

AN ABSTRACT OF THE THESIS OF

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OREGON PUMICE SOILS IN COMPARISON WITH  
SELECTED OREGON SOILS

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The objectives of this study were to evaluate and compare the availability of native and applied P in Central Oregon pumice soils with that in Willamette valley soils and calcareous soils from Eastern Oregon. The experimental work to meet these objectives included laboratory and greenhouse studies.

The removal of P from solutions in one hour of equilibration was much greater in the Willamette valley soils than in the pumice soils, and greater in the pumice soils than in the calcareous soils from Eastern Oregon. The ratio between the P removal by the Willamette valley soils and the removal by the pumice soils increased with the rate of P application, while the ratio between the removal by the pumice soils and that by the calcareous soils was fairly constant at different rates of P application.

Generally more P was extracted from these soils by the method of Bray N<sup>o</sup> 1 than by the methods of Olsen 1:10 (soil to extractant ratio = 10) and Olsen 1:20, and more P by these methods than by that of Morgan. On the Willamette valley soils the method of Olsen 1:20 extracted about 1.5 times the amount of P extracted by the Olsen 1:10 method, on the pumice soils the Olsen 1:20 method extracted slightly more P than the Olsen 1:10 method, while on the calcareous soils the Olsen 1:10 method extracted almost the same amount of P as the method of Olsen 1:20. When Morgan's procedure was compared with the methods of Bray N<sup>o</sup> 1 and both Olsen's procedures, it extracted proportionally more P on the calcareous soils than on the pumice soils, and more P on the pumice soils than on the Willamette valley soils.

With any group of soils and with all the soils considered together the values of available P obtained by the methods of Olsen 1:10, Olsen 1:20, and Bray N<sup>o</sup> 1 were highly correlated. The correlation between the method of Morgan and the methods of Olsen 1:10, Olsen 1:20, and Bray N<sup>o</sup> 1 varied with the group of soils considered, being higher on the Willamette valley soils and lower on the calcareous soils.

In greenhouse experiments with oats, P applications did not increase yields but did increase the %P and mg. P/pot in the tops of plants. In most of the experiments, particularly those with the

pumice and the calcareous soils, the oat plants showed disorder symptoms which increased with P application. It is possible that these symptoms had been related to an interaction between P and one or more essential nutrients.

In the greenhouse experiments with subterranean clover, no disorder symptoms were observed, P application increased yield and %P in tops in almost all the experiments, and the mg. P/pot in all the experiments.

Simple correlation coefficients between available P values by different methods and the percent P in tops and the mg. P/pot were in most cases high, but varied depending on the method, effect considered, and crop. The correlation values obtained by the method of Morgan were more variable than those obtained by the Olsen 1:10, Olsen 1:20, and Bray N<sup>o</sup> 1 methods.

The recovery of P applied to the soils was measured by short equilibration with P solutions, by the methods of Olsen 1:10, Olsen 1:20, Bray N<sup>o</sup> 1, and Morgan, and by oats and subterranean clover in the greenhouse.

These different procedures were generally in good agreement with respect to the relative recovery of P from the different soils. The recovery was larger in the calcareous soils, followed by the pumice soils, and last by the Willamette valley soils. The difference in recovery between the calcareous and the pumice soils was smaller

than the difference between the pumice and the Willamette valley soils.

In most cases a slightly larger percent of the added P was recovered at the rate of 50 ppm. P application than at the rate of 25 ppm. P. The recovery by plants in the greenhouse was more variable than the recovery by the laboratory methods in this respect.

Among the different procedures used to measure the recovery of P, both by chemical extraction and by plants in the greenhouse, the highest recovery was obtained by the method of Bray N<sup>o</sup> 1 and the smallest recovery was obtained by the method of Morgan.

Availability of Phosphorus in Central Oregon  
Soils in Comparison with Selected Oregon Soils

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AVAILABILITY OF PHOSPHORUS IN CENTRAL  
OREGON PUMICE SOILS IN COMPARISON  
WITH SELECTED OREGON SOILS

INTRODUCTION

Recent research work at Oregon State University has focused attention on soils in Central Oregon that have relatively large concentrations of pumice. Some physical and chemical properties (Youngberg and Dyrness, 1964), soil fertility characteristics (Youngberg and Dyrness, 1965), thermal properties (Cochran, Boersma and Youngberg, 1967), and clay mineralogy and related chemical properties (Chichester, 1967), have been studied in some of these soils.

Marked N, P, and S deficiencies have been evident when forested pumice soils in this area have been used in greenhouse experiments (Youngberg and Dyrness, 1965).

Previous research work at the Central Oregon Experiment Station<sup>1</sup> has emphasized the problems of P fertilization for potatoes and alfalfa, two of the important crops grown in this area. These studies indicated the importance of making a more complete evaluation of the P status of cultivated soils from this area.

Therefore, the present investigation was established with the following objectives:

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<sup>1</sup> Johnson, Malcolm. Superintendent of Central Oregon Experiment Station. Personal communication. Corvallis, Oregon, 1968.

1. To compare the immobilization of P from solutions by pumice soils from Central Oregon with other Eastern Oregon calcareous soils that were not affected by pumice, and with soils from the Willamette valley.

2. To compare the effect of added P on changes in P soil analyses values on these soils.

3. To compare the uptake of phosphorus and the effect of added increments of P on P uptake by oats and subterranean clover grown in the greenhouse on these soils.

4. To compare the relationship between P soil analysis values and P uptake by oats and subterranean clover in the greenhouse on this group of selected soils.

5. To compare the recovery of P applied to these soils by oats and subterranean clover grown in the greenhouse and by different extracting solutions in the laboratory.

## LITERATURE REVIEW

Forms of Inorganic P in Soils

In a very general way the soil P can be classed as inorganic or organic P. This review will deal exclusively with the inorganic soil P. This form of P is generally predominant in mineral soils, and the efficiency of P applied to soil in inorganic fertilizers and the availability of P to plants depend largely on the reactions involving inorganic forms of P. Also, the inorganic soil P has been more studied than the organic soil P.

Inorganic P occurs mainly as Ca phosphate in alkaline and calcareous soils and many parent rocks from which soils are formed. The main Ca phosphate in soils is fluorapatite,  $\text{Ca}_{10}(\text{PO}_4)_6\text{F}_2$ . As weathering proceeds and acidity develops in soils, the phosphate becomes increasingly bonded to Al and Fe ions released from silicate minerals by weathering. As weathering in soils proceeds further, some of the phosphate becomes occluded with hydrous iron oxides (Jackson, 1964; Chang and Jackson, 1958; Chang and Jackson, 1957).

Inorganic soil P may also be classified in one of the following forms: (1) surface phosphate, which is partly held against positively charged surfaces and is ill-defined insofar as molecular species; (2) sparingly soluble phosphate such as the phosphates of Fe, Al, and Ca; and (3) occluded phosphate inside particles with oxide coatings

(Fried and Broeshart, 1967).

The reactions of soluble P in soils have received considerable attention though explanations of the mechanisms involved have presented numerous problems. In a general and summary form, it can be said that the major reactions immobilizing soluble P in soils can be of the following nature: P can be adsorbed on the surface of Fe and Al hydrous oxides; P can be precipitated into insoluble compounds by reaction with Al and Fe ions in solution; P can be fixed by reaction with silicate clays; P can be precipitated into insoluble Ca compounds; P can be adsorbed on the surface of  $\text{CaCO}_3$  particles (Tisdale and Nelson, 1966; Buckman and Brady, 1960; Haseman, Brown, and Whitt, 1950; Hemwall, 1957).

The formation of the various discrete forms of phosphate in soils is apparently related to soil factors such as pH, activities of various cations, solubility products of the various phosphates, degree of chemical weathering, and fertilizer practices. At the initial stage of weathering and also right after the application of phosphate fertilizer, Ca and Al phosphates are more likely to be formed than Fe phosphate. This is attributed to the relatively higher activities in the soil of Ca and Al ions than iron ions, which are controlled by the activities of the respective cations of Ca carbonate, aluminosilicates and gibbsite, and iron oxides. Al phosphate at first increases more than Fe phosphate. As time elapses, the Ca and Al phosphates change

gradually into iron phosphate which is the least soluble among them. Iron activity associated with iron oxide increases with decrease in pH and with increasing amount of Fe oxides in soil. Iron and Al phosphate finally may become occluded by an iron oxide coating, formed in the course of chemical weathering (Chang and Jackson, 1958).

