. P Contents of Oats and Clover (mg P/Same No. of Plant) at Different Ranges of Soil pH

Chemical methods	Range of pH	Corr. Coef. (r) for		Linear regression equations ^{1/}		n
		oats	clover	oats	clover	
Olsen	5.8-6.8	.789**	.932**	$y = 4.58 + .142x$	$y = 1.18 + .202x$	185
	4.7-5.7	.741**	.584**	$y = 4.53 + .117x$	$y = 2.08 + .141x$	136
	4.7-6.8	.748**	.860**	$y = 4.55 + .132x$	$y = 1.67 + .173x$	294
Modified Olsen	5.8-6.8	.629**	.973**	$y = 5.21 + .028x$	$y = 1.65 + .052x$	185
	4.7-5.7	.446**	.572**	$y = 4.97 + .017x$	$y = 2.60 + .021x$	136
	4.7-6.8	.502**	.743**	$y = 5.04 + .023x$	$y = 2.10 + .034x$	294
Bray No. 1	5.8-6.8	.473**	.878**	$y = 5.52 + .020x$	$y = 1.90 + .046x$	185
	4.7-5.7	.910**	.613**	$y = 4.32 + .031x$	$y = 2.11 + .032x$	136
	4.7-6.8	.578**	.813**	$y = 4.95 + .026x$	$y = 1.98 + .039x$	294

** Significant at the 1% level.

^{1/} y = P content (mg P/same no. of plant).

x = soil test value (ppm P).

better prediction of the phosphorus status of the soils at the higher pH range (5.8-6.8) than at the lower pH range (4.7-5.7).

Since the correlation coefficients for all of the soil test methods vs. phosphorus content of clover were higher than those of oats, only the relationships between the soil test methods and phosphorus content of clover were chosen for further calibration studies with the field experimental data.

The scatter diagrams of the stratified correlations between the NaHCO_3 -soluble phosphorus and Modified Olsen - soluble phosphorus vs. phosphorus contents of clover, as mg P/40 plants, for the pH 5.8-6.8 group are shown in Figure 7. The linear regression of the same relationship for the pH 4.7-5.7 group, and for all soils are also shown in the same corresponding figure. All three regression lines in each case were separated and much further apart for the Modified Olsen than for the Olsen method. Both methods yielded steeper regression lines with highest correlation coefficients for the higher pH group of soils than the lower group, which indicated that the methods were more efficient in predicting the phosphorus status of slightly acid to neutral soils (>5.8) than for the strongly to moderately acid soils (<5.8).

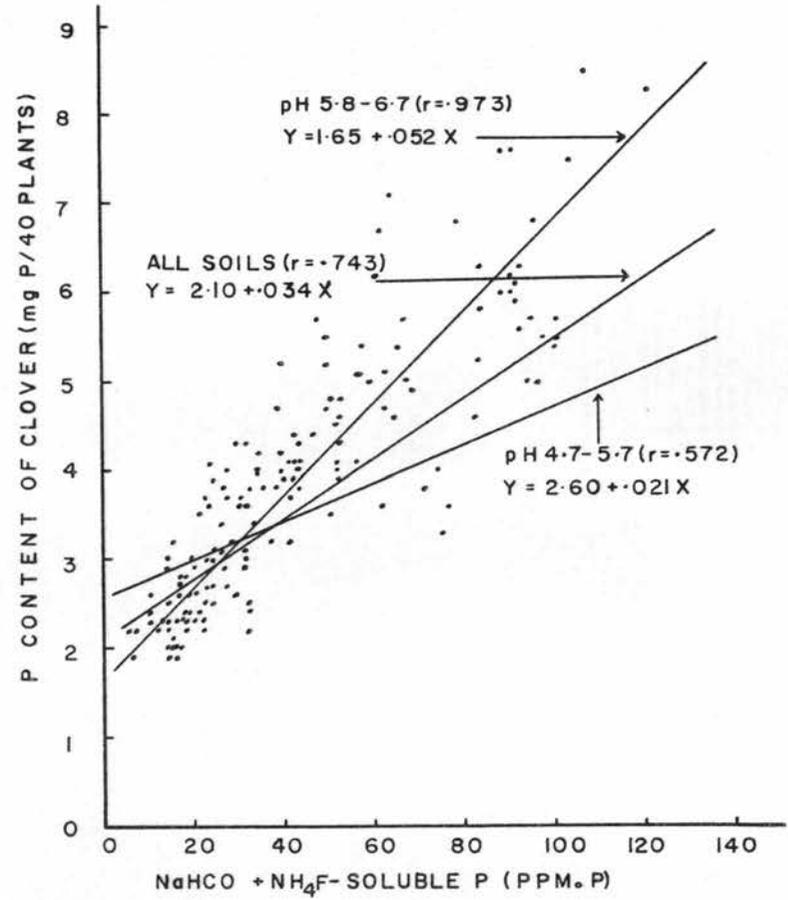
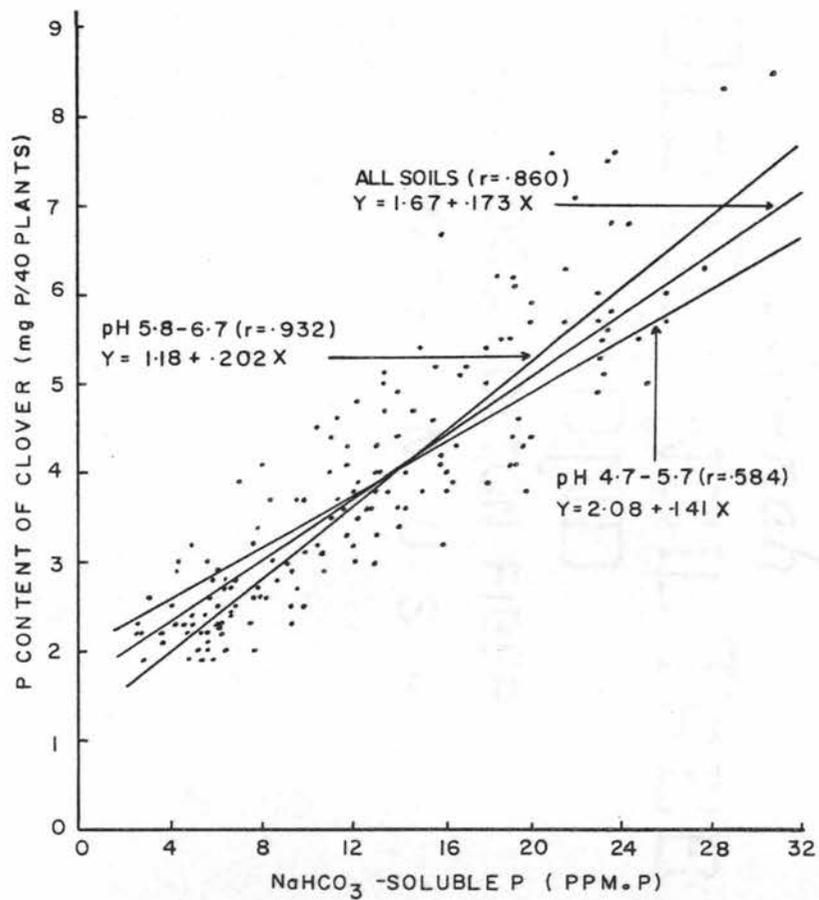


FIGURE 7 Scatter diagrams and regression lines for the stratified correlation between soil test methods vs. P contents of clover (pH 5.8-6.7). The linear regressions for pH 4.7-5.7 group and for all soils are also compared.

(2.2) The Relative Availability of Different Forms of Inorganic Soil P

Aiken soils from seven field experimental locations were fractionated according to the method of Chang and Jackson (23) for Al-, Fe- and Ca-phosphates. The soil samples from two treatments, L_0P_0 and L_3P_3 , in each location were analyzed before and after planting to oats and clover in the greenhouse.

(2.21) Correlation Between Different Forms of Inorganic P and P Content of Oats and Clover

The amount of various phosphorus fractions in the soils which were analyzed before growing oats and clover were correlated with the phosphorus content of oats and clover. The same soil sample was planted twice with oats and correlation analyses were made for both the first and the combined first and second crops. The linear regression correlation coefficients for the relation between the amounts of the three different forms of soil phosphorus and the phosphorus content of oats and clover are shown in Table 16. In the case of clover all three fractions were significantly correlated with phosphorus content of clover; that of Al-phosphate was the highest ($r = 0.782$), Ca-phosphate ranked second ($r = 0.666$) and Fe-phosphate

Table 16

Correlation Coefficients and Linear Regression Equations for the Relationship Between the Amounts of Different Forms of Soil Phosphorus and Phosphorus Content of Oats and Clover Grown on Soils With L_0P_0 and L_3P_3 Treatments in 7 Locations

Forms of Inorganic Soil Phosphorus ^{1/}	Oats			Clover		n
	Corr. coef. (r) 1st crop	Corr. Coef. (r) 1st+2nd crop	Linear regression equations ^{2/}	Corr. coef. (r)	Linear regression equations ^{2/}	
Al-phosphate	.363*	.609**	y = 6.10 + .009x	.782**	y = 2.15 + .020x	42
			y = 10.42 + .022x			42
Fe-phosphate	-.130	.056	y = 11.12 - .001x	.434	y = 3.09 + .004x	42
			y = 10.42 + .007x			42
Ca-phosphate	.540**	.649**	y = 5.22 + .087x	.666**	y = 0.88 + .104x	42
			y = 7.90 + .152x			42

* Significant at 5% level.

** Significant at 1% level.

^{1/} Determined by the method of Chang and Jackson (23).

^{2/} y = P content (mg P/same no. of plant).

x = Soil P value (ppm P).

was the lowest in the group ($r = 0.434$). In the case of oats the order between Al-phosphate and Ca-phosphate was reversed. Both fractions were significantly correlated with phosphorus content of oats. The Ca-phosphate form tended to have higher relationship with phosphorus content of oats than Al-phosphate. This was true in both cases with the first crop alone and with the combination of first and second crops of oats. There was no correlation between the Fe-phosphate fraction and the phosphorus content of oats.

(2.22) Relationship Between the Amounts of Different Forms of P Lost and P Removed by Plants

In order to obtain some idea of the forms of soil phosphorus affected or absorbed by the growing plants, soil samples were fractionated according to the method of Chang and Jackson (23) before and after the soils produced subclover and oats. Soils from four locations were used for clover and seven for oats. Since oats did not absorb phosphorus from the soil as much as clover, oat crops were grown twice on the same soil so that amounts of phosphorus removed by the plants were large enough to be detected by the fractionation method. The amount of phosphorus taken up by the plants was determined by subtracting the phosphorus content of the plants grown in

the sand culture without phosphorus from the phosphorus content of the plants grown in the treated soils. The amount of phosphorus lost was obtained by subtracting the phosphorus determined before and after the soils produced the oats and clover. The results of the correlation analysis indicate that only the amount of Al-phosphate lost has a close relation to the amount of phosphorus taken up by the plants. No relationship between the amount of Fe-phosphate and Ca-phosphates lost and the phosphorus taken up by these two plants was obtained. The correlation coefficients for the relationship between the amount of different forms of phosphorus lost are shown in Table 17. The correlation coefficients for the losses of Al-phosphate were significant at 1% level for both oats and clover, while that of Fe- and Ca-phosphates were not.

From these results, therefore, it can be concluded that the Al-phosphate (phosphorus fraction soluble in 0.5N NH_4F , pH 8.5) is an important source of the phosphorus taken up by plants from Aiken soils.

(3) Field Studies

(3.1) Scheme of the Correlation Analyses

The correlation analyses were processed through the Western Data Processing Center in the same manner as those

Table 17

Correlation Coefficients and Linear Regression Equations for the Relationship Between the Amounts of Soil P Taken up by Plants^{1/} and the Amount Lost From Various Forms of Phosphorus^{2/} as Determined by the Method of Chang and Jackson

Form of soil phosphorus	Two crops of oats grown on Aiken soil			Subclover grown on Aiken soil		
	Corr. Coeff. (r)	n	Linear regression equations ^{3/}	Corr. Coeff. (r)	n	Linear regression equations ^{3/}
Al-phosphate	0.712**	42	$y = 20.85 + 0.596x$	0.729**	24	$y = 2.43 + 0.3745x$
Fe-phosphate	0.117	42	$y = 29.90 + 0.0711x$	-0.210	24	$y = 10.04 - 0.0430x$
Ca-phosphate	0.160	42	$y = 30.09 + 0.4838x$	0.225	24	$y = 11.55 + 0.4465x$

** Significant at 1% level.

^{1/} Obtained from the subtraction of P content of plants grown in the sand culture without phosphorus, from the phosphorus content of plants grown in soil with the treatments L_0P_0 and L_3P_3 .

^{2/} Obtained from the differences of the amounts of phosphorus determined before and after planting.

^{3/} y = P uptake (mg P/same no. of plant)
 x = P fraction lost (ppm P)

for the greenhouse data. The scheme of the analysis was as follows.

(3.11) Soil Test Values vs. Field Data

Independent variables

- | | |
|-------------------------------------|--------------------------------------|
| 1. Exch. Ca + Mg
(me/100 g soil) | 3. Soil test values
determined by |
| 2. soil pH | a) Olsen |
| | b) Modified Olsen |
| | c) Bray No. 1 |

Dependent variables

First cutting alfalfa

- | | |
|------------------------------|--------------------|
| 1. Absolute yield, lbs/A | 4. P uptake, lbs/A |
| 2. per cent of maximum yield | Two cutting total |
| 3. per cent P content | 5. % of Max. yield |

A total of 15 analyses of soil tests vs. field data and 10 additional analyses for the soil pH and exch. Ca + Mg vs. the yield data were obtained.

(3.12) Greenhouse Data vs. Field Data

Independent variables

- | | |
|-------------------------------------|--------------------------|
| 1. exch. Ca + Mg
(me/100 g soil) | 3. mg of P/pot of oats |
| 2. soil pH | 4. mg of P/pot of clover |

Dependent variables were the same as those used in the section 3.11.

A total of 10 correlation analyses between greenhouse and field data and 10 analyses between pH and Ca + Mg with the field data were determined.

(3.2) Results of the Correlation Analyses

(3.21) Soil Test Values vs. Field Data

The linear correlation coefficients for the relationship between the soil test values and field data are shown in Table 18. These values were very low for all the soil test methods. It should be observed that better correlations were obtained between the soil test values and the amounts of phosphorus taken up than between the soil test values and any other field data, which would indicate that as the phosphorus soil test values increased the amounts of phosphorus taken up by the alfalfa increased. The best relationships obtained were between the soil pH and exch. Ca + Mg with the field data.

Since soil pH and exch. Ca + Mg had such a great effect on the results of the field experiments, partial correlation analyses were conducted in order to see whether or not the phosphorus soil test alone had any relationship with the field data. The results of these

analyses are shown in Table 18. In this table partial correlation coefficients for both soil pH and exch. Ca + Mg are also shown. The results showed that, for all of the soil test methods, the correlation coefficients were considerably improved, particularly in the case of Modified Olsen and Bray No. 1.

The influence of soil pH and exch. Ca + Mg on the value of phosphorus soil test in predicting the phosphorus status of the soil under field condition was also determined through multiple correlation analysis. The multiple correlation coefficients are much greater than both the simple and partial correlation coefficients which suggest that the variations in soil pH and exch. Ca + Mg must be taken into consideration when the phosphorus soil test values are used in predicting the phosphorus status of the soils.