An increase in Fe phosphate with time following the application of fertilizer P has been found to take place in many soils at the expense of Al and Ca phosphates (Shelton and Coleman, 1968; Smith, 1965; Chang and Chu, 1961). The P fractions in these studies have been determined by the Chang and Jackson (1957) method.

Some phosphate is dissolved from Ca phosphate and precipitated as Al and Fe phosphates even in soil horizons with an average pH above 7, probably in local acid root and leaching channels (Jackson, 1964).

The chemical properties of Al and Fe phosphates in soils resemble those of the mineral variscite,  $\text{Al}(\text{OH})_2\text{H}_2\text{PO}_4$ , strengite,  $\text{Fe}(\text{OH})_2\text{H}_2\text{PO}_4$ , and the isomorphous intermediate barrandite,  $(\text{Al}, \text{Fe})(\text{OH})_2\text{H}_2\text{PO}_4$ . When K or  $\text{NH}_4$  is high, these ions are incorporated as in taranakite,  $\text{K}_3\text{Al}_5\text{H}_6(\text{PO}_4)_8 \cdot 18\text{H}_2\text{O}$ , or its ammonium analogue, or other potassium or ammonium salt such as  $(\text{K}, \text{NH}_4)(\text{Al}, \text{Fe})_3\text{H}_8(\text{PO}_4)_6 \cdot 6\text{H}_2\text{O}$ . The solubilities of phosphate from Ca, Al, or Fe compounds are close to each other in the soil pH range between pH 6 and pH 7. Below this pH range, the Al and Fe

phosphates are more stable than Ca phosphate, above this range, various Ca phosphates are formed, including hydroxyapatite,  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ , dicalcium phosphate,  $\text{CaHPO}_4$ , or complex Ca phosphates intermediate between these two, one of which is octocalcium phosphate,  $\text{Ca}_8\text{H}(\text{PO}_4)_3 \cdot 3\text{H}_2\text{O}$  (Jackson, 1964).

During recent years much information has been gained on the behavior of different phosphate fertilizers in different soils. Approximately 30 crystalline phosphate compounds, in addition to colloidal precipitates of variable composition have been identified as reaction products following the addition of various fertilizer solutions to soils and soil constituents (Lindsay, Frazier, and Stephenson, 1962).

#### Availability of Inorganic P Forms and Compounds to Plants

Extensive work has been done to clarify the availability of different forms of P and also of specific P compounds to plants.

Bray and Kurtz (1945) recommended that a general division of soil P into adsorbed forms and easily acid-soluble forms should be recognized. On the basis of these forms and on the results of their studies, these authors proposed chemical methods of determining available soil P using  $\text{NH}_4\text{F}$  and HCl in the extracting solutions.

Olsen, Cole, Watanabe, and Dean (1954) proposed a method to determine the available soil P, that should have extracted Ca, Al and Fe phosphates in amounts proportional to those available to plants.

Many studies have been made to relate the available soil P, as determined by plant uptake or by extraction with chemical extractants, to the P fractions determined by the procedure proposed by Chang and Jackson (1957). This procedure makes use of differential solubility of soil P compounds to determine five main fractions: salloid bound P, extractable by  $\text{NH}_4\text{Cl}$ ; Al phosphate, extractable by  $\text{NH}_4\text{F}$ ; Fe phosphate, extractable by  $\text{NaOH}$ ; Ca phosphate, extractable by  $\text{H}_2\text{SO}_4$ ; and Fe occluded phosphate, extractable by dithionite.

In the majority of these studies, the Al phosphate, as determined by the Chang and Jackson (1957) procedure, has shown the highest correlation with the P available to plants (Chai and Caldwell, 1959; Pratt and Garber, 1964; Smith, 1965; Singh, Martens, and Obenshain, 1966; Susuki, Lawton, and Doll, 1963; Alban, Vacharotayan and Jackson, 1964; Shelton and Coleman, 1968; Hawkins and Kunze, 1965; Dumber and Baker, 1965). The number of cases where Fe phosphate has shown greater availability than Ca phosphate exceed the number of cases where the reverse has been reported to be true. Most of these studies have been done in acid to neutral soils.

The P fractions as obtained by the Chang and Jackson (1957) procedure have been studied using isotopic dilution techniques. With respect to the amounts of active solid phase P removed per unit of solid phase P, these fractions ranked in the following decreasing

order: water soluble P, Al phosphate, Fe phosphate, and Ca phosphate, in soils ranging in pH from 5.0 to 6.7 (Dunbar and Baker, 1965). Chu and Chang (1966) found that the specific surface activity of Al and Fe phosphate fractions were larger than that of Ca phosphate, in different soils.

The availability of the different phosphates to plants is greatly affected by the ionic activities in the soil solution. Ca phosphate is highly unavailable at high soil pH values, usually accompanied by high Ca activity. Fe and Al phosphates of acid soils become more available when the soil pH is raised by liming, whereby the activity of Fe and Al ions is lowered (Jackson, 1964).

The extent to which the inorganic phosphate is exchangeable or occurs in forms with a high specific surface appears to be closely correlated with plant growth and crop response to phosphate fertilizer (Jackson, 1964). According to Buckman and Brady (1960), the availability of inorganic P is determined primarily by the nature of the P compounds present in soils and by the surface area of these compounds. The degree of crystallinity may be a more important factor than specific surface in controlling the relative availability of the Al and Fe compounds in soils (Juo and Ellis, 1968).

When soluble phosphates are added to soils, fresh precipitates of Ca, or Fe and Al phosphates, and similar compounds formed on the surfaces of either  $\text{CaCO}_3$  or Fe and Al oxide particles are produced.

In each case the surface area of these freshly formed phosphates is high and consequently the availability of the P contained therein is reasonably rapid. With time, an increase in size of precipitated phosphates occurs, decreasing their surface area. Also, there is a penetration of the P held by  $\text{CaCO}_3$  and Fe or Al oxide particles into the particle itself. By these processes of aging, phosphate availability is reduced (Buckman and Brady, 1960; Juo and Ellis, 1968).

The nature of the reaction products of P fertilizer with a given soil varies with the particular P fertilizer (Lindsay et al., 1962). The availability of many of these reaction products to plants has been evaluated (Taylor, Gurney, and Lindsay, 1960; Lindsay and Taylor, 1960; Lindsay and Dement, 1961; Taylor et al., 1963; Juo and Ellis, 1968). Strengite and variscite are very poor sources of P to plants in acid soils. Amorphous Al and Fe phosphates are relatively good sources of P to plants. The availability of Al and Fe phosphates increases with soil pH. Fluorapatite is practically unavailable to plants. Other complex phosphates of Al, Fe, and Ca which may also include cations such as H, K, or  $\text{NH}_4$  have shown variable availability, depending on the particular compound.

Many reaction products have been found to be unstable in soils and to hydrolyze with formation of simpler, more stable compounds releasing part of their phosphate to the surrounding soil (Taylor, Gurney, and Lehr, 1963; Taylor and Gurney, 1964).

Available P in Soils by the Methods of Morgan, Bray and Olsen

One of the main advantages that Morgan (1941) claimed for his HOAc + NaOAc extracting solution to estimate available soil P is the fact that this solution is buffered at a hydrogen ion concentration, pH 4.8, closely approximated by that of aqueous solutions saturated with CO<sub>2</sub> in concentrations normally existing in soil air, or of weak plant root acid secretions.