When the average soil pH values and exch. Ca + Mg were plotted against the average per cent of the maximum yields of three replications from L_0P_2 , L_1P_2 and L_2P_2 treatments, a linear relationship was obtained with $r = 0.757$ and 0.756 respectively (Figure 8). According to the regression equations, the production of 95-100% of maximum yield of alfalfa would require a soil pH of 6.1-6.2 or 13-14 me of exch. Ca + Mg/100 gm soil. This would be at approximately 65-75% base saturation. The

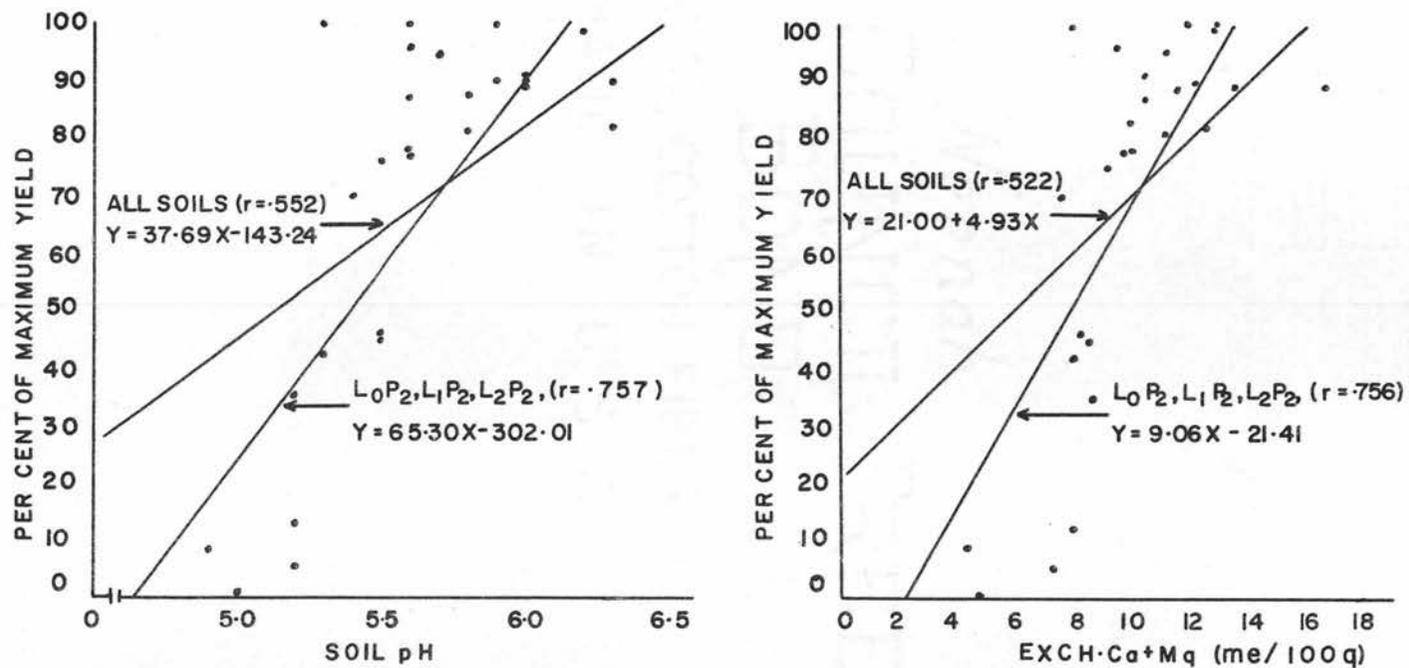


FIGURE 8 Correlation between soil pH and exch. Ca+Mg vs. per cent of max. yield from L_0P_2, L_1P_2, L_2P_2 treatments and comparison with regression line from all the treatments.

linear regression lines for all treatments, this includes all P_0 , P_1 , P_2 and P_3 treatments, are shown in the same figure with $r = 0.552$ and 0.522 for soil pH and $\text{exch. Ca} + \text{Mg}$ respectively. According to these regression equations, higher soil pH and base saturation are required to attain the same maximum yields (pH 6.4-6.5 or about 75-80% base saturation).

In order to see the effect of liming on the availability of the native and applied phosphorus, the soil pH and $\text{exch. Ca} + \text{Mg}$ was related to the phosphorus uptake by alfalfa from L_0P_0 and L_2P_0 , and from L_0P_2 , L_1P_2 and L_2P_2 plots respectively. The scatter diagram and the linear regression lines are shown in Figure 9. The regression line for all treatments is also shown in the same figure. According to the relationship between phosphorus uptake and per cent of the maximum yield, to be shown later, the uptake of 14-15 lbs of P/A by alfalfa correspond to the maximum yield (95-98%). This range of phosphorus uptake corresponds to 14-15 me and 13-14 me of $\text{exch. Ca} + \text{Mg}/100$ g soil for unphosphated and phosphated soil respectively. Since the ranges of $\text{exch. Ca} + \text{Mg}$ required for maximum yield are very close together therefore it might be hypothesized that the beneficial effect of liming the acid Aiken soils is largely to increase the availability of native soil phosphorus than applied phosphorus to the

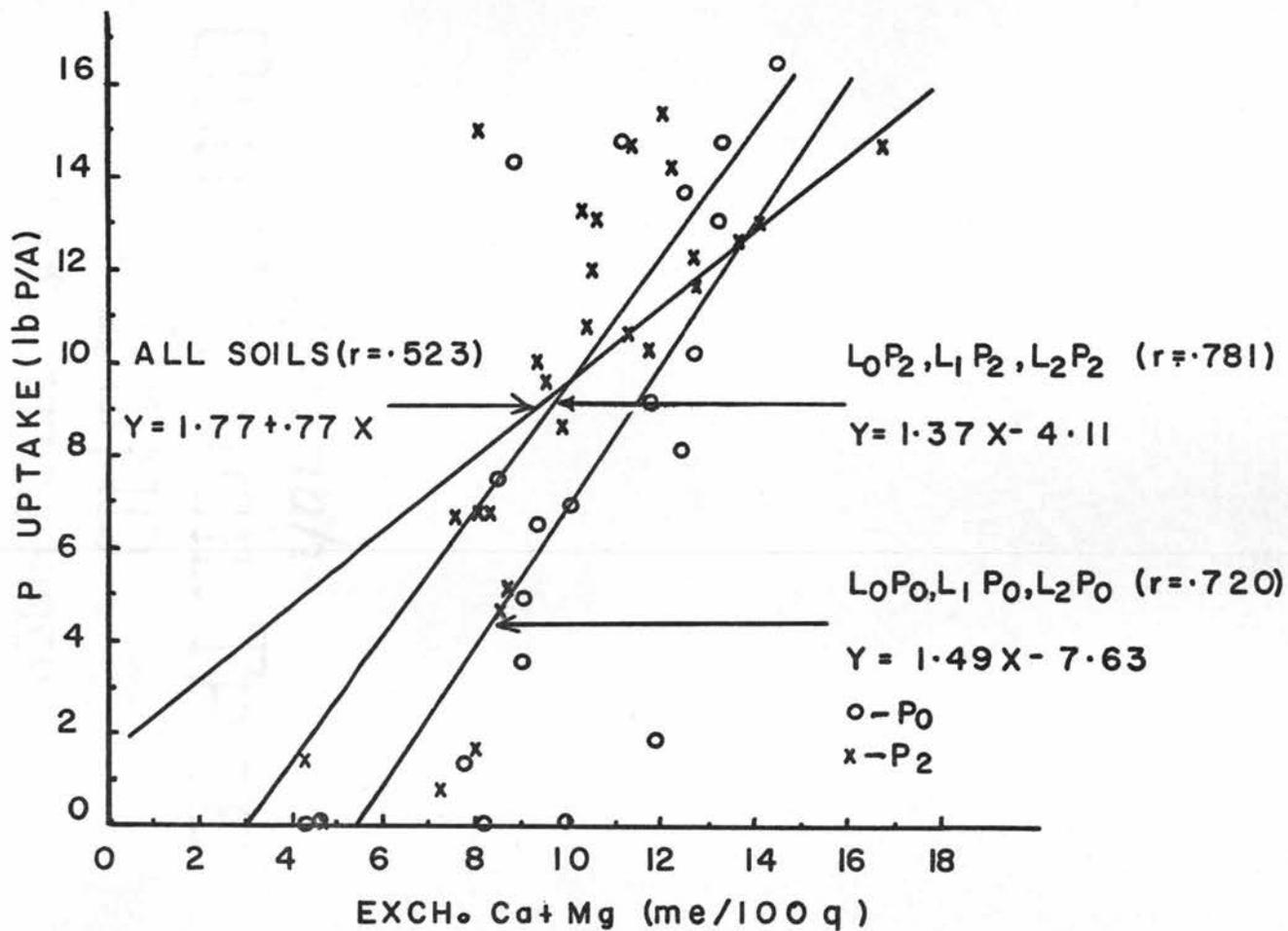


Figure 9. Correlations between exch. Ca + Mg and P uptake by alfalfa from phosphated and unphosphated plots and comparison with a line of regression from all plots.

alfalfa crop.

(3.22) Relationship Between P Soil Tests, pH and Exch. Ca + Mg

The simple correlation coefficients for the relationship among the various phosphorus soil test methods, soil pH, and exch. Ca + Mg are shown in Table 19. It should be observed that all the methods were highly correlated with each other. All the methods were negatively correlated with soil pH, the Olsen method being affected the least. Positive relationships were obtained with exch. Ca + Mg for Olsen. Both the Modified Olsen and Bray No. 1 were negatively correlated with exch. Ca + Mg while only that of the Modified Olsen was significant. Figure 10 illustrates the influence of liming on the phosphorus extracted by various chemical phosphorus soil test methods. The influence of liming on the amounts of phosphorus uptake and per cent phosphorus content of alfalfa are shown in the same figure. Only the average values for the three replications from treatments L_1P_3 and L_3P_3 were used in this figure. The same trend for the effect of liming upon the extractable phosphorus and the amounts of phosphorus taken up and per cent phosphorus content of alfalfa would have been obtained if the treatments L_0P_2 , L_1P_2 and L_2P_2 were employed. It should be noted that for the McDougal

Table 19
 Simple Correlation Coefficients for the Relationship
 Between Different Chemical Methods of P Extraction, Also
 With Soil pH and Exch. Ca+Mg

Soil Tests	Correlation Coefficients (r)				
	Modified Olsen	Bray No. 1	Olsen	Soil pH	Exch. Ca+Mg
Mod. Olsen	1.000	0.947	0.820	-0.452	-0.168
Bray No. 1		1.000	0.900	-0.345	-0.009
Olsen			1.000	-0.091	0.171
Soil pH				1.000	0.778

Significant at 1% level $r > 0.148$

5% level $r > 0.113$

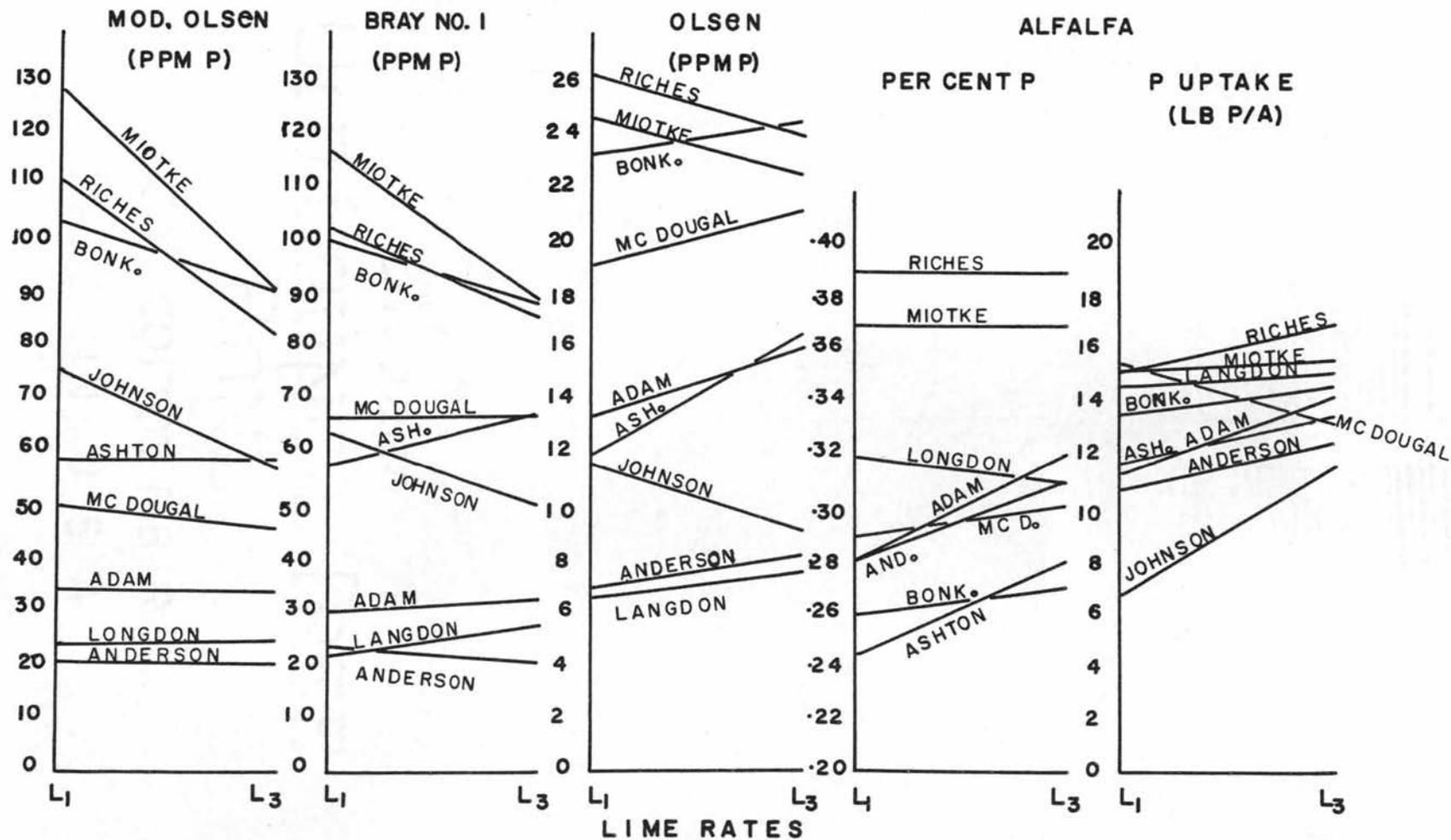


Figure 10. Effect of lime on the P soil tests and on the per cent and P uptake by alfalfa at P₃.

location the amounts of phosphorus taken up increased as the amounts of added lime increased; it reached a maximum at the L_2 level of lime and then decreased at the L_3 level of lime. Phosphorus uptake increased with increasing lime rates when the following treatments are compared - L_0P_2 , L_1P_2 and L_2P_2 .

The correlation between soil pH and exch. Ca + Mg was highly significant with $r = 0.778$.

(3.23) Greenhouse Data vs. Field Data

In order to see how well the biological tests conducted in the greenhouse could predict the fertility status of the soils under field conditions, the amounts of phosphorus taken up per pot of oats and clover grown in the greenhouse on the same soils as the alfalfa in the field were correlated with the field data for alfalfa. The results of the correlation analyses are shown in Table 20. The simple and partial correlation coefficients are about the same as those of the chemical phosphorus soil tests. Both biological and chemical tests gave about the same correlation with the amounts of phosphorus taken up by alfalfa in the field. According to this data the biological tests did not show any superiority over the chemical tests in predicting the phosphorus fertility of the soils under field conditions. The soil pH and exch.

Table 20

Simple and Partial Correlation Coefficients Between
Greenhouse Tests and Field Data from Alfalfa

Greenhouse tests and other factors	Correlation Coefficients				
	First cutting data				
	Absolute yield	% Max.	% P	lbs/A P	% max. yield from 2 cuttings
	Simple Correlation				
mg P/pot of oats	.275	.207	.292	.365	.254
mg P/pot of clover	.287	.230	.376	.446	.272
	Partial Correlation				
mg P/pot of oats	.240	.157	.238	.328	.222
Exch. Ca+Mg	.137	.135	.165	.189	.111
Soil pH	.312	.293	.094	.205	.352
mg P/pot of clover	.384	.304	.392	.526	.389
Exch. Ca+Mg	.008	.025	.032	.008	-.025
Soil pH	.416	.375	.231	.389	.455

Significant at 5% level $r > .113$
1% level $r > .148$

Ca + Mg still showed better relationships with the field data than any of the biological and chemical phosphorus soil tests.

According to the data presented in Table 20 the correlation coefficient for mg of P/pot of clover vs. phosphorus uptake by alfalfa were the highest with $r = 0.446$ and 0.526 for simple and partial correlation respectively. The relationship between these two variables is shown in Figure 11. Only the averages of 3 replications from treatments L_2P_0 , L_2P_1 and L_2P_2 were used in the plotting of the dotted curve. A hyperbolic type of a curve was indicated by this relationship. If the amounts of phosphorus uptake by alfalfa were correlated with the reciprocal of mg of P/pot of clover a negative linear relationship with $r = -0.732$ was obtained. The curvilinear relationship between phosphorus uptake and mg P/pot of clover could be appropriately described by the equation:

$$y = 19.1068 - 24.969 \frac{1}{x}$$

where $\frac{1}{x}$ = the reciprocal mg of P/pot of clover. The equation adequately described the relationship between phosphorus uptake and mg of P/pot of clover at the range of 5 mg phosphorus or less in clover and tended to deviate from the observed relationship above this value. The

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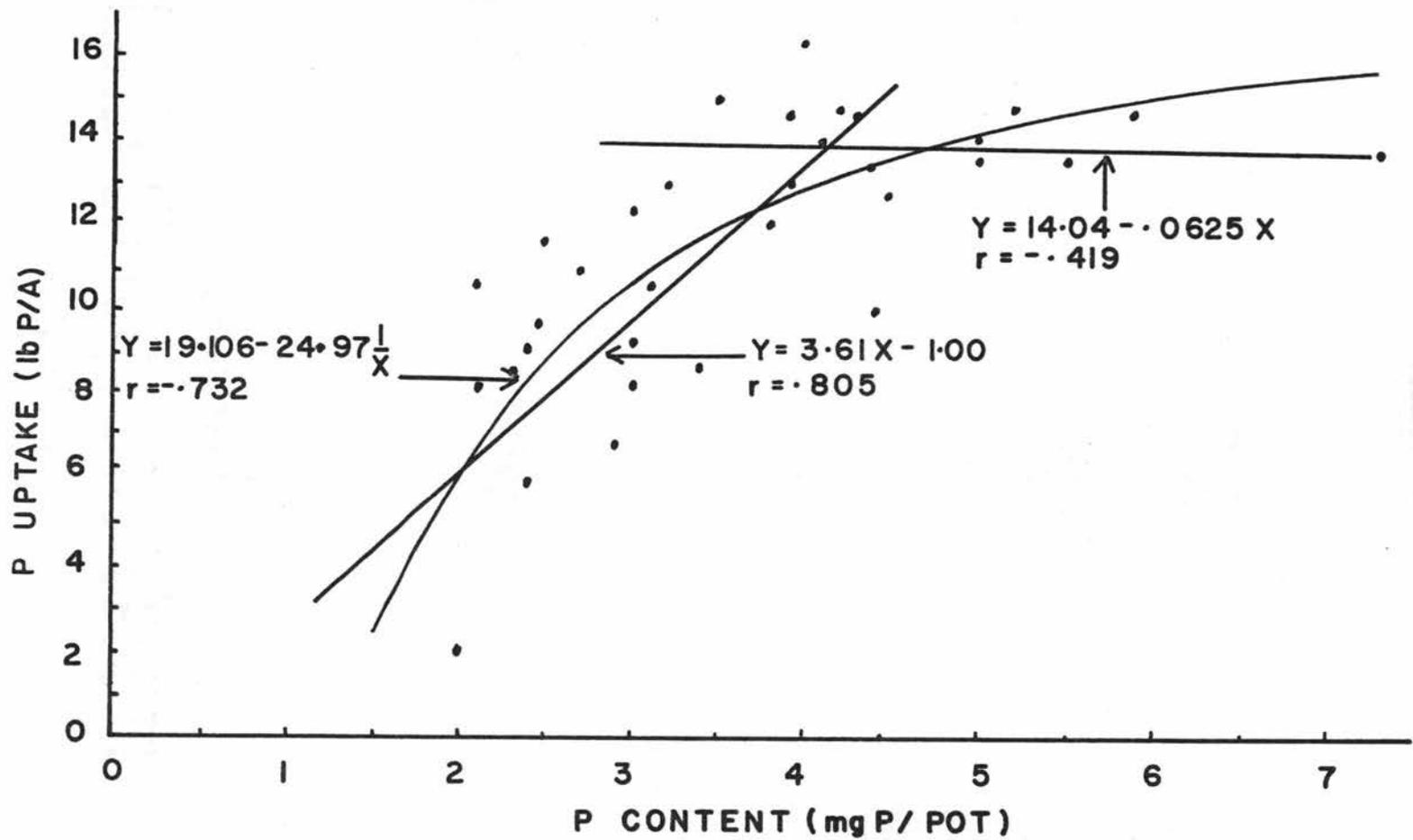


Figure 11. Correlation between P content of clover grown in the greenhouse and P uptake by alfalfa in the field for L₂P₀, L₂P₁ and L₂P₂ treatments.

curve showed a gradual change in slope and thus did not permit the determination of a level for mg of P/pot of clover corresponding to the maximum phosphorus uptake of alfalfa. Consequently, an attempt was made to more closely define this level by first separating the data into two portions. The linear regression equations for all the observations with the values less than 4.5 mg of P/pot and for all the observations with the values above 3.5 mg P/pot were calculated. The correlation coefficients obtained were 0.805 and -0.419 respectively. The linear regression equation for the first group was:

$$y = 3.610x - 1.00$$

for the second group the equation was:

$$y = 14.04 - 0.0625x$$

The two equations were solved simultaneously for the intersection (Figure 11). The value 4.1 mg P/pot thus obtained corresponded to the maximum phosphorus uptake of alfalfa in the field (14 lbs P/A). It was realized that the intersection obtained by this method could vary depending on the choice of intervals for which linear regression equations were calculated. It was felt, however, that the choice of the interval for the linear regression analysis could give a satisfactory approximation.

According to the correlation curve between the amounts

of phosphorus taken up and per cent of the maximum yield of alfalfa (Figure 15), the maximum yield of alfalfa (98%) was reached when the crop took up 14 lbs P/A. Therefore the phosphorus content of clover at around 4.0-4.2 mg of P/pot would correspond to 98% of the maximum yield of the alfalfa grown in the field.

Since the expression of phosphorus content of clover as mg of P/pot and mg of P/40 plants were not very much different, the correlation coefficient being 0.936 (Appendix 4), therefore the values 4.0-4.2 mg P/pot of clover could be related to the regression equations obtained for different phosphorus soil test method vs. mg of P/40 plants (Table 15). The corresponding phosphorus soil test values obtained were shown in Table 21. The soil test values obtained represented the levels of soil phosphorus above which no response from added phosphorus would be obtained.

(3.3) Calibration of P Soil Test Methods

In order to calibrate the phosphorus soil test methods with phosphorus response, scatter diagrams were constructed for soil test values of the different methods vs. the per cent of the maximum yield of the first cutting of the alfalfa. Only the scatter diagram for Olsen method

Table 21

Indirect Calibration of the "Available" P as Measured by Various Chemical Phosphorus Soil Test Methods

% Yield without P	Olsen, ppm P			Mod. Olsen, ppm P			Bray No. 1, ppm P		
	pH 5.8-6.8	pH 4.7-5.7	All soils	pH 5.8-6.8	pH 4.7-5.7	All soils	pH 5.8-6.8	pH 4.7-5.7	All soils
10									
20									
30									
50	3.5	--	1.2	4.42	--	--	--	--	--
60	5.85	1.9	3.9	13.5	--	7.35	9.8	7.5	9.5
75	9.45	7.1	8.1	27.3	22.4	28.5	25.4	30.0	27.9
85	11.8	10.4	10.8	36.3	44.7	42.4	35.6	44.7	40.0
90	13.1	12.2	12.3	41.4	57.0	50.0	41.4	52.8	46.8
95	14.2	13.8	13.6	45.6	67.6	56.5	46.2	59.7	52.3
96	14.4	14.2	13.9	46.5	70.0	57.9	47.1	61.2	53.6
97	14.7	14.6	14.2	47.7	72.8	59.7	48.4	63.1	55.1
98	14.8	14.8	14.4	48.4	74.5	60.5	49.2	64.0	56.0

is shown in Figure 12. The plotting included only the soil test values determined from soil samples having pH above 5.8 which amounted to about slightly more than a half of the total soil test values. The lower limit of soil pH at 5.8 was chosen because it was established that fairly good growth of alfalfa could usually be obtained from soils whose pH was above 5.8.

The scatter diagram for all of the soil test methods showed that the relationships were not linear but curvilinear. As a matter of fact, if all the soil test values were used for plotting regardless of the soil pH the same type of curve would have been obtained which seemed to indicate that the per cent of the maximum yield reached a point above 90% at a very low level of soil test values. For instance, according to Figure 12, the dotted curve consisted of the very steep positive slope followed by a sharp bend and a leveling off at around 6 ppm NaHCO_3 -soluble phosphorus. In other words, relationships between the field data and the phosphorus soil test values were not evident when the soil test values exceeded 6 ppm phosphorus for Olsen method or 15-30 ppm phosphorus for both Bray No. 1 and Modified Olsen methods. Consequently it seemed impossible to correlate and calibrate the phosphorus soil test methods by merely relating soil test values to

the corresponding field data regardless of variation in treatments previously superimposed on the soil samples. The variations in the lime rates, probably contributed a great deal to the failure to obtain good correlation between the phosphorus soil test values and the field data by this technique.

The correlation between phosphorus soil test values with the field data could be improved by plotting the average values from the three replications for the soil tests and field data while limiting the observations to treatments L_2P_0 , L_2P_1 and L_2P_2 . The scatter diagram and correlation curve of $NaHCO_3$ -soluble phosphorus vs. per cent maximum yield are shown in Figure 13. The relationship was curvilinear and could be described fairly well by the equation

$$\text{Log}(100-y) = \text{Log} 100 - c_1 b \quad (19).$$

where y = average percentage of the maximum yield
observed from L_2P_0 , L_2P_1 and L_2P_2
treatments

b = phosphorus soil test values

c_1 = constant

In this case the equation $\text{Log}(100-y) = \text{Log} 100 - .1032b$ was used and seemed to fit the observed data quite well. The correlation coefficient between the predicted yields,

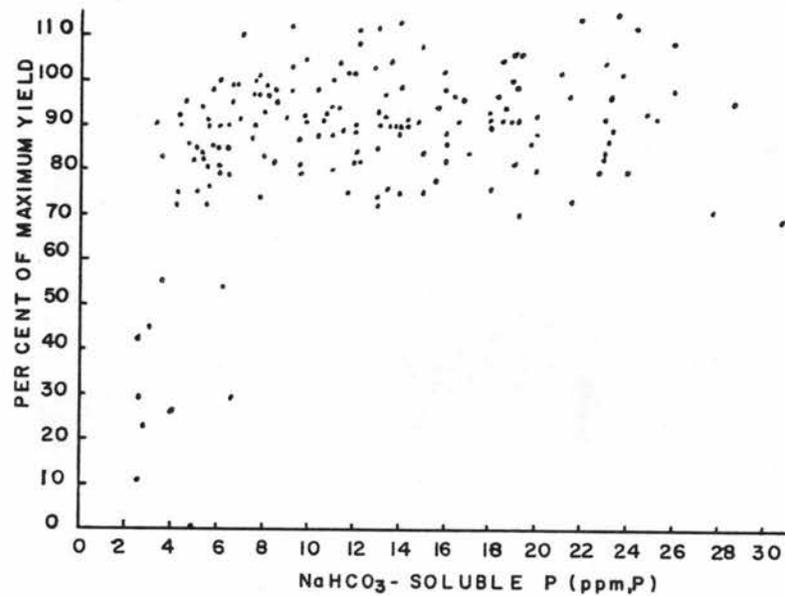


Figure 12. Scatter diagram for the relationship between NaHCO_3 -soluble P and per cent of maximum yield for soil pH above 5.8.

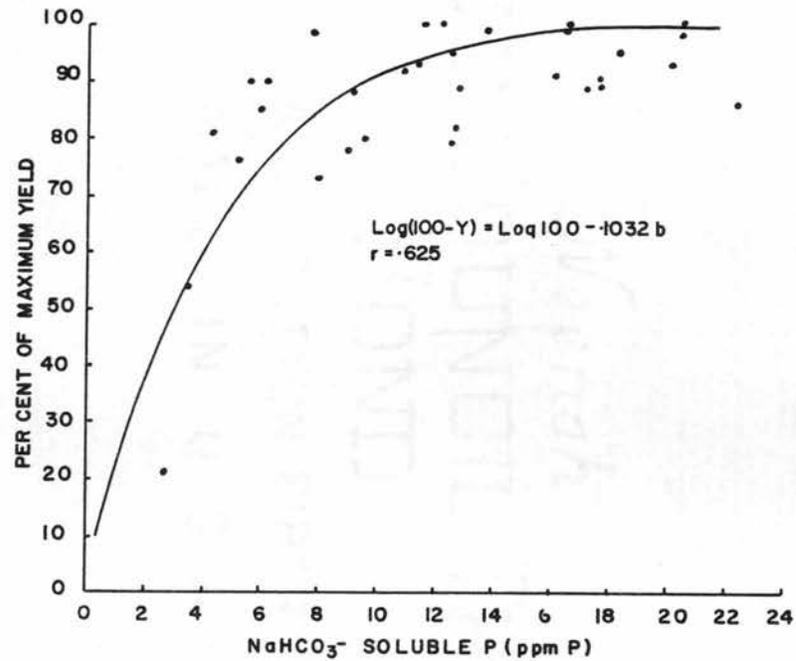


Figure 13. Correlation between NaHCO_3 -soluble P and per cent of maximum yield from L_2P_0 , L_2P_1 and L_2P_2 treatments.

calculated from this equation, and the observed yields was 0.625. The constant 0.1032 is the average of the individual c_1 values calculated from each treatment (Appendix 6). The calculated NaHCO_3 -soluble phosphorus values corresponding to various per cent of the maximum yields are shown in Table 22. The data showed that the maximum yield of alfalfa (98%) could be produced from the Aiken soils containing 16.46 ppm NaHCO_3 -soluble phosphorus or above.

Equations describing the same type of relation between per cent of maximum yield and soil test values for the other methods could be determined by calculating the average c_1 values. The average c_1 values for Modified Olsen and Bray No. 1 were 0.03495 and 0.03757 with $r = 0.702$ and 0.668 respectively. Therefore the equations to be used are:

$$\text{Log}(100-y) = \text{Log } 100 - 0.03495 b \text{ for Modified Olsen}$$

$$\text{and } \text{Log}(100-y) = \text{Log } 100 - 0.03757 b \text{ for Bray No. 1.}$$

According to these equations 48.6 ppm Modified Olsen-soluble phosphorus and 45.2 ppm Bray No. 1-soluble phosphorus corresponded to the maximum yields (98%) of alfalfa.

It was found that the best correlations were obtained between the soil tests and the amounts of phosphorus taken up by alfalfa (Table 18). A scatter diagram and correlation curve were constructed to show the relationship

Table 22
Calibration of the NaHCO_3 -soluble P with the Crop Responses
and Phosphorus Uptake of Alfalfa

% of Max. Yield	Calculated soil test, ppm P		Calc. P ^{3/} Uptake lbs/A	P Uptake lbs/A	Calc. ^{4/} soil test ppm P
	Figure ^{1/} 13	Figure ^{2/} 16	Figure 15		Figure 14
10	0.44	0.49	0.49	2	1.07
20	0.94	1.05	1.04	5	3.21
30	1.50	1.67	1.67	8	5.50
50	2.92	3.25	3.24	10	7.75
60	3.85	4.30	4.29	12	10.88
75	5.83	6.51	6.49	14	15.95
85	7.98	8.91	8.88	15	20.60
90	9.69	10.81	10.77	16	32.55
95	12.61	14.06	14.02		
98	16.46	18.36	18.30		

^{1/} Correlation between NaHCO_3 -soluble P(b) vs. per cent of maximum yield (y) from L_2P_0 , L_2P_1 and L_2P_2 plots.

$$\text{Log}(100-y) = \text{Log } 100 - 0.1032b$$

^{2/} Same as ^{1/} except y = per cent maximum yield from L_2P_0 treatment.

$$\text{Log}(100-y) = \text{Log } 100 - 0.0925 b$$

^{3/} Correlation between P uptake by alfalfa (b) vs. per cent maximum yield from L_2P_0 , L_2P_1 and L_2P_2 plots.

$$\text{Log}(100-y) = \text{Log } 100 - 0.09281 b$$

^{4/} Correlation between NaHCO_3 -soluble P(b) vs. P uptake by alfalfa (y).

$$\text{Log}(100-y) = \text{Log } 100 - 0.00533 b$$

between NaHCO_3 -soluble phosphorus and phosphorus uptake of alfalfa. The average values from the three replications for L_2P_0 , L_2P_1 and L_2P_2 treatments were plotted, and shown in Figure 14. The graph showed a good curvilinear relationship between the NaHCO_3 -soluble phosphorus and the amounts of phosphorus taken up by alfalfa. Since the relationship follows Mitscherlich's law of diminishing returns, the equation

$\text{Log}(A-y) = \text{Log } A - c_1 b$ was used to describe the relationship.

where A = The maximum phosphorus uptake of alfalfa among the 10 locations, which was 16.3 lbs P/A

y = phosphorus uptake, lbs P/A, obtained from L_2P_0 , L_2P_1 and L_2P_2 plots

b = NaHCO_3 -soluble P ppm P

c_1 = constant

In this case the equation

$\text{Log}(16.3-y) = 1.212 - 0.00533 b$ could be used to describe this relationship. The constant 0.00533 was obtained by taking an average of the individual c_1 computed from the corresponding y and b of each treatment in various locations (Appendix 6). The value 1.212 is the logarithm of 16.3. According to this equation, the