In addition, the solvent action of this extracting solution is practically unchanged by contact with the soil. Its total acidity and buffer capacity are sufficient to prevent a significant change of pH in most soils (Morgan, 1941). The acetate anion replaces some P in soils (Kurtz, Deturk, and Bray, 1946), and 0.5 N HOAc has been shown to be a good solvent for mono and dicalcium phosphates (Ghani, as cited by Chai and Caldwell, 1959).

Bray and Kurtz (1945) claimed that a general division of certain soil phosphates into the adsorbed forms and the easily acid-soluble forms should be recognized.

These authors proposed two methods for determining available soil P. N<sup>o</sup> 1 using 0.03N NH<sub>4</sub>F + 0.025N HCl as extracting solution, which should extract mostly the adsorbed forms. Method N<sup>o</sup> 2, using 0.03N NH<sub>4</sub>F + 0.1N HCl, should extract both the adsorbed and the easily acid-soluble P.

The fluoride ion has the special property of complexing Al and

Fe ions in acid solution, with consequent release of P held in the soil by these trivalent ions. Inclusion of acid results in the dissolution of the more active Ca phosphates and prevents the precipitation, as Ca phosphate, of P dissolved by fluoride (Jackson, 1958).

The 0.5M NaHCO<sub>3</sub> extracting solution at pH 8.5 used in the method of Olsen et al. (1954) decreases concentration of Ca in solution by causing precipitation of Ca as CaCO<sub>3</sub>. As a result, the concentration of P in solution increases. The reagent also extracts some phosphate from the surface of Al and Fe phosphates, which increase in solubility as pH increases (Jackson, 1958). The main effect of the NaHCO<sub>3</sub> on acid and neutral soils probably would be through ionic competition of HCO<sub>3</sub><sup>-</sup>, CO<sub>3</sub><sup>2-</sup>, and OH<sup>-</sup> anions for phosphate adsorbed on the surface of soil particles (Olsen et al., 1954).

The bicarbonate anion has been shown to replace more P than the acetate anion on acid soils (Kurtz et al., 1946). Secondary precipitation reactions in acid and calcareous soils are reduced to a minimum because the concentration of Al, Ca, and Fe remains at a low level in this extractant (Jackson, 1958).

Sodium bicarbonate extracted about one half of the amount of P on the surface of soil particles which readily exchanges with p<sup>32</sup> in the soil solution of different soils (Olsen et al., 1954). According to Jackson (1958), the procedure of Olsen can be likened to the brief

extraction procedure of Bray and Kurtz since the most reactive (high specific surface) phosphate is extracted from phosphates of Al, Fe, and Ca.

## EXPERIMENTAL MATERIALS AND METHODS

Selection of Soils

Samples from 12 selected soils were used in evaluating the objectives outlined for this study.

Soils one and two were from the Willamette valley. Soil one was from the Willamette series. The Willamette series is among the better drained members of the old valley floor soils. Uptake of P by plants growing on these soils has never been considered a problem. Many of these soils have adequate available P to satisfy the needs of many crops without addition of P fertilizers. Soil two was from a foothill location. The identity of this soil sample was lost. These soils are generally well drained but are frequently low in P. The lack of mottling would indicate that this sample was from a well drained foothill soil.

The remaining 10 soils were from areas east of the Cascade mountains and were developed under 10 inches of rainfall or less.

Soils three through 7 were from Central Oregon, with soils three, four, and five being Deschutes sandy loam from areas south of Redmond. These soils had the highest concentration of pumice. Soils six and seven were Madras series, and were from areas north of Madras where the concentration of pumice was less, although volcanic ash deposits can be readily identified in this area.

Soils eight and nine were Greenleaf silty loam from Ontario Experiment Station, near Idaho; soil ten was the Shano series, from Central Washington. There is little if any effect from pumice on these soils.

Soils 11 and 12 were Hosley and Harriman series, respectively, from the Klamath Counth, south of Klamath Falls. Since the prevailing winds are from the west and southwest, the pumice depositions from Crater Lake eruption did not have much effect on the mineral soils in this area. Any significant concentration of pumice in the soils in the Klamath basin was carried by water and was deposited in the areas of peat and muck soils.

The soil samples used in the present investigation were taken from the 0 to 8 top inches. The samples were air dried for at least 48 hours and then ground and sieved through a 2 mm. screen.

The numbers adopted to refer to these soils in this study, the location of sampling, soil series, results of mechanical analysis and initial soil chemical analyses values are given in Table 1. A description of each soil series is given in the Appendix.

#### Soil Analyses

The pH, exchangeable Ca, Mg, and Na, available P, texture, and the capacity of the soils to remove P from solutions were determined for all the 12 soils used in this study.

Table 1. Sample number, location, soil series, soil chemical analyses, and particle size distribution.

No	Soil* Series	pH	P ppm.	meq./100 g exchangeable				Particle size distribution			
				Ca	Mg	K	Na	% clay	% silt	% sand	Texture
1	Willamette	5.5	59	7.0	2.1	1.1	0.04	23.5	39.1	37.4	loam
2	Foothill soil**	6.0	8	9.3	4.2	1.5	0.26	40.0	32.2	27.9	clay loam
3	Deschutes	5.8	14	9.5	4.6	1.5	0.52	13.9	28.9	57.2	sandy loam
4	Deschutes	6.1	12	5.8	2.1	1.1	0.13	9.9	21.5	68.7	sandy loam
5	Deschutes	5.8	10	6.3	2.9	0.7	0.26	10.9	19.4	69.7	sandy loam
6	Madras	6.9	19	11.0	8.2	1.8	0.91	22.4	39.8	37.8	loam
7	Madras	5.7	23	6.5	5.7	0.7	0.22	16.6	30.5	53.0	sandy loam
8	Greenleaf	7.5	9	12.8	6.8	1.6	0.87	23.0	53.2	23.8	silt loam
9	Greenleaf	7.4	15	13.3	8.8	1.4	0.78	28.7	51.4	20.0	silt loam
10	Shano	7.8	2	9.8	3.8	0.5	0.13	6.9	59.5	33.7	silt loam
11	Hosley	7.7	5	8.8	3.3	1.6	0.30	7.9	16.3	75.9	sandy loam
12	Harriman	6.4	18	6.3	3.5	1.6	0.09	11.7	15.2	73.2	sandy loam

\*Locations:

1. North Willamette Exp. Sta. - Aurora, Ore.
2. Willamette valley foothill soil
3. Bayley farm - Powell Butte, Ore.
4. Beasley farm - Redmond, Ore.
5. Fredericks farm - Redmond, Ore.
6. Madras Exp. Sta. - Madras, Ore.
7. Siegenhagen farm - Madras, Ore.
8. Ontario Exp. Sta. - Ontario, Ore.
9. Ontario Exp. Sta. - Ontario, Ore.
10. Othello Exp. Sta. - Othello, Wash.
11. Klamath Falls Exp. Sta. - Klamath Falls, Ore.
12. Hill farm - Klamath Falls, Ore.

\*\*Soil from a foothill location. The identity of this soil sample was lost.

The pH was determined by the glass electrode method using a 1:2 soil:water suspension.

The exchangeable Ca, Mg, and Na were extracted using 1N ammonium acetate adjusted to pH 7.0, on a single extraction with a 1:10 soil to extractant ratio (Schollemberg and Simon, 1945). The determination was made by flame emission spectrophotometry.

The available P was determined by the method of Olsen (Olsen et al., 1954) as used in the Oregon State University Soil Testing laboratory. The extraction is made with 0.5M NaHCO<sub>3</sub> adjusted to pH 8.5 using a 1:10 soil to extractant ration. The extracted P was determined by the chlorostannous-reduced molybdophosphoric blue color in hydrochloric acid system method (Jackson, 1958), in a Bausch and Lomb Spectronic 20 spectrophotometer.

The soil texture was determined by the hydrometer method, with previous acidification and organic matter removal.

The capacity of the soils to remove P from solutions was measured by shaking 2.5 gr. of soil for one hour with 25 ml. of solutions containing 0, 25, 50, 100, 200, 400, and 600 ppm. P with respect to the soil, as NH<sub>4</sub>H<sub>2</sub>PO<sub>4</sub>. The P in the supernatant liquid was determined with molybdenum blue color after centrifugation and filtration to clear the supernatant liquid.