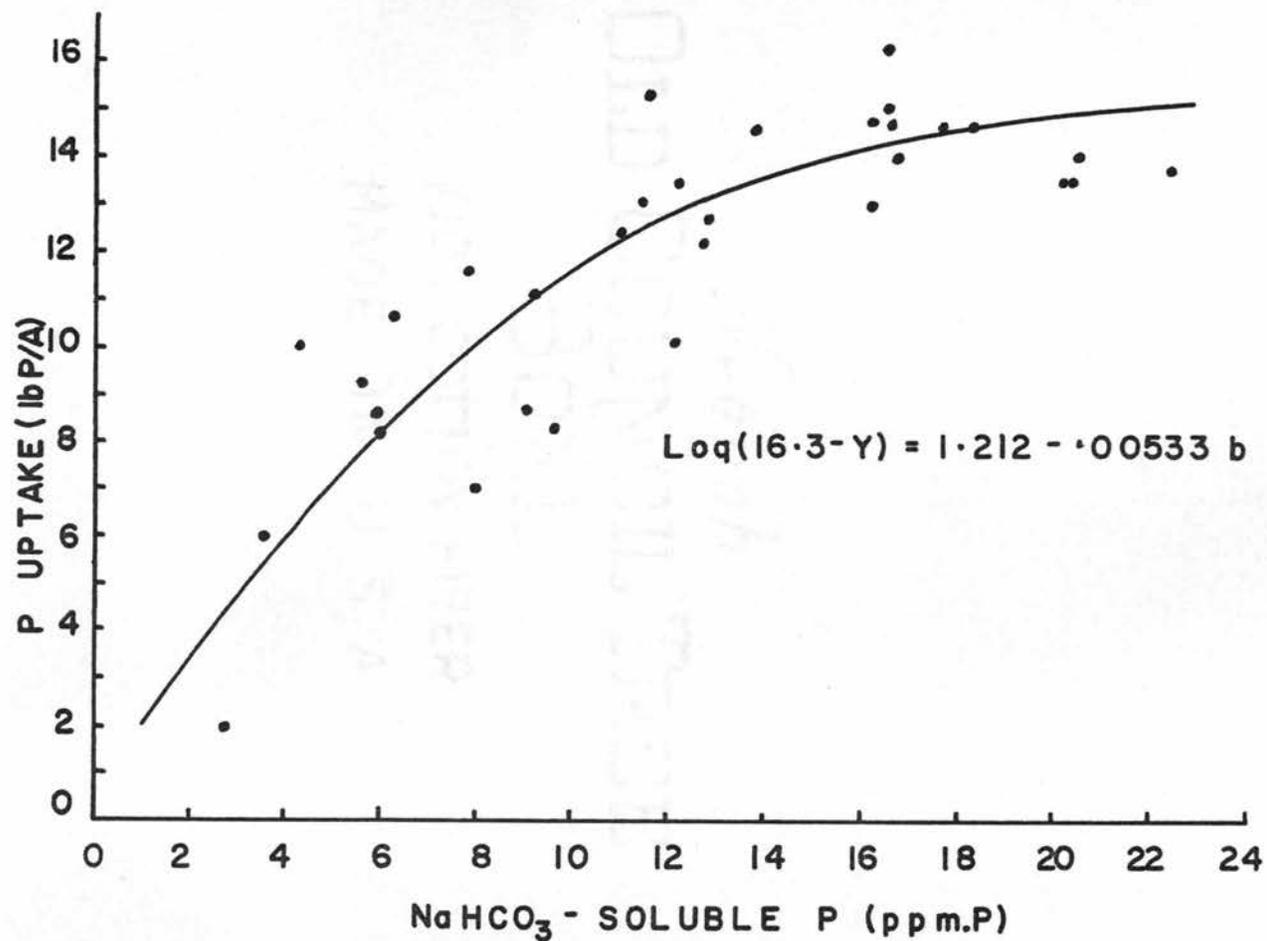


Figure 14. Correlation between NaHCO₃-soluble P and phosphorus uptake by alfalfa from L₂P₀, L₂P₁ and L₂P₂ treatments.

the phosphorus taken up by alfalfa reached the maximum 14-15 lbs P/A when the NaHCO_3 -soluble phosphorus read 16-20 ppm phosphorus (Table 22, Figure 14). It was also found that the amount of phosphorus taken up by alfalfa was highly correlated with the per cent of the maximum yield of alfalfa. The correlation coefficient was 0.928 (Appendix 5). The scatter diagram for the relationship between the phosphorus uptake and the per cent of the maximum yield was constructed for the L_0P_0 , L_2P_1 and L_2P_2 treatments and is shown in Figure 15. The curve showed a somewhat curvilinear relationship. The equation $\text{Log}(100-y) = \text{Log } 100 - 0.09281 b$ was used to describe this relationship. According to this equation the yields of alfalfa reached the maximum (95-98%) when the crop took up 14-18 lbs P/A (Table 22), which evidently agreed with the amount taken up as determined by linear regression line for all treatments (Figure 15). The relationship between the NaHCO_3 -soluble phosphorus vs. phosphorus taken up by alfalfa and the phosphorus taken up by alfalfa vs. per cent maximum yield, as shown in Figures 14 and 15, agreed with each other very well. The former relationship indicated that 16-20 ppm- NaHCO_3 -soluble phosphorus corresponds to the maximum phosphorus uptake (14-15 lbs P/A) and the latter relationship showed that the yield of alfalfa reached the

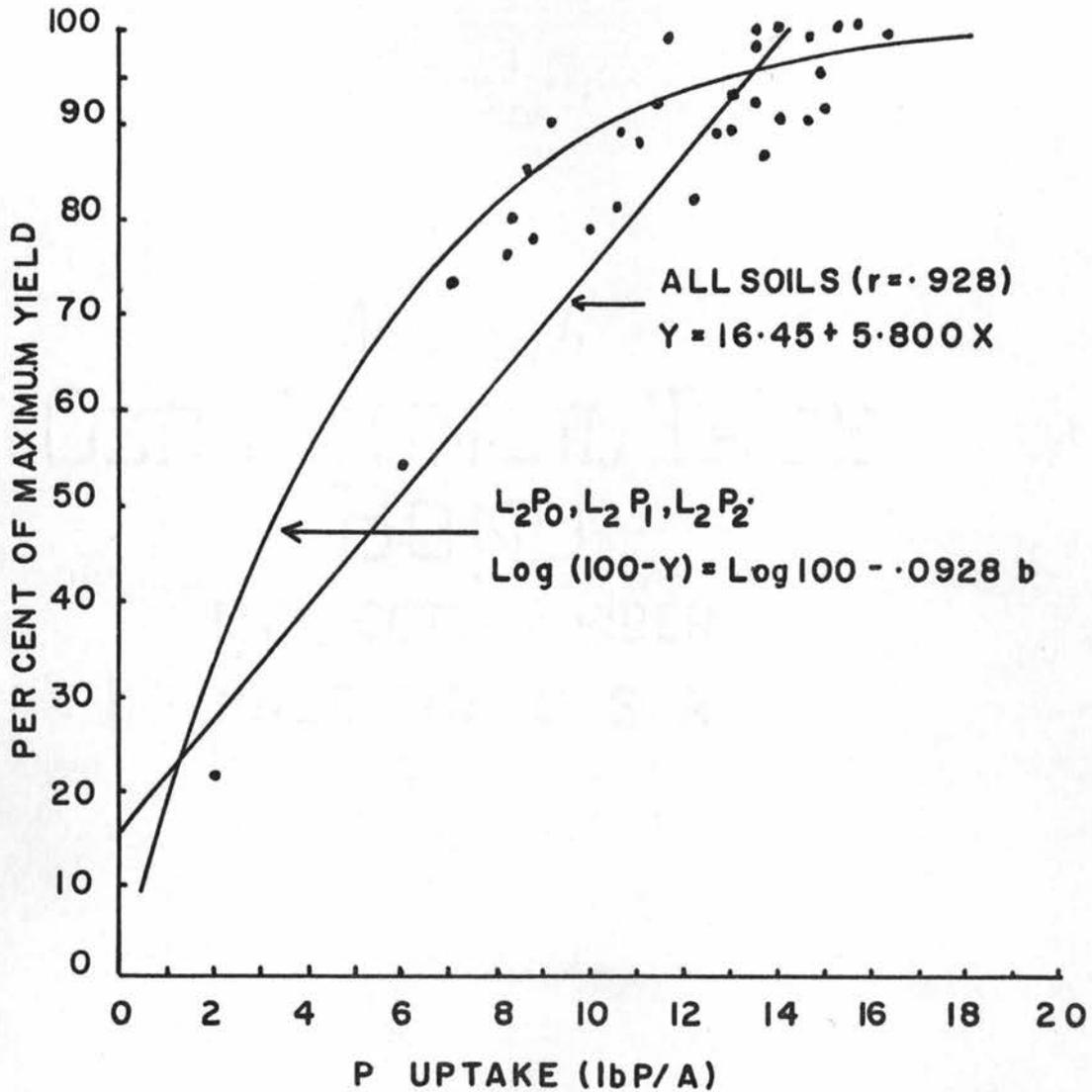


Figure 15. Correlation between P uptake of alfalfa and per cent of maximum yield from L_2P_0 , L_2P_1 and L_2P_2 . A line of linear regression for the same relationship for all treatments is also compared.

maximum (95-98%) when alfalfa took up about 14-18 lbs P/A.

The method of correlating and calibrating phosphorus soil test procedures according to the Bray technique (19) could also be applied to this study. The correlation procedure requires only two treatments in each location, in this case the treatment L_2P_0 and the treatment that produced the maximum yield, which could vary from one location to the other, were used. The average per cent of maximum yield of the three replications for the L_2P_0 treatment were plotted against the average soil test values. With one exception the treatment L_1P_0 and L_2P_0 in the experiment 105 were treated as a single treatment, that is, the average per cent of maximum yield and the soil test values obtained from these two treatments were averaged again before plotting. The results of the plotting showed the relationship similar to a typical curve of the law of diminishing returns, for Olsen method. Therefore, the Modified Mitscherlich's equation (19) could be applied for this relationship. The correlation curve and the equation for the relationship between the Olsen method vs. per cent of the maximum yield are shown in Figure 16. For Bray No. 1 and Modified Olsen a somewhat different relationship from that of Olsen was obtained. For both methods the soils from 10 locations tended to divide into two groups:

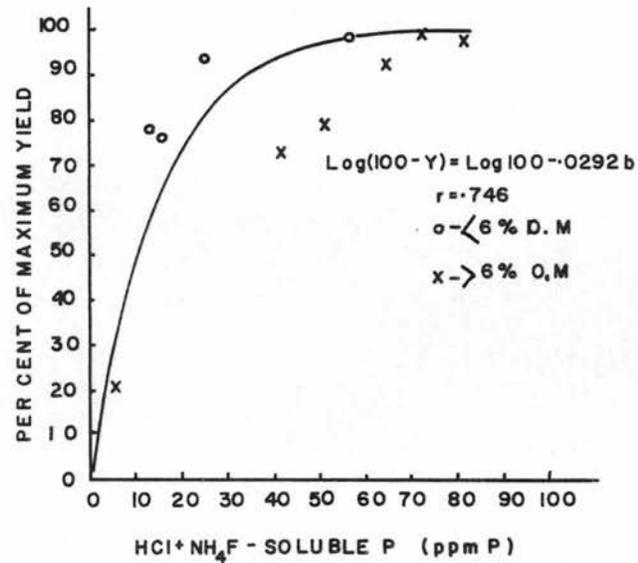
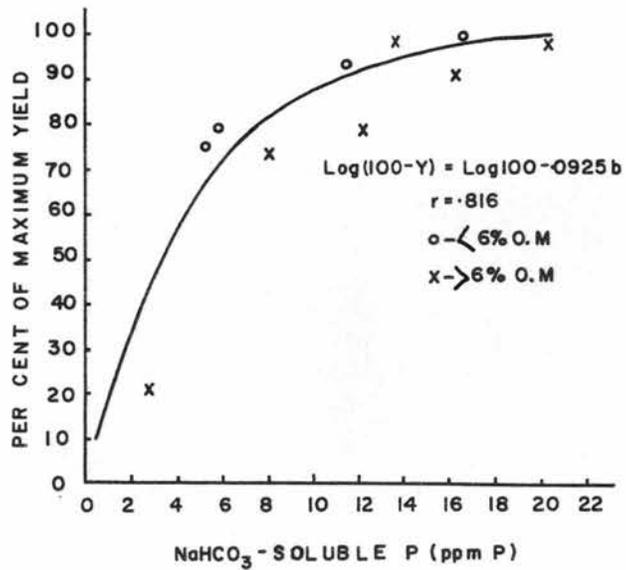


FIGURE 16 Correlations between Olsen and Bray No. 1 soil test methods vs. per cent of maximum yield from treatment L₂P₀ ○

(1) soils containing organic matter greater than 6% and
(2) those less than 6%. Both groups of soils showed separate correlation curves. They were slightly curvilinear but that of the group of the soils containing organic matter greater than 6% covered the wider range of phosphorus soil test values than that of the other group of soil. An example of the scatter diagram of these types of relationship was shown in Figure 16 for the Bray No. 1 method. It has not been determined why both Modified Olsen and Bray No. 1 tend to underestimate the Aiken soil containing less organic matter than those containing higher organic matter; however, it has been observed from the results of the clay mineralogy studied of soils from these locations, that soils from the locations high in organic matter ($> 6\%$) contained mostly kaolinite type of alumino silicate mineral while the soils from the locations lower in organic matter contained considerable 2:1 type of alumino silicate clay mineral, especially illite. It has been generally recognized that soils containing the kaolinite type of clay mineral tend to have somewhat greater fixing capacity than the 2:1 type of clay minerals (63). Therefore, the differences in the type of the clay minerals between these two groups of soils may have some bearing on the ability of these soils to supply phosphorus

to alfalfa. Further work is needed to verify whether or not this is the case.

For the relationship between the Olsen method and per cent of maximum yield, the following equation

$$\text{Log}(100-y) = \text{Log } 100 - 0.0925 b$$

was used and seemed to fit the data quite well, with $r = 0.816$.

Where y = per cent of the maximum yield obtained from the unphosphated soils

b = ppm P of the NaHCO_3 -soluble phosphorus

$c_1 = 0.0925$ (Appendix 6)

According to this equation 14-18 ppm NaHCO_3 -soluble phosphorus corresponded to the maximum yield (95-98%) while 6-7 ppm phosphorus corresponded to 75% yield and 3-4 ppm phosphorus to 50-60% yield. It should be observed that the correlation curve constructed according to Bray's methods (19) agreed very well with the one shown in Figure 13. Table 22 summarized the various calibration curves obtained between the per cent of maximum yield and NaHCO_3 -soluble phosphorus with the amount of phosphorus taken up by alfalfa is also presented in the same table. Appendix 6 summarized the yield response of alfalfa, phosphorus uptake of alfalfa and subclover in relation to NaHCO_3 -soluble phosphorus with the special references to

treatments L_2P_0 , L_2P_1 and L_2P_2 including L_2P_3 and L_2P_6 of experiment No. 105. Detail data of the field, greenhouse and phosphorus analyses by different methods are shown in Appendix 3.

The same type of equations could be determined for Modified Olsen and Bray No. 1 by calculating the average c_1 values for each method. The average c_1 values for Modified Olsen and Bray No. 1 were 0.02826 and 0.02921 with the corresponding $r = 0.598$ and 0.746 respectively (predicted vs. observed). Therefore, the equations to be used are:

$$\text{Log}(100-y) = \text{Log } 100 - 0.02826 b \text{ for Modified Olsen and}$$

$$\text{Log}(100-y) = \text{Log } 100 - 0.02921 b \text{ for Bray No. 1.}$$

According to these equations the maximum yield of alfalfa (98%) corresponded to 60.0 and 58.3 ppm phosphorus for Modified Olsen and Bray No. 1 respectively.

In addition to the calibration of the phosphorus soil test method for a "critical level",^{5/} it would be of practical value, if the soil test values could be calibrated

^{5/} The use of the term "critical level" in this thesis implies the level of "available" P, as determined by various methods, above which no response of the crops to the added phosphorus fertilizer could be obtained. It is realized that this level, as determined by any soil test method, will vary to certain extent for different crops and various divergent soil properties. However, this does not eliminate the possible practical use of "critical level" since the level determined will be applied to the area and crop from which the soil test methods were calibrated.

also in terms of phosphorus fertilizer requirement for maximum yield or a desired percentage of maximum yield. Since the relationship between the Olsen method with per cent of maximum yield were better than Bray No. 1 and Modified Olsen, and the method is presently employed by the Oregon State University Soil Testing Laboratory, therefore only the Olsen method will be calibrated for this purpose.

The calibration of the NaHCO_3 -soluble phosphorus in terms of the fertilizer requirement for the production of 98% yield was done according to the method of Bray (19) by relating the per cent yield obtained under varying increments of phosphorus fertilizer to the soil test values (b), and the rates of the fertilizer applied (x) according to the equation:

$$\text{Log}(100-y) = \text{Log } 100 - 0.0925 b - cx$$

The constant c, expressing the efficiency of utilization of the applied phosphorus fertilizer, was calculated for each increment giving an intermediate yield between the 0 rate and the optimum rate on each location. In this case L_2P_0 was the 0 rate, L_2P_1 and L_2P_2 were used as the intermediate rates where as the optimum rate was the rate that produced the maximum yield and could vary from one location to the other. In this study only 3 field experimental locations yielded the results that permitted

calculation of the c values. The rest of the locations gave either the maximum yield at the 0 rate or percentage yield reaching the maximum at intermediate rates of phosphorus. The calculated c values under these conditions gave unrealistic results (2).

The calculated c values and a mean value of 0.01442 were shown in Table 23; therefore the equation could be written as:

$$\text{Log}(100-y) = \text{Log } 100 - 0.0925 b - 0.01442 x$$

where b = soil test value based on Olsen method in ppm P,
 x = rate of P fertilizer in lb P O /A required to produce a desired percentage of maximum yield.

By means of this equation the expected percentage yield can be calculated for any combinations of soil test value and rate of fertilizer to be applied. And, in addition, the approximate rate of phosphorus fertilizer necessary to supplement the soil supply of phosphorus as measured by the Olsen method, can be calculated for any desired percentage of the maximum yield. Table 24 gave the tentative phosphorus fertilizer requirement for the acid "Red Hill" soils, in order to produce 98% of the maximum yield of alfalfa. Since the data were based on the soils limed with 3-6 tons of CaCO_3/A (L_2) and the pH of the soils was raised to an average of 6.0. Therefore,

Table 23
Calculated C Values for Alfalfa

Exp. No.	Treatment		% Max. ^{1/} yield (y)	Soil ^{1/} test (b) ppm P	C ^{2/}
	Lime T/A	lb/A P ₂ O ₅ (x)			
502	4	0	21.3	2.7	--
	4	90	53.7	3.5	.01528
	4	180	81.0	4.7	.00705
514	4	0	73.2	7.9	--
	4	45	80.1	9.6	.01800
	4	90	77.8	8.9	.00973
108	4	0	76.4	5.2	--
	4	45	84.7	5.9	.02570
	4	90	98.7	7.9	.01078
			Mean		.01442

^{1/} Each value is the average of 3 replications.

^{2/} Calculated from equation

$$\text{Log}(100-y) = \text{Log } 100 - 0.0925 \text{ b-cx}$$

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Table 24

Phosphorus Requirement^{1/} of Alfalfa Based on the Olsen Soil Test Method

Soil test ppm P	% yield without P	P requirement ^{2/} for 98% yield 1b P ₂ O ₅ /A	Proposed Range of Response	Olsen et al. (86)		Olson et al. (87)	
				Soil test ppm P	Range of Response	Soil test ppm P	Range of Response
0.49	10	114.6	↑ Response	0	↑ Response	0	↑ Assured Response
1.05	20	111.1					
1.67	30	107.1					
3.25	50	96.9					
4.30	60	90.2	X	5.46 (25 lbs P ₂ O ₅ per acre)	X A probable response	8.0	X Likely response
6.51	75	76.2					
8.91	85	60.6	A probable response	X	X	12.0	X Probable response
10.81	90	48.5					
14.06	95	28.4					
15.10	96	20.7	X	X	X	16.0	X Response unlikely
16.40	97	12.4					
18.36	98	--	Response unlikely				

^{1/} The application of data is limited to acid "Red Hill" soils and required liming up to the average pH of 6.0.

^{2/} Based on sulfur free concentrated super phosphate.

this fertilizer requirement table would be more specifically applicable to the acid soils which have already been limed to around pH 6.0. The pH value of 6.0 was the average soil pH of all the plots treated with L_2 rate of lime. About 85% of the soils from these plots have the pH values of 5.8 and above.

V. GENERAL DISCUSSION

(1) Evaluation and Calibration of Chemical P Soil Test Methods

Two approaches, direct and indirect, were used to study the evaluation, correlation and calibration of the different chemical phosphorus soil test methods. The indirect approach was accomplished through the use of the relationship existing between chemical analyses of soil phosphorus and the greenhouse results; whereas, the direct approach employed the established relationship between the chemical analysis data with the field data. The results obtained from both means will be discussed and evaluated accordingly.

(1.1) Indirect Approach

The "available" phosphorus as measured by various chemical methods were correlated with the phosphorus content of oats and clover grown on corresponding soils under the greenhouse conditions. According to the data shown in Table 14, all methods were highly correlated with the greenhouse data and no method seemed to be markedly superior to the other. In general, however, the Olsen method showed somewhat higher correlation coefficients than the other methods which suggested the selection of

this method for prediction of the phosphorus status of the Aiken soils.

It was found that both soil pH and $\text{exch. Ca} + \text{Mg}$ influenced the chemical analysis of the soil phosphorus by all the methods studied, very markedly so for Modified Olsen and Bray No. 1 (Table 19). As the soil pH increased the phosphorus soil test values decreased. The data (Table 14), however, did not show a marked influence of the increase of soil pH and $\text{exch. Ca} + \text{Mg}$ on the phosphorus content of oats and clover. The effect of soil pH and $\text{exch. Ca} + \text{Mg}$ on both soil test values and phosphorus content of oats and clover can be minimized to certain extent by means of stratified correlation within certain pH range as shown in Table 15 where stratified and nonstratified correlation coefficients, including their corresponding linear regression equations were presented.

In general, the data obtained seemed to indicate that all the methods attained higher reliability in predicting the phosphorus status of the acid soils limed to pH above 5.8 than the limed and unlimed soils whose pH were lower than 5.8. This is especially true for the Modified Olsen method. In order to improve the reliability of the phosphorus soil test methods, in predicting the phosphorus fertility of soils, separate regression equations according

to the soil pH should be employed. In this case, for instance, if the pH of the soils to be evaluated were lower than 5.8 the regression equation of the lower stratification of the pH range should be used. For the soils with pH values greater than 5.8 a more reliable prediction of the phosphorus level of the soil could be obtained if the stratified regression equations of the higher pH range were used.

According to Table 14 clover proved to be superior to oats as an indicator plant for phosphorus uptake study from these soils because all the correlation coefficients obtained were better than those of oats. Consequently, the relationship between phosphorus soil test vs. phosphorus content of clover was chosen for further work on the calibration of the "critical level" for the soil test methods.

The correlation between the soil test values vs. phosphorus content of plants grown under greenhouse conditions can only be used to evaluate the ability of different chemical methods to predict the phosphorus fertility of soils. The results did not permit the calibration of the selected method for the "critical level" or the level of the "available" phosphorus sufficient for the maximum yield in the field. However, the "critical level" can be

determined for these methods indirectly. This was done by relating the greenhouse data to the field data. The results presented in Table 20 showed that relationship between phosphorus uptake of alfalfa in the field and phosphorus content of the clover was the best. This relationship was thus selected so that the phosphorus content of clover, mg P/pot, corresponding to the phosphorus uptake of alfalfa that produced the maximum yield could be determined.

The relationship between phosphorus content of clover vs. phosphorus uptake by alfalfa was curvilinear. Since the equation for a hyperbolic function did not describe the relationship with the observed data at the range of phosphorus uptake by alfalfa corresponding to the maximum yield accurately, therefore two linear regression equations were employed to describe this relationship and found to be more satisfactory. The first regression equation

$$y = 3.610 x - 1.00$$

covered all the observations less than 4.5 mg of clover P/pot with $r = 0.805$. The other equation

$$y = 14.04 - 0.0625 x$$

covered the observation above 3.5 mg of P/pot of clover with $r = -0.419$. The intersection of the two regression

lines (Figure 11) was found to be at 4.1 mg of P/pot of clover and phosphorus uptake of alfalfa at 14 lbs P/A, which corresponded to the maximum yield of alfalfa (Figure 15). Therefore the first regression equation accurately described the relationship between mg of P/pot of clover vs. phosphorus uptake of alfalfa for the range far enough for the calibration purpose. The "critical level" for the phosphorus soil tests could be determined by solving this regression equation and those presented in Table 15 simultaneously. Besides the "critical level", other levels of "available" phosphorus as measured by any soil test method, corresponding to the various percentage of maximum yield can also be determined from the same equations.

The equation $y = 3.610 x - 1.00$ is presented as

$$x_3 = b_2 x_2 - a_2 \quad \text{-----1}$$

and the regression equations presented in Table 15 as

$$x_2 = a_1 + b_1 x_1 \quad \text{-----2}$$

combining the two equations and solving for x_1 , the equations are reduced to

$$x_1 = \frac{x_3 + a_2}{b_1 b_2} - \frac{a_1}{b_1} \quad \text{-----3}$$

where x_1 = "critical level" or "available" phosphorus sufficient to produce maximum yield or at any desired percentage of maximum yield.

x_2 phosphorus content of clover, mg P/pot,
corresponding to x_3 .

x_3 phosphorus uptake of alfalfa corresponding
to the maximum yield (98%) or at any per-
centage of maximum yield.

b_1, b_2 = coefficient of x_1 and x_2 respectively.

a_1, a_2 = interception of equation 2 and 1 respectively.

The equation $y = 16.45 + 5.800 x$ ($r = 0.928$) was
used to determine the amount of phosphorus uptake by
alfalfa (x or in this case x_3) corresponding to any
desired percentage of the maximum yield (y).

The calibrated "available" phosphorus as measured by
various chemical methods for both unstratified and strati-
fied according to pH are presented in Table 21. It was
observed that the calibrated "available" phosphorus of the
Olsen method did not differ greatly from one stratifica-
tion to the other; whereas, those of the Modified Olsen
and Bray No. 1 gave distinctly different calibrated soil
test values for lower and higher pH ranges.

As previously mentioned, all three methods are
equally good so far as the studies in this section are
concerned, for predicting the phosphorus fertility of the
Aiken soils. Olsen method has an advantage of being the
least affected by the soil pH and therefore the use of
separate calibration curves may not be necessary. It does

have the disadvantage of not extracting a large percentage of the phosphorus present in these soils.

Fifteen ppm "available" phosphorus as measured by this method was sufficient for maximum yield. This resulted in a narrow calibrated interval for the lower per cent of the maximum yield. Analytical errors must be minimized as much as possible when this method is used.

Both Modified Olsen and Bray No. 1 have about the same calibration curves. Both were influenced by the soil pH. The methods tend to overestimate the phosphorus status of soils low in pH (< 5.8) consequently separate calibration curves must be used for soils with different degrees of acidity for satisfactory results. Since the measurement of soil pH is always made in general soil testing program, the problem of deciding which calibrated curve to be used with the phosphorus analysis is not much of the problem. An advantage of these methods over the Olsen method is that the greater phosphorus extracting power allows a wider range of calibrated soil test values.

(1.2) Direct Approach

The more meaningful and useful soil test methods are those that are directly related to crop performance in the field. In most cases, the relationship obtained between

the soil test values and the yield of the crop grown under field conditions is not as good as the relationship obtained under greenhouse condition. This is shown from the data (Table 18) obtained when the soil test values were related with various kinds of field observations. Regardless of the small size of the correlation coefficients obtained, the Olsen method had the best simple relationship with the field data. The highest simple correlation coefficients obtained were between NaHCO_3 -soluble phosphorus vs. phosphorus uptake of alfalfa, $r = 0.417$. According to the data obtained, soil pH and exch. Ca + Mg were the important factors influencing the yield of alfalfa and the availability of phosphorus from these soils.

If the influence of soil pH and exch. Ca + Mg were eliminated, by holding them constant, the relationship between the phosphorus soil test values vs. field data was improved, especially in the case of the Modified Olsen method. The same was true when soil pH, exch. Ca + Mg and phosphorus soil test values were simultaneously correlated with the field data. Consequently both phosphorus analysis and soil pH were proved to be equally important as the indices of phosphorus status of the soils. Therefore, the recommendations based on a phosphorus soil test should be modified by the soil pH. Again, according to the data

shown in Table 18, it can be concluded that all soil test methods are about equally efficient in predicting the phosphorus status of the soil if either soil pH or $\text{exch. Ca} + \text{Mg}$ is not allowed to vary too much.

The relationship between the phosphorus soil test values and per cent of maximum yield was improved if both soil pH and lime rates were allowed to vary as little as possible (Figure 13, where L_2 rate of lime was used, about 85% of the soil pH values were above 5.7, and the rates of phosphorus applied were allowed to vary from P_0 to P_2). These restrictions made it possible to develop a better direct calibration for "critical level" of "available" phosphorus as measured by various phosphorus soil test methods. The diminishing return type of the equation as suggested by Bray (19) satisfactorily described this relationship, with $r = 0.685$, 0.702 and 0.668 for Olsen, Modified Olsen and Bray No. 1 respectively. According to these equations the "critical level" of "available" phosphorus measured by these methods in order to produce 98% yield were 16.5, 48.6 and 45.2 ppm phosphorus for Olsen, Modified Olsen and Bray No. 1 respectively.

The second method of direct calibration of the phosphorus soil test methods followed the technique described by Bray (19), (Figure 16). In this case the correlation

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between Olsen methods proved to be slightly better than the other methods and the Bray's equation gave better agreement between the predicted and observed data ($r = 0.816$) than the other two methods ($r = 0.598$ for Modified Olsen and 0.746 for Bray No. 1). According to these equations, the calculated "available" phosphorus corresponding to around 97-98% were 16-18, 60.0 and 58.3 ppm phosphorus for Olsen, Modified Olsen and Bray No. 1 respectively. The "critical level" of "available" phosphorus for the Olsen method agreed in both cases. Slightly higher values were obtained for the other two methods by means of the Bray technique.

According to the calibration curves indirectly obtained from the greenhouse experiment, the "critical level" for Olsen method was in the best agreement with those obtained directly from the field experiment. The "critical level" for Modified Olsen and Bray No. 1 for all soils (Table 21) agreed with those obtained by the Bray technique; whereas, the "critical level" of the stratified pH 5.8-6.8 data agreed with those obtained with the first direct method. This would indicate that the NaHCO_3 - soluble phosphorus is more reliable as an index of phosphorus status of the soils than other methods and should be recommended for a routine phosphorus testing program of

Aiken and other closely related "Red Hill" soils. The calibration curve as shown in Table 24 is proposed for use as a guide for the interpretation of the soil test values. The proposed range of the calibrated NaHCO_3 -soluble phosphorus may be grouped in term of degree of response of alfalfa crop as follows:

below 6.5 ppm P response assured,

6.5-16.0 ppm P response possible,

above 16.0 ppm P response unlikely.

This range of the NaHCO_3 -soluble phosphorus level is slightly wider than the one originally proposed by Olsen et al. (86) but generally agrees with the one proposed by Olson et al. for use with both acid and calcareous soils of Nebraska (87).

The calibration of the NaHCO_3 -soluble phosphorus in term of phosphorus fertilizer requirement was also prepared and is presented in Table 22. This fertilizer requirement table, regardless of the restriction in its usefulness, can be used as a general guide for the interpretation of the soil test values. The interpretation will be nearly accurate if the results are applied under the climatic and soil conditions under which the correlations were made.

(2) Distribution and Availability
of Various Forms of P in Aiken Soils

The studies of the distribution of various forms of inorganic soil phosphorus by fractionation methods and their relative availability of these fractions to plant have been done by several workers (71, 141). The method of phosphorus fractionation is, of course, empirical since there is no rigid separation between the various phosphorus forms being determined. However, the method still has some merit as a tool in studying the fate of the natural and applied phosphorus in soils. Such a study can also give information regarding the fraction or fractions, removed by the various extractants, which can be made available to the plants or correlated with the amounts of soil phosphorus available to plants.

(2.1) Distribution of Various Fractions of Inorganic
Soil P

The results of the present study of the acid Aiken soils showed that the largest portion of the native phosphorus of these soils was in the form of Fe-phosphate. The amount of Al-phosphate and Ca-phosphate were about 20-45% and 13-17% of the amount of Fe-phosphate present respectively.

When the soluble phosphorus was added to the limed and unlimed acid Aiken soils under the laboratory condition both Al- and Fe-phosphate fractions were increased whereas no change in the Ca-phosphate form was observed. This can be explained from the fact that since the soils are acidic the amounts of active Fe and Al (referring to both Fe and Al in ions and sesquioxides forms) probably reacted completely with the applied phosphorus (39.3 ppm phosphorus). Some Ca-phosphate might have formed in the limed soils but it is felt that these newly formed Ca-phosphate compounds must be those of mono and dicalcium phosphates (73) which later react to form Fe- and Al-phosphates. Also these Ca-phosphates are soluble in 0.5N NH_4F and would escape detection of H_2SO_4 which was the last extraction. The results obtained seem to indicate that the addition of lime tends to depress the formation of Fe-phosphate and increase the formation of Al-phosphate. The soils which are high in fixing capacity (against extraction with Bray No. 1) tend to retain the largest proportion of applied phosphorus in the form of Fe-phosphate whereas the soils which are relatively low in fixing capacity retain larger parts of the added phosphorus in the form of Al-phosphate. These results are found to be in agreement with Laverty and McLean (71).