In addition to the above mentioned analysis, four different procedures to determine available soil P were used on the soil samples

that had been treated with 0, 25, and 50 ppm. P and incubated for three weeks for the greenhouse experiments. These procedures, including the constituents of the extracting solutions, soil to solution ratios, and time of shaking are listed in Table 2. The colorimetric determinations of the soil P were all made by measuring the chlorostannous-reduced molybdophosphoric blue color in hydrochloric acid system (Jackson, 1958) using a Bausch and Lomb Spectronic 20 spectrophotometer.

Table 2. Methods used in determining available soil P; extracting solution, soil to solution ratio, and time of shaking.

Method	Extracting solution	Soil:solution ratio	Time of shaking
Olsen(1954)	0.5M NaHCO <sub>3</sub> at pH 8.5	1:10	30 min.
Olsen(1954)	0.5M NaHCO <sub>3</sub> at pH 8.5	1:20	30 min.
Bray N <sup>o</sup> 1(1945)	0.025N HCl + 0.03N NH <sub>4</sub> F	1:7	1 min.
Morgan(1941)	0.73N NaOAc + 0.52N HOAc	1:5	30 min.

### Greenhouse Experiments

The effect of P application on yield, P content, and total uptake of P for oats and subterranean clover on the 12 soils selected for this study were evaluated under greenhouse conditions. The Crater variety of oats and the Mount Barker variety of subterranean clover were used for these experiments.

Each experiment consisted of three treatments, with an application of 0, 25, 50 ppm. P with respect to the soil, with four

replications, in a randomized complete block design.

The P was applied as  $H_3PO_4$  in dilute solution, by spreading the solution over a thin layer of one Kg. of soil in a plastic container. An additional measured amount of distilled water was immediately added to the soil to bring it to a moist condition, and the mixture was thoroughly mixed. After treatment, the moist soils were kept in close plastic bags for three weeks at room temperature.

After the three-week treatment period, the soils were air dried and pulverized. Plastic containers were used as pots. Holes were punched on the bottom of the containers to provide drainage, but each hole was covered with a thin layer of glasswool to avoid losses of solid particles.

A layer of quartz sand was placed in the bottom of the pots to raise the level of the soil in the pots.

Oat seeds of a uniform weight, and clover seeds were soaked in water in a germinator for about 18 hours, to hasten and obtain a uniform germination.

Fifty soaked seeds of oats and clover were planted per pot. The clover seeds were inoculated at planting time. The seeds were covered with a thin layer of quartz sand and watered, the sand was covered with a piece of moist cheese cloth, and the pots were covered with tight plastic bags. When the seeds germinated, the cheese cloth and the plastic bags were removed.

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Blanket fertilization of oats included 250 lb. N/A and 286 lb. S/A as  $(\text{NH}_4)_2\text{SO}_4$  at planting time, and 250 lb. N/A as  $\text{NH}_4\text{NO}_3$  applied 16 days after germination. The clover experiments received 100 lb. N/A and 114 lb. S/A as  $(\text{NH}_4)_2\text{SO}_4$  at planting time. The experiments with Shano soil, known to be deficient in Zn, received a blanket application of one ppm. Zn as the commercial chelate product "Sequestrene 330 Zn", a week after germination.

In the clover experiments, germination and seedling development were not uniform, and "damping off" disease killed a number of seedlings. As a consequence of this, some experiments had to be replanted and the number of clover plants per pot was thinned to 20.

The plants were watered at least once a day, usually two times a day. The temperature in the greenhouse was controlled at 55-60 °F. at night and 75-80 °F. in the daytime. Supplementary light was furnished to the plants to increase light intensity and to provide a photoperiod of 13 hours of light.

The oats were allowed to grow 23 days, and the clover 46 days after germination. The oats were cut at the soil level, while the clover was cut immediately below the crown. The lower part of the tops was dampened in  $\text{H}_2\text{O}$  to wash off soil contamination. The tops were put in paper bags and dried for at least 72 hours at 137 °F. in a forced draft oven.

The oven-dried tops were weighed to evaluate yields, and finely ground in a Willey mill in preparation for digestion and subsequent

plant chemical analysis.

### Plant Analysis

Digestion of the plant material was made by wet ashing with perchloric acid (Jackson, 1958).

The molybdate-vanadate colorimetric method was used to determine P in the perchloric acid digest. The color intensity was measured on a Bausch and Lomb spectronic 20 spectrophotometer at 430 millimicrons.

The content of Ca, Mg, Fe, Mn and Zn in the plants was determined in a Perkin Elmer, model 303, atomic absorption spectrometer.

The K content was determined in a Beckman Model D. U. spectrophotometer with flame emission attachment (Brown et al., 1948).

## RESULTS AND DISCUSSION

P Fixation in Short-term Laboratory Studies

The rate of reaction of soluble P with soils and soil minerals that fix P is initially rapid and subsequently slow. The initial rapid stage has been observed to last from less than one hour to a few hours (Haseman et al., 1950; Chai and Caldwell, 1959; Hsu, 1964). It is believed that both stages of P fixation proceed through the same chemical reaction. The rapid fixation resulting from the reaction of P with already available Al and Fe, and the slow fixation resulting from the reaction of P with Al and Fe that are released through decomposition of the respective minerals with aging (Haseman et al., 1950; Hsu, 1964).

The capacity of the soils to remove P from solution was measured in the laboratory by shaking the soil samples one hour with P solutions and then determining colorimetrically the P in the supernatant liquid. This capacity was assumed to be an estimate of the relative P fixation by soils, and for simplicity will be referred to as P fixation in the following discussion. The results are presented in Tables 3 and 4, and in Figure 1.

The fixation of P was highest in the Willamette valley soils, followed by the pumice soils and last by the non-pumice calcareous soils (soils 8-12). The differences in P fixation between the

Table 3. Phosphorus fixation by soils during one hour of equilibration with  $\text{NH}_4\text{H}_2\text{PO}_4$  solutions\*.

Soil N <sup>o</sup>	ppm. P added					
	25	50	100	200	400	600
	ppm. P fixed					
1	22	44	78	140	225	278
2	23	44	82	143	236	311
3	15	27	41	60	77	99
4	12	21	32	48	70	78
5	17	29	45	64	96	111
6	17	31	49	71	102	117
7	15	27	45	67	103	116
8	14	23	38	60	92	107
9	14	26	41	67	106	125
10	13	22	34	51	72	77
11	5	11	12	22	44	56
12	10	17	25	37	59	72
mean 1-2	22	44	80	142	231	295
mean 3-7	15	27	42	62	89	104
mean 8-12	11	20	30	47	74	87

\*Means of two replications

Table 4. Phosphorus fixation, as percent of added P, by soils during one hour of equilibration with  $\text{NH}_4\text{H}_2\text{PO}_4$  solutions\*.