(2.2) Availability of Various Fractions

The first experiments reported in this section (Table 16) indicated that all three forms of inorganic soil phosphorus were correlated with the phosphorus contents of clover. The order of the degree of the relationship from high to low is Al-phosphate, Ca-phosphate and Fe-phosphate. In the case of oats only Al-phosphate and Ca-phosphate are significantly related to the phosphorus content of oats. The magnitude of the correlation coefficients for the relationship between various forms of phosphorus and phosphorus content of the plants are higher for clover than for oats. This suggests that clover can utilize phosphorus from these soils with greater efficiency than oats.

The significant relationship between Al-phosphate fraction and phosphorus uptake by the plant was also confirmed by the results obtained from the final part of the study in this section. In this study losses in the Al-phosphate fraction detected by the present method of fractionation was found to be significantly correlated with the amounts of phosphorus taken up by the plants (Table 17).

(3) Influence of Liming on the Yield and P Uptake

It was obvious that liming increased yield and phosphorus uptake of alfalfa. Highly significant relationships between soil pH and exch. Ca + Mg with the per cent of the maximum yield and amounts of the phosphorus uptake by alfalfa were obtained (Table 18). Sufficient liming of the acid Aiken soils alone have brought about the maximum yield and phosphorus uptake from many soils studied (Appendix 3, Figures 8 and 9). According to the linear regression equation for the relationship between exch. Ca + Mg vs. phosphorus uptake by alfalfa, both maximum phosphorus uptake and yield of alfalfa had been produced when the soils were limed to raise the exch. Ca + Mg to 14-15 me/100 g soil (approximately 65-75% base saturation. Only slightly lower levels of exch. Ca + Mg (13-14 me/100 g soil) produced the same maximum yield and phosphorus uptake when 180 lbs of P_2O_5/A were added in connection with liming. The increase in phosphorus uptake by alfalfa when lime was applied alone and the lack of response of the crop to added phosphorus alone or in combination with lime of these soils thus seems to indicate that the beneficial effect of liming was largely increasing the availability of the native soil phosphorus. This study did not give any indication, however, on how long this effect of

liming would be obtained. Since both total phosphorus content and per cent of organic matter of these soils are quite high the influence of liming on the native supply of soil phosphorus to alfalfa will probably remain for some time.

The increase in yield and phosphorus uptake of alfalfa from liming acid Aiken soils could have resulted from numerous effects of lime. There was evidence to indicate that liming increased the availability of molybdenum which is essential for the crop, especially for the symbiotic bacteria that fix nitrogen and consequently affect the utilization of phosphorus. This in turn might have increased the efficiency of the plant to absorb more phosphorus from the soil. Also, since alfalfa has better ability to take up phosphorus from the native sources and survive better in soils low in available phosphorus than most crops (81), therefore, the favorable conditions resulting from liming assured the alfalfa crop to take up enough phosphorus for its growth from these soils which apparently seems to be rather low in phosphorus for some other crops. The ability of alfalfa to take up phosphorus from soils has been reported to be associated with the high cation exchange capacity of the roots (38). Liming evidently promotes the growth and proliferation of root which resulted in a greater area of contact and absorption

of soil phosphorus.

The influence of liming on the availability of soil phosphorus derived from the mineralization of organic matter may be of significance. The organic matter contents of these soils are relatively high; the majority are greater than 6%. Previous studies of organic phosphorus of some western Oregon soils by Bertramson and Stephenson (8) indicate that the organic phosphorus content of Aiken and other "Red Hill" soils are the highest among soils of Willamette Valley. The increase in availability of organic phosphorus promoted by liming acid soils has been suggested to be the result of the soil microorganism mineralizing the organic matter and releasing phosphorus that can be made available to plants (56, 57). Certain metabolic products of microbiological decomposition could also form stable compounds with Fe and Al and could result in releasing fixed phosphate from Fe- and Al-phosphates and become available to plants (29, 125).

Liming increases the hydroxyl ion concentration which could both replace the phosphate ions bound by Fe and Al oxides and hydrolyze the Fe- and Al-phosphate compounds. As suggested by many workers (4, 135), phosphates released are available to plants and may be partly responsible for the increase in the availability of soil phosphorus in these soils.

Some evidence from the present study indicates that liming depressed the formation of Fe-phosphate which is less available to the plant but did not depress the formation of Al-phosphate which is more available to the plants.

The results of the present study indicated that no method could reliably determine the amounts of inorganic soil phosphorus that could be made more available by liming of these acid soils. In general, there were some tendencies for the amounts of phosphorus extracted by Bray No. 1 and Modified Olsen to decrease with the limed soils whereas Olsen reflected no effect from lime. At the present time no method has been developed to successfully evaluate the effect of liming on the phosphorus status of acid soils. That these chemical methods of evaluating soil phosphorus fail to reflect the increase in soil phosphorus caused by liming acid soils can be partly explained by the fact that the increase in availability of soil phosphorus to plants could have been either a direct or indirect effect of liming. Evidently no chemical method can account for all these effects. If the applied lime reacts with either native or applied phosphorus to form products which are readily available to the plants and at the same time readily soluble in the extracting solution, a good correlation could be expected between the biologically available

phosphorus and extractable phosphorus. However, if the effect of lime is primarily the promotion of root growth and other biological activities which in turn result in increasing yield and phosphorus uptake of the crop, it is rather impossible that the same chemical method can detect these effects.

VI. SUMMARY AND CONCLUSIONS

1. The primary objective of this research was to find a phosphorus soil test method which could best predict the phosphorus status of the Aiken and other closely related soils. The studies of the phosphorus fertility of these soils as reflected by the distribution and relative availability to the plants of the various forms of inorganic soil phosphorus were the second objective. The influences of liming on the availability of the native and applied soil phosphorus and the distribution of the formation of the applied phosphorus into various forms of phosphorus were also the subjects of secondary concern of the present studies.

2. The preliminary chemically evaluation of 11 different chemical phosphorus soil test methods have been made on the basis of sensitivity and extracting power of the methods. Bray No. 1, Modified Olsen No. 2 and Olsen methods were selected for correlation studies with the greenhouse and field data.

3. The data for the additional studies on the influence of NH_4F solution alone and in combination with 0.5M NaHCO_3 solution were presented and discussed. The results obtained can be summarized as follows:

3.1 As the concentration of NH_4F solution both alone and in combination with 0.5M NaHCO_3 was increased, the amounts of extractable phosphorus increased and tend to reach the maximum at concentration of $0.5\text{N NH}_4\text{F}$.

3.2 When the concentration of NH_4F was 0.1N or higher, the amounts of phosphorus extracted by $\text{NH}_4\text{F-NaHCO}_3$ mixture were greater than the combined amounts of phosphorus extracted by the NaHCO_3 solution and by the corresponding concentration of NH_4F alone. The reverse situation was true for the concentration of NH_4F at 0.05N or lower.

3.3 The amounts of phosphorus extracted by NH_4F solution alone or in combination with NaHCO_3 decreased with liming. The depressing effect of liming tends to diminish when the concentration of NH_4F was increased. The decrease in the amounts of extractable phosphorus due to liming was believed to be a result of the precipitation of fluoride by calcium forming insoluble CaF_2 and consequently decrease the extracting power of NH_4F . This same reason also explains the decrease in the amounts of extractable phosphorus from the limed soils by both Bray No. 1 and Modified Olsen methods.

4. Recognizing that only arbitrary and rather empirical separation of various forms of soil phosphorus could

be made, three different forms of inorganic soil phosphorus were determined by the method of Chang and Jackson with certain modification. The Fe-phosphate comprised the greatest portion, 63-80% of the total three forms, whereas Al-phosphate ranked second, 13.6-28.2% and Ca-phosphate the least, 4.8-8.6% of the total three fractions.

5. According to the fractionation method employed, when soluble phosphorus was applied to the limed and unlimed acid soils, under laboratory conditions, almost all of the applied phosphorus formed Al- and Fe-phosphates. Lime tends to increase the formation of Al-phosphate and depress the formation of Fe-phosphate.

6. Soil higher in fixing capacity (against Bray No. 1) retained the larger proportion of the applied phosphorus in Fe-phosphate form than in Al-phosphate form. The reverse is true for the soil lower in fixing capacity.

7. Under field conditions the addition of phosphorus fertilizer in connection with the lime resulted in the depression of the formation of Fe-phosphate and increased the formation of Al- and Ca-phosphates.

8. The "available" phosphorus removed by the three phosphorus soil test methods could be accounted for by the reduction in the Al- and Fe-phosphate forms. The NaHCO_3

solution was shown to remove considerable amounts of Fe- and Al-phosphates.

9. The study of the availability of various forms of inorganic soil phosphorus, indicated that Al-phosphate (fraction soluble in NH_4F) was the form that gave the closest relationship with phosphorus contents of the plants and was taken up by the plants in the largest quantity. Fe- and Ca-phosphates did show some relationship with phosphorus contents of plants but the data were not conclusive. However, it could be concluded that both forms were not as important as Al-phosphate so far as the availability to the plants was concerned.

10. The correlations between various chemical phosphorus soil test methods with field and greenhouse data were presented and discussed. They are summarized briefly as follows:

10.1 For greenhouse results, no method was proved to be significantly superior to the other. The correlation coefficients obtained were high for all methods and the order from higher to lower coefficients was Olsen, Bray No. 1 and Modified Olsen.

The partial and multiple correlation analyses did not improve the correlation coefficient obtained except in the

case of Modified Olsen. However, the correlation analysis, when stratified according to the pH range, greatly improved the correlation coefficients of the higher stratification (pH 5.8-6.8) but slightly poorer correlation coefficients were obtained for the lower stratification (pH 4.8-5.7).

Clover was shown to be a better indicator crop for the study of phosphorus uptake than oats since all the correlation coefficients obtained for the relationship between phosphorus content vs. soil test values were much higher than those for oats.

10.2 For field results, the correlation coefficients obtained were much smaller than those obtained from the greenhouse. The order of the methods according to the size of the coefficients from the largest is Olsen, Bray No. 1 and Modified Olsen.

The relationship between soil pH and $\text{exch. Ca} + \text{Mg}$ with all the field data were much higher than any of the phosphorus soil test methods. When the partial and multiple correlation analyses were carried out, greatly improved correlation coefficients were obtained and both phosphorus soil test and soil pH were proved to be equally important in predicting the phosphorus status of the soils. Again no phosphorus soil test method proved to be significantly superior to the other but the Olsen method was the

method least affected by the soil pH and exch. Ca + Mg; it was preferred to the other methods.

11. Liming of Aiken soils increase yield and phosphorus uptake of alfalfa. Therefore, the efficient interpretation of the soil test results required the consideration of the soil pH.

12. A calibration table for the various soil test methods according to various soil pH ranges was presented.

13. The Olsen method was recommended for routine phosphorus testing program of Aiken and other closely related "Red Hill" soils. A calibration curve and phosphorus fertilizer requirement table for use as a general guide in the interpretation of the Olsen soil test value was proposed.

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APPENDIX 1

Profile Description of a Typical Aiken Soil

Aiken silty clay loam (Reddish Brown Lateritic Soil, locally called Reddish Brown Latosol.)

Location: NE 1/4, section 10, T. 14S, R. 1W. Bonkowski farm, Linn County, Oregon.

Description by: E. G. Knox, July 26, 1957 in connection with Oregon Agricultural Experiment Station Project 331.

Site: Soil from basalt, 10% east slope.

<u>Horizon</u>	<u>Depth</u> (in.)	<u>Description</u>
A _p	0-6	Dark reddish brown (5YR 3.5/3) dry, dark reddish brown (5YR 3/2) moist; silty clay loam; weak, very fine sub-angular blocky structure; hard, plastic, and sticky; few fine soft shot; abrupt, smooth lower boundary.
B ₁	6-15	Dark reddish brown (5YR 2.5/3) moist; silty clay; moderate, very fine sub-angular blocky breaking to moderate, very fine granular structure; slightly hard, friable, very plastic, very sticky, very thin nearly continuous clay flows; clear, smooth lower boundary.
B ₂₁	15-26	Dark reddish brown (4YR 3/4) moist; silty clay; weak, medium and fine sub-angular blocky breaking to moderate, very fine sub-angular blocky structure; friable, very plastic, and very sticky; thin, nearly continuous clay flows; clear, smooth lower boundary.
B ₂₂	26-40	Dark reddish brown (4YR 3/4) moist; silty clay; moderate, coarse sub-angular blocky breaking to moderate, fine angular blocky structure; firm, very plastic, very sticky; common, large black MnO ₂ coatings; thin, continuous clay flows.

Appendix 2
 Characterization of the Typical Aiken Soil (Bonkowski)

Horizon	Depth Inches	Organic ^{1/} Matter %	Mechanical Analysis ^{2/}			CEC ^{3/} me/100g	Exch. Ca, ^{3/} Mg, K, & Na me/100g	pH 1:1	P ^{4/} ppm
			Clay %	Silt %	Sand %				
Ap	0-6	6.11	63	28	9	23.9	9.4	5.3	13.0
B ₁	6-15	4.33	66	26	8	24.0	9.3	5.4	6.2
B ₂₁	15-26	2.82	70	23	7	21.4	8.8	5.2	8.5
B ₂₂	26-40	0.94	75	20	5	19.8	8.1	5.3	14.0
Deep	52-72	0.29	76	19	5	21.9	7.0	5.3	--

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^{3/} Schollenberger, C. J. and R. H. Simon. Determination of exchange capacity and exchangeable bases in soils - ammonium acetate method. Soil Science 59:13-24. 1945.

^{4/} Olsen, S. R. et al. Estimation of available phosphorus in soils by extracting with sodium bicarbonate. Washington, D.C., 1954. 19 p. (U.S. Department of Agriculture. Circular 939)

APPENDIX 3

Field, Greenhouse and Soil Analysis Data Employed in Various Phases of this Study.

Expt. No.	Rep.	Trt.	Field Data				Greenhouse Data							P Soil Tests, ppm P				
			Yield lbs/A	First Cutting			2 Cuttings % max. yield	Oats			Clover			Exch. Ca+Mg	Soil pH	Mod. Olsen	Bray No. I	Olsen
				% max. yield	% P	lbs P/A		mgP/75 pls.	% P	mgP/ pot	mgP/40 pls.	% P	mgP/ pot					
105	1	10	1574	289	18	292	966	505	28	505	269	11	249	86	60	244	235	55
105	2	10	4632	849	18	824	900	515	22	508	242	9	236	92	61	183	90	49
105	3	10	4442	814	20	897	760	502	23	475	287	13	287	105	64	202	125	50
105	1	11	4502	825	20	900	849	712	36	598	299	10	262	103	63	244	176	24
105	2	11	4042	741	21	833	1025	557	24	550	279	11	272	108	64	169	121	28
105	3	11	4702	862	16	1290	875	557	24	483	218	11	229	100	62	220	99	47
105	1	13	5379	986	25	1366	984	622	32	555	263	10	283	89	61	295	191	31
105	2	13	5622	1031	24	1249	1022	637	27	626	254	11	248	100	64	316	214	32
105	3	13	5357	982	21	1103	993	588	26	598	287	13	316	100	61	261	130	33
105	1	16	5200	953	23	1191	878	607	32	502	305	11	236	89	62	258	148	35
105	2	16	4599	843	29	1315	879	743	33	744	211	14	379	119	63	432	376	35
105	3	16	5368	984	24	1278	984	631	27	580	291	13	321	116	63	310	191	35
105	1	20	4437	814	20	905	818	536	29	529	219	9	219	97	63	175	91	35
105	2	20	5324	976	19	1038	1000	525	25	511	257	11	250	114	65	159	119	37
105	3	20	4946	907	17	831	884	556	23	534	235	11	253	141	66	179	110	33
105	1	21	5471	1003	30	1619	876	558	30	483	232	10	215	97	65	169	95	50
105	2	21	4643	851	19	873	781	533	23	526	278	10	215	136	66	175	178	64
105	3	21	4540	832	16	726	935	530	23	523	194	12	209	108	65	155	95	63
105	1	23	4745	870	23	1110	882	590	31	618	267	9	254	103	64	266	180	95
105	2	23	4989	914	25	1257	913	651	27	625	309	12	302	114	64	311	222	95
105	3	23	4745	870	20	973	914	567	26	567	231	12	255	115	63	224	157	74
105	1	26	5379	986	27	1463	957	594	31	451	243	10	268	81	61	320	220	66
105	2	26	4805	881	22	1081	931	640	29	648	337	13	321	125	66	310	250	66
105	3	26	4875	893	26	1277	1003	654	28	637	322	13	330	103	64	292	219	64

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Expt-Rep-Trt No.	Field Data				Greenhouse Data							P Soil Tests, ppm P				
	Yield lbs/A	First Cutting			2 Cuttings % max yield	Oats		Cloyar			Exch. Soil		Mod. Olsen	Bray No. I	Olsen	
		% max yield	% P	lbs P/A		mgP/75 pls	% P	mgP/pot	mgP/40 Pls	% P	mgP/pot	Ca+Mg				pH
10R 1 00	3241	786	24	762	683	464	29	464	272	11	286	99	59	172	140	64
10R 2 00	1255	304	29	359	323	405	21	367	193	10	198	87	56	133	118	43
10R 3 00	1385	336	29	396	316	509	26	509	261	10	261	83	56	215	169	53
10R 1 02	1190	288	25	292	260	425	28	414	256	11	275	75	54	224	202	56
10R 2 02	1542	374	27	423	381	504	25	478	214	10	203	89	56	225	191	62
10R 3 02	2917	707	25	741	682	462	25	462	221	10	232	90	56	180	176	49
10R 1 11	3144	762	23	723	688	506	32	486	296	12	318	112	59	193	144	56
10R 2 11	3433	841	27	933	811	488	23	475	189	8	180	102	60	145	165	47
10R 3 11	2955	719	21	623	647	527	27	506	229	11	252	109	58	136	140	42
10P 1 12	3447	835	28	976	889	471	31	371	261	12	300	107	61	197	224	79
10P 2 12	3771	914	29	1075	1012	504	24	471	253	11	260	117	60	215	239	68
10P 3 12	3863	936	26	1016	846	580	33	555	219	10	230	128	59	136	169	53
10P 1 13	4145	1005	27	1119	835	453	30	359	342	12	359	107	60	256	275	73
10R 3 13	4096	993	29	1184	914	496	27	463	279	11	279	128	61	215	244	68
10R 1 20	3387	821	24	826	716	435	34	394	226	10	221	117	62	117	154	49
10R 2 13	3712	900	27	987	875	568	28	568	197	9	192	135	63	163	187	64
10R 2 20	2976	721	25	747	801	501	24	454	205	9	205	117	62	141	151	56
10R 3 20	3095	750	26	789	713	550	28	542	200	9	211	139	63	150	161	51
10R 1 21	3268	792	24	778	675	469	30	456	234	10	257	146	64	172	191	60
10P 2 21	3701	897	26	955	815	447	22	364	207	9	192	137	65	153	169	56
10R 3 21	3512	851	24	850	694	580	26	412	226	11	249	137	61	163	199	60
10R 1 22	4350	1054	29	1275	925	473	27	322	306	10	275	133	62	240	265	98
10R 2 22	4139	1003	29	1200	994	553	27	539	205	9	195	130	64	163	212	76
10R 3 22	3734	905	28	1031	803	531	26	517	247	11	272	117	60	163	140	60
10R 1 31	3907	947	28	1082	948	409	26	251	245	10	258	137	65	210	234	66
10R 2 31	3490	846	27	932	896	530	26	516	189	10	199	165	66	145	154	58
10R 3 31	3945	956	24	939	809	512	27	505	230	11	253	147	63	133	125	45
10P 1 33	4010	972	30	1183	944	464	28	396	272	10	238	154	66	232	244	73
10P 2 33	3731	905	34	1270	1047	513	25	465	265	10	239	146	65	193	212	76
10R 3 33	4639	1122	28	1296	1008	592	24	553	229	10	252	211	67	197	161	92

APPENDIX 3
Field, Greenhouse and Soil Analysis Data Employed in Various Phases
of this Study.

Expt- No	Rep- Trt.	Field Data				Greenhouse Data							P Soil Tests, ppm P		
		Yield lbs/A	% max- yield	First Cutting		2 Cuttings % max- yield	Oats		Clover		Exch. Soil		Mod- Olsen	Bray No-1	Olsen
				% P	lbs P/A		mgP/ 75 pls	% P	mgP/ pot	mgP/ 40 pls	% P	mgP/ pot			
502	1	00													
502	2	00													
502	3	00													
502	1	02	801	161	30	244									
502	2	02													
502	3	02													
502	1	11	2186	440	23	501									
502	2	11	2614	527	21	541									
502	3	11	1315	265	23	306									
502	1	12	4464	899	28	1259									
502	2	12	3387	682	23	864									
502	3	12	3441	693	25	864									
502	1	13	4778	963	32	1519									
502	2	13	4724	952	33	1540									
502	3	13	4242	855	32	1366									
502	1	20	1450	292	19	271									
502	2	20	1163	234	18	209									
502	3	20	557	112	16	86									
502	1	21	2987	602	22	651									
502	2	21	2770	558	22	607									
502	3	21	2240	451	24	533									
502	1	22	3880	782	26	1024									
502	2	22	3734	752	26	971									
502	3	22	4453	897	27	1180									
502	1	31	4561	919	26	1177									
502	2	31	4118	830	23	947									
502	3	31	2067	416	25	511									
502	1	33	5443	1097	33	1780									
502	2	33	4810	969	29	1405									
502	3	33	4632	933	30	1376									

APPENDIX 3
Field, Greenhouse and Soil Analysis Data Employed in Various Phases
of this Study.

Expt-Rep-Trt No-	Field Data					Greenhouse Data						P Soil Tests, ppm P				
	Yield lbs/A	First Cutting		2 Cuttings % max- yield	P/A	Oats		Clover		Exch. Soil		Mod. Olsen	Bray No.1	Olsen		
		% max- yield	% P			mgP/ 75 pls- P	% P	mgP/ 40 pls- P	% P	mgP/ Ca+Mg	pH					
506 1 00	3474	805	30	1042	796	535	28	514	378	13	359	119	57	620	610	119
506 2 00	4323	1002	30	1314	913	623	29	613	476	12	333	76	52	1000	750	164
506 3 00	3111	721	29	915	813	647	37	647	444	17	466	66	51	917	765	152
506 1 02	3717	861	34	1256	857	574	32	505	615	16	462	73	54	1160	955	170
506 2 02	4578	1061	35	1602	1017	752	35	682	693	18	520	81	53	1350	1250	256
506 3 02	4653	1078	35	1629	960	758	38	728	419	16	399	86	53	1170	925	193
506 1 11	4286	993	34	1453	986	531	28	517	389	12	341	71	54	790	594	123
506 2 11	4150	952	35	1448	856	584	27	561	440	13	363	78	54	850	625	141
506 3 11	3360	779	29	984	754	655	37	646	527	16	462	94	55	620	515	109
506 1 12	3869	896	36	1393	1000	566	32	559	401	14	361	99	56	768	630	136
506 2 12	3463	802	32	1115	794	682	33	664	516	18	426	113	57	865	776	175
506 3 12	3988	924	37	1484	928	714	40	733	557	17	418	102	56	1110	1015	202
506 1 13	3468	804	37	1280	900	590	33	616	531	17	584	70	52	1460	1190	217
506 2 13	4085	946	38	1569	952	992	45	836	827	19	579	121	58	1200	1190	236
506 3 13	4756	1102	36	1717	1032	999	47	498	535	20	589	107	57	1200	1140	238
506 1 20	4156	963	35	1442	989	547	27	503	337	12	345	81	54	716	685	117
506 2 20	4183	969	34	1405	971	632	27	615	471	13	342	132	59	620	716	134
506 3 20	4464	1034	35	1545	990	707	39	709	450	18	473	119	57	914	795	162
506 1 21	3847	891	35	1362	892	618	32	610	405	13	355	127	59	745	655	162
506 2 21	3977	921	34	1352	852	712	32	655	618	17	402	116	58	905	685	183
506 3 21	3230	748	37	1185	830	776	42	755	444	16	422	140	61	670	585	140
506 1 22	3811	899	35	1350	923	667	32	536	365	13	365	91	56	845	716	136
506 2 22	3839	896	38	1455	900	656	35	542	500	15	375	148	62	670	735	179
506 3 22	3918	908	36	1418	970	821	39	810	550	17	482	127	53	970	890	187
506 1 31	4426	1026	36	1571	885	566	32	513	362	13	353	135	61	620	570	128
506 2 31	3523	816	33	1233	782	679	33	615	669	16	468	168	63	613	540	159
506 3 31	4221	978	33	1393	961	655	35	637	454	16	398	148	62	514	422	104
506 1 33	4058	940	35	1436	985	687	37	577	502	17	477	107	58	935	920	157
506 2 33	3826	886	38	1462	842	870	37	739	561	19	435	165	63	925	745	134
506 3 33	4718	1093	38	1812	1174	999	52	999	596	20	552	182	63	895	930	200

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Expt-Rep-Trt. No.	Field Data					Greenhouse Data						Exch. Soil		P Soil Tests, ppm P		
	Yield lbs/A	First Cutting			2 Cuttings % max- yield	Oats		Cloyer		mgP/ pot	Ca+Mg pH	Mod- Olsen	Bray No-1	Olsen		
		% max- yield	% P	lbs P/A		mgP/ 75 pls.	% P	mgP/ pot	mgP/ 40 pls.						% P	
508 1 00						510	28	496	316	11	309	58	48	789	655	126
508 2 00						583	33	544	358	14	322	56	49	870	755	141
508 3 00						747	40	697	462	15	462	34	47	1260	1160	210
508 1 02	1139	254	36	413	164	588	29	511	591	19	621	44	49	1040	815	181
508 2 02						723	40	723	469	17	458	47	46	1230	1090	248
508 3 02						776	43	621	590	19	561	38	49	1230	1001	246
508 1 11	4443	993	32	1413	978	569	31	546	534	14	508	83	54	664	640	141
508 2 11	4630	1034	36	1653	915	626	36	526	497	17	447	91	55	776	815	160
508 3 11	4354	973	34	1476	1024	722	38	635	599	17	599	110	57	775	735	170
508 1 12	4057	906	37	1517	928	641	31	624	575	16	575	96	55	700	695	187
508 2 12	3759	840	38	1428	874	826	40	595	647	20	583	99	57	836	820	203
508 3 12	5053	1129	37	1849	1040	723	39	665	693	19	624	91	55	1010	845	206
508 1 13	4089	913	39	1582	996	884	42	872	626	18	657	140	57	920	960	246
508 2 13	3752	838	38	1437	884	759	43	688	748	21	655	130	59	1030	955	234
508 3 13	4093	914	39	1580	975	847	46	790	721	20	758	78	52	1400	1170	302
508 1 20	4026	899	34	1385	876	723	36	714	407	14	447	162	65	565	535	143
508 2 20	4898	1094	35	1734	1091	649	32	640	615	17	539	110	57	740	700	164
508 3 20	4169	931	32	1317	1002	757	37	646	543	19	570	124	59	648	700	179
508 1 21	3342	747	33	1116	878	614	31	565	539	17	553	138	61	570	670	149
508 2 21	5122	1144	38	1931	1255	774	36	330	714	22	768	154	42	628	710	216
508 3 21	3087	690	34	1062	867	944	42	579	847	20	868	148	60	1060	875	309
508 1 22	3690	824	34	1236	922	659	32	615	581	16	537	124	57	672	685	155
508 2 22	4748	1061	36	1686	1017	605	36	500	623	20	545	94	57	735	785	179
508 3 22	4356	973	34	1481	976	719	46	624	630	21	693	118	58	920	825	216
508 1 31	4281	956	34	1456	982	663	32	654	506	16	544	165	62	625	605	168
508 2 31	3846	859	34	1304	924	778	38	612	379	14	388	190	64	710	770	198
508 3 31	5034	1125	37	1847	1069	958	48	664	684	19	684	135	60	953	795	244
508 1 33	5165	1154	38	1952	1056	767	38	737	683	22	751	157	61	776	755	236
508 2 33	4568	1020	40	1827	949	796	40	531	765	22	688	113	59	877	900	210
508 3 33	3431	796	39	1357	864	957	54	817	634	18	634	170	64	830	940	278

APPENDIX 3
Field, Greenhouse and Soil Analysis Data Employed in Various Phases
of this Study.

Expt. No.	Rep.	Trt.	Field Data				Greenhouse Data							P Soil Tests, ppm P					
			Yield lbs/A	% max. yield	% P	lbs P/A	2 Cuttings % max. yield	Oats		Clover			Exch. Soil Ca+Mg pH	Mod. Olsen	Bray No.1	Olsen			
								mgP/75 pls.	% P	mgP/40 pls.	% P	mgP/ pot							
510	1	00	1878	385	24	44.3	368	451	31	470	285	11	313	75	54	300	335	34	
510	2	00	4469	917	26	116.2	859	631	29	623	302	11	324	99	56	232	191	30	
510	3	00	2576	529	27	69.0	505	569	28	599	401	14	421	80	54	367	290	123	
510	1	02	2013	413	27	82.3	326	580	31	518	461	14	484	83	55	354	296	115	
510	2	02	3328	683	26	85.2	593	760	31	634	323	11	323	87	56	295	303	93	
510	3	02	1385	284	26	35.5	243	679	32	679	305	13	305	77	54	322	226	109	
510	1	11	4264	875	30	126.9	914	607	33	534	396	12	386	115	61	266	216	109	
510	2	11	3966	814	28	110.3	769	639	30	622	278	10	292	114	63	215	199	96	
510	3	11	4020	825	27	108.1	845	706	31	697	303	13	319	109	61	240	208	131	
510	1	12	4096	840	24	96.7	823	638	34	496	432	13	443	97	60	308	250	117	
510	2	12	4805	986	30	143.2	857	755	32	755	362	11	362	127	63	290	268	143	
510	3	12	4356	894	28	120.2	933	644	29	601	331	14	389	92	56	340	356	117	
510	1	13	3455	717	30	103.8	826	660	34	447	401	13	431	89	58	336	296	130	
510	2	13	4534	928	27	120.8	925	796	39	785	400	12	350	97	59	388	350	132	
510	3	13	4486	920	26	118.0	914	798	33	692	376	15	395	89	57	320	266	142	
510	1	20	5043	1035	32	160.4	1026	495	28	488	366	11	366	112	61	302	232	113	
510	2	20	4448	913	27	121.4	900	629	27	621	249	9	233	130	63	240	171	98	
510	3	20	4129	847	26	107.4	879	717	33	669	299	13	351	151	66	308	268	130	
510	1	21	4978	1021	34	166.8	1033	560	30	515	380	12	380	113	61	260	227	113	
510	2	21	4237	869	29	124.1	924	728	33	728	290	11	297	114	62	235	227	107	
510	3	21	5400	1108	31	168.5	1043	690	30	662	353	13	362	157	68	212	168	122	
510	1	22	4394	902	34	150.7	931	596	33	596	381	12	419	117	63	325	250	130	
510	2	22	3998	818	31	125.2	888	784	35	679	381	12	353	114	62	348	376	132	
510	3	22	3615	742	25	90.7	782	741	30	494	332	13	366	137	65	320	250	130	
510	1	31	4480	919	33	148.3	994	594	33	555	368	11	350	127	62	220	223	98	
510	2	31	4291	880	29	120.2	994	711	29	607	320	11	336	162	67	276	199	104	
510	3	31	4405	904	31	135.7	822	652	34	652	359	14	377	154	67	235	246	140	
510	1	33	5460	1120	35	190.6	1084	725	35	638	430	14	452	119	62	290	342	130	
510	2	33	4145	850	30	124.4	871	809	36	776	357	12	357	135	65	310	240	128	
510	3	33	3896	799	30	115.7	878	970	36	944	400	15	470	163	66	438	404	228	
			Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ

APPENDIX 3
Field, Greenhouse and Soil Analysis Data Employed in Various Phases
of this Study.