Soil N <sup>o</sup>	ppm. P added					
	25	50	100	200	400	600
	P fixed, expressed as % of P added					
1	86	88	78	70	56	46
2	92	88	82	72	59	52
3	61	53	41	30	19	17
4	47	42	32	24	18	13
5	66	59	45	32	24	19
6	68	62	49	35	25	20
7	60	55	45	34	26	19
8	54	47	38	30	23	18
9	54	51	41	34	26	21
10	50	45	34	25	18	13
11	20	22	12	11	13	9
12	39	34	25	18	15	12
mean 1-2	89	88	80	71	58	49
mean 3-7	60	54	42	31	22	17
mean 8-12	44	40	30	24	19	15

\*Means of two replications

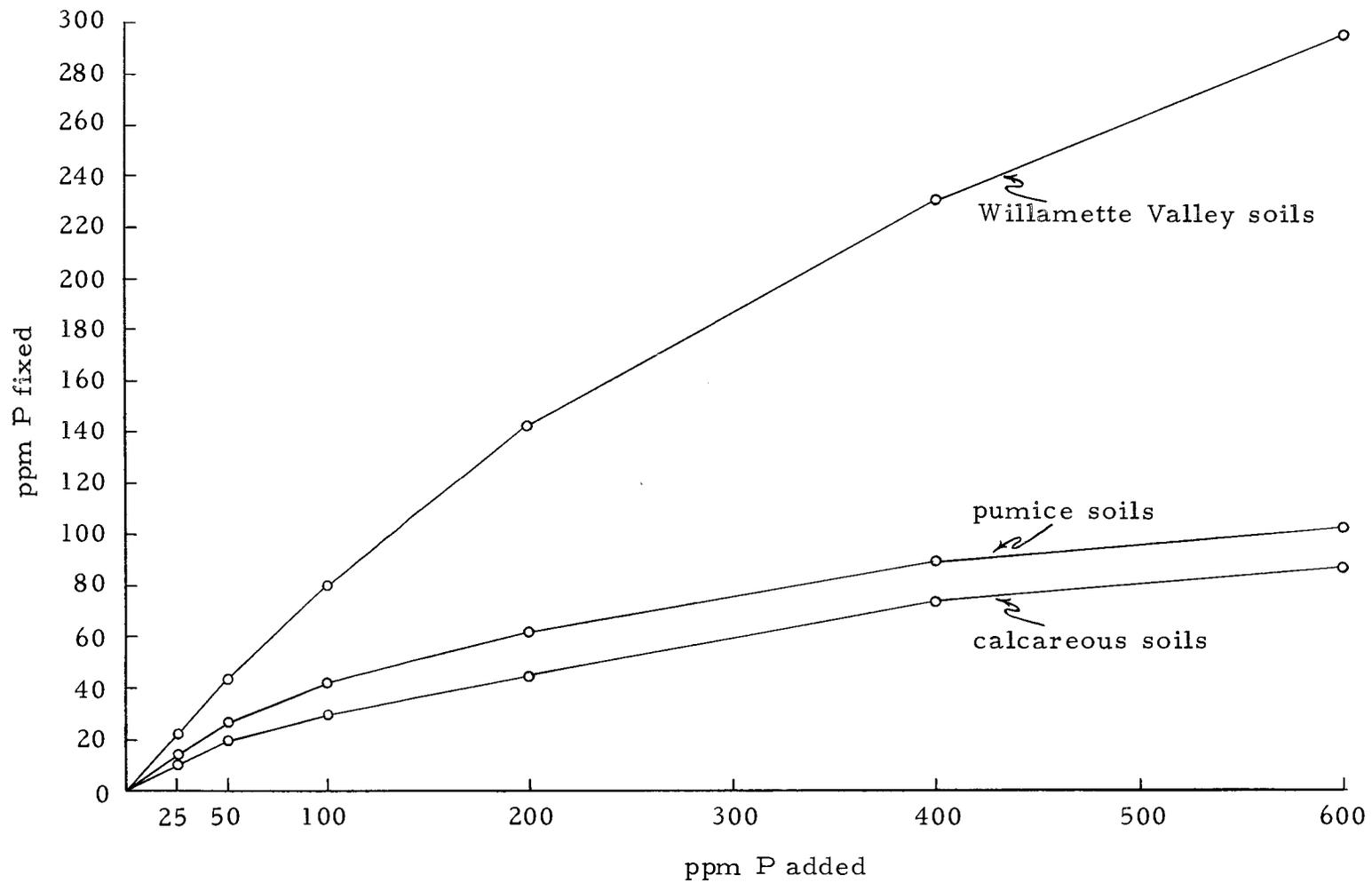


Figure 1. Phosphorus fixation by three groups of soils after one hour of equilibration with  $\text{NH}_4\text{H}_2\text{PO}_4$  solutions.

Willamette valley soils and that of the pumice soils was more marked at higher than at lower rates of P added. At 25 ppm. P added, the Willamette valley soils fixed 1.5 times the amount of P fixed by the pumice soils, while at 600 ppm. P added the ratio increased to 2.8.

The ratio between the P fixation by the pumice soils and that of soils 8-12 was quite constant and decreased from 1.4 at 25 ppm. P added to 1.2 at 600 ppm. P added.

In absolute amounts of P fixed, the difference in P fixation between the Willamette valley soils and the pumice soils was about two times greater than the corresponding difference between the pumice soils and soils 8-12 at 25 ppm. P added, but it was five times greater at the 600 ppm. P rate.

The points mentioned above are presented graphically in Figure 1 which shows that the soils from the Willamette valley not only fix more P at any rate of added P, but that the slope of their fixation curve is always greater, compared to the other two groups of soils. This indicates that the amount of P needed to saturate the P fixation capacity to any degree is greater in the Willamette valley soils. The slopes of the fixation curves of the pumice soils and of soils 8-12 becomes about the same for rates greater than 100 ppm. P added.

The variation in P fixation among soils within a group was relatively low, except for soils 8-12 where the soils 11 and 12 showed distinctly less P fixation than soils 8, 9, and 10. Soils 8, 9, and 10

are silt loam while soils 11 and 12 are sandy loam (Table 1). Soils 8 and 9 have a much higher clay content (23%, 29% vs. 8% and 12% for soils 11 and 12) with soil 10 having a very high silt content (60%). The percent sand was 24, 20 and 34 for soils 8, 9, and 10, compared to the much higher 76 and 73% for soils 11 and 12. Soil 10 had a somewhat higher pH (7.8) while soil 12 had a pH (6.4) much lower than the rest of the soils in this group (Table 5).

Table 5. Soil pH, available P, percent clay, P fixation per unit clay, and P fixation at the 50 ppm. P rate.

Soil No	pH	available P* ppm.	clay %	(ppm. P fixed**) % clay	P fixed** ppm.
1	5.5	59	23.5	1.9	43.9
2	6.0	8	40.0	1.1	44.1
3	5.8	14	13.9	1.9	26.6
4	6.1	12	9.9	2.1	21.1
5	5.8	10	10.9	2.7	29.4
6	6.9	19	22.4	1.4	31.1
7	5.7	23	16.6	1.6	27.3
8	7.5	9	23.0	1.0	23.3
9	7.4	15	28.7	0.9	25.6
10	7.8	2	6.9	3.2	22.3
11	7.7	5	7.9	1.4	11.1
12	6.4	18	11.7	1.4	17.1
<u>Mean</u>					
1-2	5.8	34	31.8	1.5	44.0
3-7	6.1	16	14.7	2.0	27.1
8-12	7.4	18	15.6	1.6	19.9

\*by the method of Olsen et al. (1954)

\*\*at the 50 ppm. P rate

This variation in P fixation among soils 8-12 does not invalidate the conclusion that the pumice soils fix more P than soils 8-12, since individually the only pumice soil that showed the tendency to fix less P than some of the soils in the 8-12 group was soil 4, a soil which had the lowest clay content among the pumice soils.

Some properties that affect P fixation by soils, the amounts of P fixed by the different soils and by unit percent of clay are presented in Table 5.

In spite of the variability in other factors that affect P fixation, the amounts of P fixed tended to increase with clay content, within each group of soils (Figure 2).

The amount of P fixed per unit of clay was on the average greater in the pumice soils (2.0) than on soils 8-12 (1.6). The wide variation in P fixation per unit of clay for the two Willamette valley soils limits the comparisons that should be made between these soils and the other two groups of soils.

It has been shown that clay minerals have the ability to fix P, but this ability varies for different clay minerals (Haseman et al., 1950).