Expt No	Rep	Trt.	Field Data				Greenhouse Data						P Soil Tests, ppm P					
			Yield lbs/A	First Cutting		2 Cuttings % max. yield	Oats		Clover		Exch. Soil		Mod. Olsen	Bray No.1	Olsen			
				% max. yield	% P		lbs P/A	mgP/ 75 pls.	% P	mgP/ pot	mgP/ 40 pls	% P				mgP/ pot	Ca+Mg	pH
512	1	00	1012	183	26	264	168	558	33	469	349	12	384	102	52	334	489	1330
512	2	00	1677	304	27	444	278	617	28	609	363	13	372	96	52	450	560	1330
512	3	00	1499	272	27	400	281	698	31	670	344	14	370	68	52	450	510	1430
512	1	02	2056	373	24	485	380	584	34	584	319	11	351	102	53	430	505	1445
512	2	02	2143	388	26	811	360	597	31	597	369	13	347	70	53	410	335	1330
512	3	02	2797	507	27	752	481	704	35	704	433	14	422	68	53	500	465	1330
512	1	11	6022	1091	29	1752	1000	664	37	611	399	13	399	104	57	394	580	1351
512	2	11	5346	969	28	1497	888	625	34	625	389	12	380	106	59	397	610	1324
512	3	11	5189	940	28	1453	939	694	35	694	433	14	422	99	57	402	675	1333
512	1	12	5027	911	27	1332	914	619	36	570	433	13	411	111	58	427	615	166
512	2	12	4773	865	26	1255	908	586	31	586	408	13	358	102	58	410	605	1330
512	3	12	4783	867	28	1358	872	669	33	642	405	14	405	96	57	520	590	131
512	1	13	5021	910	28	1406	875	744	41	744	469	14	516	196	59	492	675	133
512	2	13	5806	1052	29	1678	1085	696	36	687	434	14	380	102	58	524	615	1300
512	3	13	5103	925	31	1577	971	682	35	682	481	15	529	104	60	500	715	134
512	1	20	5763	1042	31	1781	976	750	41	689	383	12	412	163	63	382	472	136
512	2	20	5617	1018	28	1584	1012	660	32	642	325	12	333	121	61	370	557	1330
512	3	20	5076	920	30	1543	1001	632	31	624	436	14	469	121	64	424	635	2000
512	1	21	5990	1085	25	1503	1069	666	41	480	425	13	447	163	63	387	560	151
512	2	21	5005	907	28	1376	937	624	32	608	468	13	398	116	61	375	543	147
512	3	21	5511	999	28	1549	993	683	33	656	414	13	424	114	62	430	650	191
512	1	22	5038	913	29	1481	862	634	33	451	400	11	410	231	62	340	565	143
512	2	22	5189	940	27	1417	931	691	35	682	519	14	402	134	62	366	573	1507
512	3	22	4610	835	32	1489	939	758	37	740	516	16	478	137	64	492	735	230
512	1	31	5400	978	27	1431	951	689	38	542	419	12	419	237	65	340	543	160
512	2	31	4172	756	30	1208	804	735	36	725	394	13	434	164	66	416	635	181
512	3	31	4718	855	28	1330	823	616	31	567	380	13	380	82	54	565	655	162
512	1	33	4010	727	30	1187	741	692	41	498	567	15	524	179	64	474	735	215
512	2	33	3874	702	31	1216	816	710	35	663	406	14	446	147	65	424	615	193
512	3	33	5341	968	30	1592	933	812	37	801	522	17	580	169	67	468	690	232

APPENDIX 3
Field, Greenhouse and Soil Analysis Data Employed in Various Phases
of this Study.

Expt No.	Rep	Trt	Field Data				Greenhouse Data						P Soil Tests, ppm P					
			First Cutting				2 Cuttings	Oats			Clover			Exch. Soil		Mod. Olsen	Bray No. 1	Olsen
			Yield lbs/A	% max. yield	% P	lbs P/A		% max. yield	mgP/75 pls.	% P	mgP/pot	mgP/40 pls.	% P	mgP/pot	Ca+Mg			
514	1	00					497	33	500	268	9	262	60	51	423	320	66	
514	2	00					541	28	504	207	10	202	42	49	625	472	79	
514	3	00					532	30	447	345	14	362	39	49	935	580	117	
514	1	02					527	31	486	282	10	289	60	51	488	380	78	
514	2	02					496	26	483	261	12	275	39	50	942	655	143	
514	3	02					535	28	527	306	13	329	44	49	765	580	104	
514	1	11	4610	1223	21	977	833	552	34	541	261	9	274	96	54	407	350	62
514	2	11	2419	642	15	351	437	534	27	434	260	11	286	76	52	675	505	94
514	3	11	1245	330	18	222	225	517	24	379	319	12	335	64	57	840	635	109
514	1	12	2770	735	24	656	719	541	33	559	258	9	278	89	53	459	350	62
514	2	12	2960	786	27	796	535	589	31	582	337	11	269	69	53	827	650	129
514	3	12	2170	576	26	566	775	581	31	566	312	11	336	69	57	800	605	119
514	1	13	1894	503	26	498	506	629	36	571	351	11	334	89	54	506	480	88
514	2	13	2895	768	28	802	523	553	31	567	291	12	342	74	53	932	745	132
514	3	13	2684	712	28	746	485	600	33	584	331	12	365	69	57	840	690	130
514	1	20	2359	626	21	500	891	539	29	492	288	9	266	94	56	413	338	60
514	2	20	3609	958	28	992	652	538	26	459	295	11	295	110	56	526	428	79
514	3	20	2310	613	25	573	417	544	28	531	294	11	309	86	55	675	510	98
514	1	21	1234	328	28	339	223	492	31	548	277	8	263	104	55	423	350	62
514	2	21	3728	989	28	1025	1029	542	29	528	280	11	308	110	56	617	494	92
514	3	21	4096	1087	28	1126	1150	620	30	595	321	12	345	78	54	867	710	124
514	1	22	1650	438	24	403	435	554	34	558	295	10	317	110	57	431	422	70
514	2	22	3870	1027	32	1242	973	534	27	547	299	12	322	104	56	530	450	76
514	3	22	3279	870	30	971	973	573	31	573	423	14	380	81	54	892	735	122
514	1	31	2024	537	26	528	612	473	28	456	224	9	241	148	60	321	325	62
514	2	31	4166	1106	29	1225	1053	540	29	512	297	12	289	99	56	604	472	92
514	3	31	3853	1023	32	1233	696	662	32	521	332	13	357	123	58	750	705	117
514	1	33	3634	957	30	1063	979	476	30	466	317	11	301	135	58	407	380	76
514	2	33	4334	1150	34	1452	1111	557	30	549	303	12	295	115	57	552	484	85
514	3	33	3366	893	29	990	909	538	29	517	361	13	397	100	58	765	650	115

APPENDIX 3
Field, Greenhouse and Soil Analysis Data Employed in Various Phases
of this Study.

Expt. Rep. Trt. No.	Field Data					Greenhouse Data						P Soil Tests, ppm P				
	Yield lbs/A	% max. yield	Cutting		2 Cuttings % max. yield	Oats		Clover		Exch. Soil Ca+Mg pH	Mod. Olsen	Bray No. I	Olsen			
			% P	lbs P/A		mgP/75 pls.	% P	mgP/40 pls.	% P					mgP/pot		
516 1 00	563	100	25	140	80	659	40	659	468	16	562	79	50	924	810	139
516 2 00	514	91	30	153	94	671	33	662	377	14	405	76	52	1048	775	246
516 3 00	574	102	26	147	81	682	35	673	411	17	452	88	53	1059	870	194
516 1 02	3533	627	26	915	574	612	36	504	571	16	514	91	52	895	845	189
516 2 02	760	135	27	202	120	655	31	646	482	16	507	83	53	1006	860	204
516 3 02	1575	279	27	432	207	828	39	828	542	19	569	88	52	1108	1090	240
516 1 11	5032	893	26	1298	856	518	36	560	515	16	515	115	56	803	750	174
516 2 11	4583	813	26	1182	821	736	37	726	449	15	494	117	55	1102	885	217
516 3 11	4702	834	24	1138	778	683	34	674	507	17	557	117	57	1005	830	228
516 1 12	4881	866	26	1250	888	686	39	640	593	16	563	96	53	1002	925	215
516 2 12	6840	1213	28	1838	1125	793	41	793	543	17	489	120	57	975	1020	232
516 3 12	5111	921	26	1496	987	680	35	680	497	18	534	145	58	970	985	252
516 1 13	5341	947	25	1346	910	718	42	708	539	16	566	109	53	1006	1090	220
516 2 13	5384	955	29	1400	926	718	35	708	525	17	512	106	55	1102	975	242
516 3 13	5027	892	27	1332	805	613	31	605	499	18	549	106	56	1007	965	240
516 1 20	5563	987	26	1419	973	619	36	578	614	16	476	131	58	913	790	192
516 2 20	4594	815	23	1034	814	573	29	566	438	15	438	120	59	860	757	191
516 3 20	6417	1138	25	1604	997	693	34	666	550	18	578	122	57	925	870	228
516 1 21	5103	905	25	1291	927	682	41	608	557	16	571	120	57	890	840	128
516 2 21	5265	934	27	1406	972	743	36	723	546	17	532	142	59	1004	1010	243
516 3 21	5146	913	27	1369	924	713	36	713	599	18	554	158	61	900	890	230
516 1 22	5974	1060	24	1452	1012	691	40	626	548	17	562	136	59	834	710	189
516 2 22	5952	1056	27	1589	1073	717	38	708	440	16	437	136	59	815	717	194
516 3 22	4994	886	23	1159	872	557	29	549	507	19	521	117	57	1003	930	232
516 1 31	4951	878	25	1258	951	741	46	741	593	18	593	133	58	913	815	200
516 2 31	4897	869	25	1229	960	688	34	679	539	18	566	145	60	1002	945	232
516 3 31	5871	1042	26	1532	1041	711	35	711	566	18	566	166	62	940	915	232
516 1 33	5676	1007	27	1533	1063	629	37	604	759	19	626	155	61	905	855	238
516 2 33	4534	804	28	1274	878	712	34	684	576	18	490	166	62	830	836	236
516 3 33	5530	981	26	1421	957	782	38	760	573	19	559	166	62	995	975	250

APPENDIX 3
Field, Greenhouse and Soil Analysis Data Employed in Various Phases
of this Study.

Expt. No.	Rep.	Trt.	Field Data				2 Cuttings % max. yield	Greenhouse Data					Exch. Soil		P Soil Tests, ppm P			
			Yield lbs/A	% max. yield	% P	lbs P/A		Oats		Clover			Ca+Mg	pH	Mod. Olsen	Bray No.1	Olsen	
								mgP/ 75 pls.	% P	mg P/ pot	mg P/ 40 pls.	% P						mgP/ pot
51R	1	00					493	29	427	282	100	303	79	503	466	434	100	
51R	2	00					551	29	551	312	128	320	84	503	490	478	113	
51R	3	00					559	29	544	371	15	436	76	502	729	524	130	
51R	1	02	1292	229	23	302	155	542	30	513	366	12	357	86	503	610	493	113
51R	2	02	836	148	26	214	100	547	31	510	341	13	375	79	502	685	543	125
51R	3	02						683	33	647	415	15	446	76	51	880	636	145
51R	1	11	4960	879	23	1156	813	426	26	408	348	12	348	110	55	525	406	98
51R	2	11	4865	862	22	1075	871	476	23	445	327	13	360	100	55	535	505	115
51R	3	11	4788	848	24	1125	895	669	32	660	439	15	428	100	54	821	715	149
51R	1	12	4717	836	25	1179	796	499	30	492	390	13	429	100	56	510	446	100
51R	2	12	4474	793	24	1060	824	586	35	578	459	14	436	117	57	615	560	132
51R	3	12	4047	717	25	1024	786	498	27	518	414	14	404	96	56	655	580	128
51R	1	13	4622	819	25	1142	828	704	39	479	380	13	418	100	55	630	550	111
51R	2	13	5179	918	23	1202	933	618	33	577	360	13	387	115	57	610	643	138
51R	3	13	4498	797	26	1183	811	621	33	588	492	17	529	110	56	550	542	132
51R	1	20	4474	793	22	1002	783	445	26	427	370	12	388	138	60	412	430	96
51R	2	20	4527	802	22	996	790	498	27	445	360	13	396	112	57	490	494	111
51R	3	20	4433	785	23	1037	969	694	35	666	460	17	540	128	60	642	610	156
51R	1	21	5639	1003	24	1364	1007	614	35	524	346	14	408	138	60	498	483	109
51R	2	21	6074	1076	24	1440	1104	521	28	514	387	15	387	130	60	517	540	122
51R	3	21	5197	921	24	1252	890	588	31	572	509	16	522	148	61	575	486	134
51R	1	22	4338	769	25	1085	799	652	36	626	435	14	478	140	61	465	505	109
51R	2	22	4296	761	24	1044	808	649	34	658	501	15	400	146	60	590	540	134
51R	3	22	6400	1134	26	1683	1117	687	34	650	486	16	462	122	60	665	544	141
51R	1	31	4225	749	24	1018	840	678	38	642	414	14	445	162	62	525	446	117
51R	2	31	5108	905	24	1216	955	612	32	620	481	17	500	162	61	525	495	122
51R	3	31	4759	843	26	1214	915	706	34	659	523	17	549	153	62	685	584	170
51R	1	33	5310	941	28	1492	998	647	43	569	455	15	500	143	59	524	503	113
51R	2	33	4842	858	27	1298	879	716	37	716	616	19	570	167	62	600	780	192
51R	3	33	4504	798	28	1266	963	827	38	783	569	18	626	146	61	665	766	200

Appendix 4
Correlation Between Greenhouse Data

Greenhouse data	Oats			Clover			Soil pH	Mg+Ca
Greenhouse data	Mg.P/ 75 pl.	% P	Mg.P/ pot	Mg.P/ 40 pl.	% P	Mg.P/ pot		
Oats								
Mg.P/75 plants	1.000	0.816	0.814	0.688	0.701	0.698	0.135	0.293
% P		1.000	0.654	0.721	0.697	0.739	-0.020	0.252
Mg.P/pot			1.000	0.533	0.558	0.532	0.085	0.222
Clover								
Mg.P/40 plants				1.000	0.913	0.936	-0.099	0.193
% P					1.000	0.924	-0.102	0.155
Mg.P/pot						1.000	-0.105	0.198
Soil pH							1.000	0.778

Appendix 5
Correlation Between Field Data

Field data	Field data	Abs. yield #/A	% Max. yield	% P	#/A P	% Max. y. total	Soil pH	Exch. Ca+Mg
Absolute yield #/A		1.000	.942	.582	.915	.925	.569	.544
% Maximum yield			1.000	.696	.928	.958	.552	.522
% P				1.000	.751	.688	.345	.400
# P/A					1.000	.914	.487	.523
% Max. yield total						1.000	.594	.546

Appendix 6
Calculated c₁ Values and Their Corresponding "b" and "y" Values

Exp. No.	Treatment	NaHCO ₃ -soluble P ppm P (b)	Mg. P/pot of clover (b, y)	Cut 1 Alfalfa		Calculated c ₁ ^{2/} Figure			
				% Max. yield (y)	P uptake lbs. P/A (y)	13	14	15	16
502	20	2.7	1.98	21.3	1.9	.0358	.0020	.0547	.0358
	21	3.5	2.38	53.7	6.0	.0954	.0023	.0557	
	22	4.3	3.06	81.0	10.6	.1677	.0118	.0680	
506	20	13.8	3.87	98.9	14.6	.1419	.0071	.1342	.1419
	21	16.2	3.93	88.7	13.0	.0584	.0045	.0728	
	22	16.7	4.07	90.1	14.1	.0601	.0052	.0712	
508	20	16.2	5.19	91.5	14.8	.0661	.0064	.0724	.0661
	21	22.4	7.30	86.0	13.7	.0381	.0040	.0623	
	22	18.3	5.92	95.3	14.7	.0726	.0055	.0903	
510	20	11.4	3.17	93.2	12.9	.1024	.0064	.0905	.1024
	21	11.6	3.46	99.9	15.3	.2590	.0104	.1961	
	22	12.7	3.79	82.1	12.2	.0588	.0048	.0612	
512	20	16.5	4.05	99.3	16.3	.1306	--	.1322	.1306
	21	16.6	4.23	99.7	14.7	.1520	.0061	.1716	
	22	17.7	4.30	89.6	14.6	.0555	.0055	.0673	
514	20	7.9	2.90	73.2	6.9	.0724	.0030	.0829	.0724
	21	9.6	3.05	80.1	8.3	.0730	.0032	.0844	
	22	8.9	3.40	77.8	8.7	.0735	.0037	.0752	
516	20	20.4	4.97	98.0	13.5	.0833	.0038	.1258	.0833
	21	20.3	5.52	91.7	13.5	.0532	.0038	.0801	
	22	20.5	5.07	100.0	14.0	--	.0041	--	
518	20	12.2	4.41	79.0	10.1	.0556	.0034	.0671	.0558
	21	12.8	4.39	100.0	13.5	--	.0060	--	
	22	13.6	4.47	88.8	12.7	.0699	.0048	.0749	

Appendix 6, continued

Exp. No.	Treatment ^{1/}	NaHCO ₃ -soluble P ppm P (b)	Mg. P/pot of clover (b, y)	Cut 1 Alfalfa		Calculated c ₁ ^{2/} Figure			
				% Max. yield (y)	P uptake lbs. P/A (y)	13	14	15	16
108	20	5.2	2.12	76.4	8.2	.1206	.0058	.0765	.1206
	21	5.9	2.33	84.7	8.6	.1381	.0055	.0948	
	22	7.8	2.47	98.7	11.7	.2420	.0070	.1595	
105	20	5.6	2.41	89.9	9.2	.1778	.0064	.1083	.1136
	21	7.4	2.13	89.5	10.7	.1323	.0063	.0915	
	23	9.2	2.70	88.5	11.1	.1021	.0054	.0846	
	26	10.9	3.06	92.0	12.4	.1006	.0057	.0885	
Average						.1032	.00533	.09281	.09250

^{1/} First digit represents rate of lime; second digit represents rate of phosphorus. The actual amounts of lime and phosphorus applied are referred to in Section III 2.2.

^{2/} Calculated from the equation:
 $\text{Log}(100-y) = \text{Log } 100 - c_1 b$