Chichester (1967) found that amorphous components were predominant in the clay size fraction of soils formed on Mazama pumice. He suggested that many, if not all, of the soil minerals classified under the category of amorphous, including discrete colloidal hydrous

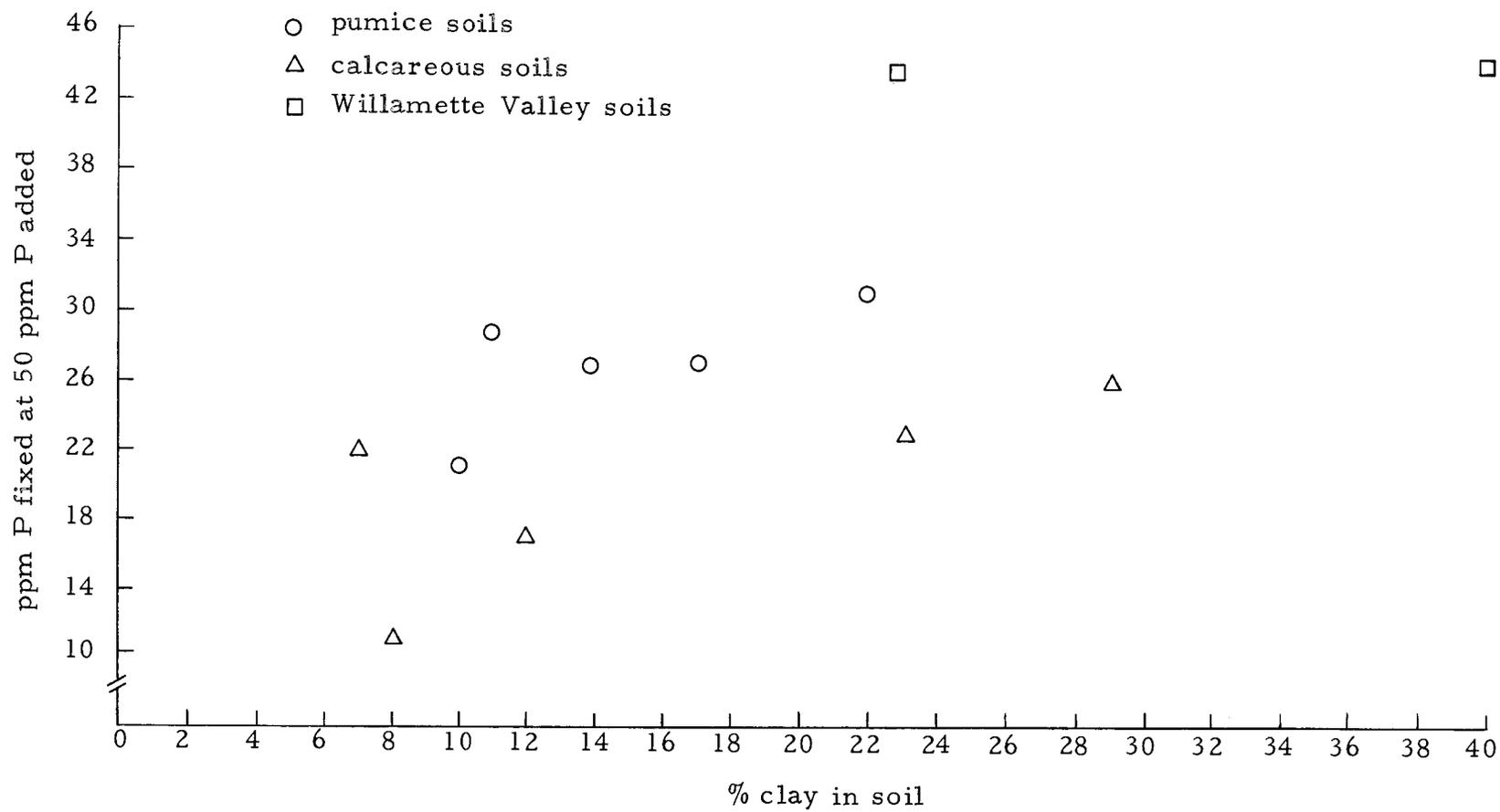


Figure 2. Percent clay vs. P fixation in one hour of equilibration at 50 ppm P added.

oxides of Al, Si, and Fe, and the various solid solutions of silica, alumina, and water referred to as allophane probably occur in the amorphous component of the clay fraction of these soils.

The high specific surface and high Al and Fe activity of allophane cause high P fixation capacity in soils containing much allophane (Jackson, 1964).

Among the pumice soils, soils 3, 4, and 5 fixed larger amounts of P per unit percent of clay (1.9, 2.1, 2.7) than soils 6 and 7 (1.4, 1.6). Soils 3, 4, and 5 are Deschutes series and had more influence of pumice than soils 6 and 7, which are from the Madras series<sup>1</sup>. At the same time, soils 3, 4, and 5 had lower values of available P (14, 12, 10 ppm. P) than soils 6 and 7 (19, 23 ppm. P).

Soil 10 (Shano) had the highest amount of P fixed per unit percent of clay (3.2) while soil 9 had the lowest (0.9), both being calcareous non-pumice soils. Soil 10 had a more alkaline pH (7.8) than soil 9 (7.4), and a much lower value of available P (2 ppm.) than soil 9 (15 ppm.). Soil 10 also had a higher silt content (60%) than any of the other soils in this study.

The initial available soil P per se, as estimated by the method of Olsen et al. (1954), did not show an apparent association with P fixation for the soils studied. For any group, some soils with high

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<sup>1</sup> Jackson, T. L. Professor of soils, Oregon State University. Personal communication. Corvallis, Oregon, 1968.

available P contents fixed as much or more P than some soils with low values of available P, suggesting that other soil factors were more important than the available P status in determining P fixation. However, as pointed out in the preceding paragraphs, the initial values of available P may explain part of the variation in P fixation per unit of clay content.

The mean soil pH of the Willamette valley soils was 5.8, while that of the pumice soils was 6.1, and that of soils 8-12 was 7.4. The Willamette valley soils are more weathered and more acid than soils from Central and Eastern Oregon. Therefore, aluminum and iron phosphates may predominate over calcium phosphates in the Willamette valley soils. Alban et al., (1964) found in Reddish Brown Lateritic soils of Western Oregon a ratio of  $\text{NH}_4^-$  to  $\text{NaOH}^-$  to  $\text{H}_2\text{SO}_4^-$  extractable phosphate of about 3.3:12.0:1.0, using the Chang and Jackson (1957) fractionation method, which attributes these fractions to Al-, Fe-, and Ca- phosphates respectively. Ca- phosphates tend to predominate on calcareous soils, and this may be the case in soils 8-12 that are all calcareous except N<sup>o</sup> 12 which has a pH of 6.4. The pumice soils had pH values closer to the range in pH where the soil P is generally considered to have its maximum availability (Buckman and Brady, 1960).

Further discussion on the subject of P fixation by these soils is presented in a following section where data on the recovery of applied

P by plants and by different extracting solutions is presented and discussed.

Amounts of Native and Applied P Extracted  
by Different Laboratory Methods

The available P was estimated on the soils which had received 0, 25, or 50 ppm. P (and incubated for three weeks to be used in the greenhouse experiments), by four different laboratory methods (Table 6).

Bray's method extracted more P than the other procedures on all soils except for the P zero treatment on soil 11 where Morgan's method extracted 0.9 ppm. more P. Olsen's procedure extracted more P than Morgan's procedure on all soils except 10 and 11.

The ratio between P extracted by Bray's method and P extracted by the methods of Olsen 1:10 and Olsen 1:20 did not vary much for the different soils. Bray's method extracted about 1.5 to 2.5 times the amount of P extracted by the method of Olsen 1:10.

On the Willamette valley soils the method of Olsen 1:20 extracted about 1.5 times the amount of P extracted by the Olsen 1:10 method. On the pumice soils the method of Olsen 1:20 extracted slightly more P than the method of Olsen 1:10. In soils 8-12 the method of Olsen 1:10 extracted almost the same amount of P as the method of Olsen 1:20 did.

The ratio between P values obtained by the method of Morgan and

Table 6. Available P in soils treated with different P rates, as determined by different chemical extraction methods.

Soil N <sup>o</sup>	P applied ppm. P	Extraction method			
		Olsen 1:10	Olsen 1:20	Bray N <sup>o</sup> 1	Morgan
		ppm. available P			
1	0	58.8	83.7	149.7	10.0
	25	63.6	88.0	160.0	11.2
	50	69.8	95.7	177.0	12.3
2	0	7.7	13.3	20.0	1.2
	25	10.9	16.3	24.7	1.7
	50	14.7	22.4	29.4	2.6
3	0	13.9	15.6	23.2	5.5
	25	25.4	26.5	35.6	10.5
	50	35.7	37.4	53.4	16.4
4	0	11.9	12.4	22.6	3.3
	25	20.4	22.7	35.9	6.9
	50	29.5	34.7	49.9	12.7
5	0	10.3	12.7	15.5	3.1
	25	18.5	22.0	26.3	6.6
	50	28.4	32.8	39.4	10.3
6	0	19.2	23.1	36.8	10.6
	25	30.9	34.1	48.2	16.3
	50	41.9	46.4	65.7	22.4
7	0	22.8	26.8	44.2	5.9
	25	31.0	37.1	59.6	8.7
	50	41.9	45.5	73.7	12.2
8	0	8.5	9.1	12.8	7.4
	25	18.0	18.3	26.7	13.5
	50	31.3	33.6	40.7	22.9
9	0	15.0	17.1	21.9	7.2
	25	26.1	26.6	36.6	13.3
	50	36.0	40.5	49.9	19.3
10	0	1.9	2.4	5.1	4.3
	25	10.4	11.8	20.0	14.7
	50	23.0	23.4	38.9	27.6
11	0	4.8	5.2	7.9	8.8
	25	16.4	18.2	24.7	21.5
	50	32.5	37.3	44.2	38.1
12	0	18.0	19.2	32.9	8.8
	25	29.0	31.1	49.9	15.5
	50	41.7	43.2	67.4	23.9

P values obtained by any of the other three methods was dependent on the particular group of soils in question. The ratio between P extracted by the Morgan method and the Olsen 1:10 method was about 1:6 in the Willamette valley soils, about 1:3 to 1:4 in the pumice soils, and about 1:2 to 2 in soils 8-12.

Chai and Caldwell (1959) extracted more P from alkaline than from acid soils with the Morgan method. At the same time they found that Morgan's extractable P was highly correlated with the Ca phosphate, and negatively correlated with the Al and Fe phosphates fractions determined by the Chang and Jackson (1957) procedure. Ghani (as cited by Chai and Caldwell, 1959) showed that 0.5N HOAc was a good solvent for mono and dicalcium phosphates. Ca-phosphates are expected to be predominant in soils 8-12, which are calcareous with the exception of soil 12.

The Morgan method was found to be unsatisfactory for acid soils of Pennsylvania because it did not remove substantial amounts of applied P and also the results were significantly affected by soil pH (Baker and Hall, 1967).

Simple correlation coefficients were calculated between the values of P extracted by the four procedures (Table 7).

Table 7. Simple correlation coefficients among available soil P values determined by different laboratory methods.

Soils	Method	Simple correlation coefficient		
		Olsen 1:20	Bray N <sup>o</sup> 1	Morgan
1-2	Olsen 1:10	0.99	0.99	0.99
	Olsen 1:20		0.99	0.99
	Bray N <sup>o</sup> 1			0.99
3-7	Olsen 1:10	0.99	0.96	0.85
	Olsen 1:20		0.96	0.84
	Bray N <sup>o</sup> 1			0.74
8-12	Olsen 1:10	0.99	0.97	0.70
	Olsen 1:20		0.96	0.72
	Bray N <sup>o</sup> 1			0.65
1-12	Olsen 1:10	0.98	0.94	0.39
	Olsen 1:20		0.98	0.27
	Bray N <sup>o</sup> 1			0.18

For any group of soils and for all the soils considered together, the values from the methods of Olsen 1:10, Olsen 1:20, and Bray N<sup>o</sup> 1 were highly correlated with the values of R, the linear correlation coefficient, being of at least 0.94.

The correlation between the P extracted with Morgan's solution and the three other methods varied depending on the group of soils, and decreased in the order Willamette valley, pumice, soils 8-12, and all soils together. For any group of soils there was a better correlation between Morgan's procedure and the procedures of Olsen than with the method of Bray N<sup>o</sup> 1.

## Phosphorus Experiments in the Greenhouse

### Oat Experiments

The oat plants were grown for 23 days. About 12 days after emergence the plants in some experiments started to show chlorotic symptoms which increased with time. By harvest time most of the experiments showed some degree of these symptoms. The symptoms consisted of intense yellowing mostly in old leaves starting generally from the tip, resulting in a final necrosis with bronzed and brown coloration.

The day before harvesting visual grades ranging from 0 where no symptoms were observable to 5 where the plants showed the maximum intensity of the symptoms, were given to the plants (Table 8).

It was apparent that the intensity of the symptoms tended to increase with P application, and that it was more marked in the pumice soils and soils 8-12 than in soils from the Willamette valley.

There were no reasons to believe that these symptoms were a result of disease caused by pathogenic organisms. Since two blanket applications of N, amounting to a total of 500 lb. N/A in water soluble forms, were made, it seemed very unlikely that the problem was a N deficiency.

Phosphorus applications did not increase the yields of tops of oats in any of the experiments, but did increase the percent P in the

Table 8. Visual grading of chlorotic symptoms in the oat experiments.

Experiment Nº	P applied ppm.	Visual grading*		Rank
		treatment mean	experiment mean	
1	0	0.5	1.2	9
	25	1.3		
	50	1.8		
2	0	0.3	0.2	12
	25	0.0		
	50	0.3		
3	0	0.8	1.0	10
	25	0.8		
	50	1.3		
4	0	1.8	2.6	3
	25	2.8		
	50	3.3		
5	0	1.3	1.3	8
	25	1.0		
	50	1.8		
6	0	2.3	3.2	1
	25	3.3		
	50	4.0		
7	0	1.5	2.3	4
	25	2.5		
	50	2.8		
8	0	1.8	2.1	5
	25	2.3		
	50	2.3		
9	0	1.0	1.5	6
	25	1.8		
	50	1.8		
10	0	0.3	0.8	11
	25	1.0		
	50	1.0		
11	0	1.0	1.4	7
	25	1.8		
	50	1.5		
12	0	2.5	2.8	2
	25	2.3		
	50	3.5		

\* Grades are from 0 for the absence of symptoms, to 5 for the pots where the maximum intensity of symptoms was observed. The results are means of four replications.

tops and the uptake of P per pot from all soils (Table 9).

In fact two soils, N<sup>o</sup> 6 and 12, showed a decrease of about 10% in the yields of tops with the 50 ppm. P treatment as compared with the check without P application. These two experiments ranked in the first two places in intensity of the symptoms, both had soils with relatively high levels of available P (Table 6), and both produced plants with the highest percent P (along with soil 1) with or without P application (Table 9).

These facts seemed to indicate that P was involved in the problem (s) causing the symptoms.

In the oats experiments P applications tended to increase the Mn content but did not affect the Zn content of tops (Appendix Table 1). In the clover experiments no symptoms of disorder were observed, P applications increased the yields and Mn content of tops, but tended to decrease Zn content of tops (Appendix Table 2).

It was concluded that the symptoms might have been resulted from an interaction between P and one or more essential nutrients, possibly including Zn. Chemical analysis of plant tops did not suggest a solution to this problem.

#### Subterranean Clover Experiments

Symptoms of disorder, as those observed in the oat experiments, were not apparent in the clover studies. The results are presented in

Table 9. Effect of P on oats in the greenhouse experiments\*.

Experiment N <sup>o</sup>	P applied ppm. P	yield# gr./pot	P content# %P	P uptake# mg. P/pot
1	0	2.07	.46	9.54
	25	2.08	.48	10.04
	50	2.14	.52	11.09
2	0	2.15	.21	4.51
	25	2.12	.24	4.98
	50	2.25	.26	5.79
3	0	2.36	.24	5.73
	25	2.35	.33	7.81
	50	2.36	.41	9.67
4	0	1.98	.24	4.65
	25	2.00	.31	6.16
	50	2.04	.38	7.69
5	0	2.12	.19	4.08
	25	2.13	.28	5.87
	50	2.06	.36	7.36
6	0	2.18	.38	8.32
	25	2.16	.46	9.88
	50	1.98	.54	10.62
7	0	1.97	.33	6.41
	25	2.01	.38	7.60
	50	2.01	.41	8.30
8	0	2.24	.22	4.97
	25	2.20	.30	6.55
	50	2.24	.39	8.68
9	0	2.25	.32	7.10
	25	2.24	.39	8.71
	50	2.29	.47	10.70
10	0	1.90	.20	3.81
	25	2.02	.31	6.17
	50	2.05	.43	8.75
11	0	2.14	.22	4.61
	25	2.13	.31	6.60
	50	2.19	.43	9.34
12	0	2.22	.35	7.66
	25	2.14	.44	9.33
	50	1.95	.54	10.11

\*Means of four replications

#Based on the dry weight of tops

Table 10.

All the experiments except N<sup>o</sup> 1 showed an increased yield of tops from P application. Soil N<sup>o</sup> 1 had the highest value of available P (Table 6) and the tops of clover in this experiment had the highest P content with or without P application among all the clover experiments.

The percent P in tops increased with P application in all experiments except N<sup>o</sup> 2, in spite of the low P values in the tops and low values of available P in this soil (Table 6). Soil N<sup>o</sup> 2 had the highest P fixation capacity among all the soils included in this work (Table 3).

The uptake of P per pot increased with P application in all the experiments. The increase was larger in the experiments with pumice soils and soils 8-12 than in those with Willamette valley soils. The latter showed higher P fixation in the laboratory (Table 3). The increase in P uptake per pot from the pumice soils was about the same as that of soils 8-12, with the exceptions of soils 10 and 11, which were the lowest in available soil P and percent P on tops of clover, and which showed a higher increase in P uptake per pot than any other soil with increasing P application.

Correlation Between Available P by Different Methods  
and Content and Uptake of P in Greenhouse Experiments

Simple correlation coefficients were calculated between

Table 10. Effect of P on clover in the greenhouse experiments\*.

Experiment N <sup>o</sup>	P applied ppm. P	yield# gr. /pot	P content# %P	P uptake# mg. P/pot
1	0	1.97	.23	4.43
	25	2.02	.23	4.68
	50	2.09	.28	5.71
2	0	2.20	.12	2.57
	25	2.30	.14	3.16
	50	2.53	.13	3.28
3	0	2.45	.11	2.57
	25	2.91	.14	4.08
	50	3.00	.19	5.74
4	0	1.32	.12	1.60
	25	1.66	.18	2.95
	50	1.95	.24	4.58
5	0	1.52	.12	1.75
	25	1.77	.17	2.92
	50	1.97	.21	4.03
6	0	2.13	.17	3.66
	25	2.33	.22	5.04
	50	2.39	.27	6.51
7	0	1.28	.18	2.26
	25	1.59	.22	3.50
	50	1.83	.25	4.53
8	0	1.64	.10	1.68
	25	2.37	.16	3.84
	50	2.49	.22	5.45
9	0	2.02	.15	3.01
	25	2.34	.20	4.67
	50	2.38	.27	6.40
10	0	0.88	.095	0.83
	25	2.48	.21	5.09
	50	2.76	.28	7.74
11	0	1.30	.088	1.13
	25	1.98	.18	3.46
	50	2.34	.26	5.96
12	0	1.99	.19	3.58
	25	2.36	.22	5.08
	50	2.61	.26	6.77

\*Means of four replications

#Based on the dry weight of tops

extractable soil P values determined by different methods and the percent P in tops, and the uptake of P per pot for oats and clover grown in the greenhouse experiments (Table 11).

Table 11. Simple correlation coefficients between available soil P determined by different methods and P content and uptake by oats and clover in the greenhouse.

Soils	Method	Effect			
		Simple correlation coefficient			
		Oats		Clover	
		%P	mg P/pot	%P	mg P/pot
1-2	Olsen 1:10	0.99	0.98	0.93	0.89
	Olsen 1:20	0.99	0.98	0.93	0.89
	Bray N <sup>o</sup> 1	0.99	0.98	0.93	0.89
	Morgan	0.99	0.98	0.94	0.90
3-7	Olsen 1:10	0.89	0.85	0.88	0.87
	Olsen 1:20	0.89	0.83	0.91	0.85
	Bray N <sup>o</sup> 1	0.85	0.77	0.88	0.75
	Morgan	0.94	0.95	0.76	0.97
8-12	Olsen 1:10	0.95	0.95	0.84	0.83
	Olsen 1:20	0.95	0.95	0.84	0.82
	Bray N <sup>o</sup> 1	0.97	0.94	0.85	0.84
	Morgan	0.69	0.65	0.78	0.77
1-12	Olsen 1:10	0.86	0.84	0.75	0.64
	Olsen 1:20	0.78	0.75	0.67	0.53
	Bray N <sup>o</sup> 1	0.71	0.67	0.60	0.45
	Morgan	0.66	0.66	0.70	0.78

On the Willamette valley soils all the four methods tested were highly correlated with both P content and P uptake by oats and clover.

On the pumice soils the method of Morgan had the highest correlation coefficient with percent P and mg. P/pot in oats and mg. P/pot clover, followed by the two procedures of Olsen which had very similar coefficients, and last by Bray N<sup>o</sup> 1 method. With respect to

percent P in clover, however, the two procedures of Clsen and the Bray No<sup>o</sup> 1 method had similar correlation coefficients and were higher than that obtained by the method of Morgan.

On soils 8-12 the Clsen 1:10, Olsen 1:20, and Bray No<sup>o</sup> 1 methods had similar correlation coefficients with respect to percent P and mg. P/pot in oats and clover, and were higher than those obtained by the method of Morgan. This difference was more marked in the oats than in the clover experiments. The correlation coefficients tended to be greater with oats than with clover, except for the method of Morgan where the opposite was true.

When all soils were considered together the correlation coefficients between percent P or mg. P extracted per pot and the different P soil analyses methods were in the following order: for oats (percent P and mg. P/pot) Olsen 1:10 > Olsen 1:20 > Bray  $\geq$  Morgan; for clover (percent P) Olsen 1:10 > Morgan = Olsen 1:20 > Bray, (mg. P/pot) Morgan > Olsen 1:10 > Olsen 1:20 > Bray.

The correlation coefficients tended to be greater for oats than for clover with Olsen's and the Bray extracts. The opposite was evident with Morgan's extract where there was a better correlation with clover measurements than with oats.

Recovery of Applied P by Plants in the Greenhouse  
and by Different Laboratory Methods

A good agreement was generally found among the different

procedures used to measure the recovery of P applied to different soils. No matter which procedure was used to assess the recovery of P added to soils, either by different extracting solutions, or by rapid equilibration in the laboratory, or by different plants in the greenhouse, the recovery of applied P was on the average larger in the soils 8-12, followed by the pumice soils, and last by the Willamette valley soils (Table 12, and Figure 3).

The difference in recovery between soils 8-12 and the pumice soils was smaller than the difference between the pumice and the Willamette valley soils. There was some variation within groups of soils, and in some cases some pumice soils had a higher recovery than some 8-12 soils. This did not happen when P was extracted by the method of Morgan or by clover plants in the greenhouse, where an equal amount or more P was recovered from all 8-12 soils than for any pumice soil.

When the average of each group of soils is considered, the recovery in the pumice soils was from 1.6 (by Bray N<sup>o</sup> 1) to 4.8 (by Morgan) times that in the Willamette valley soils (Table 13, Figure 3). The recovery in the 8-12 group was from 1.9 (Bray N<sup>o</sup> 1) to 10 (by Morgan) times that in the Willamette valley soils. The recovery in the 8-12 group was from 1.1 (by both procedures of Olsen) to 2.1 (by Morgan) times that in the pumice group.

Table 12. Recovery of P applied to soils by plants in the greenhouse and by different laboratory methods. \*

Soil No.	P added ppm.	Olsen 1:10	Olsen 1:20	Bray No. 1	Morgan	equilibrium	oats	clover
		P recovered as % of P added**						
1	25	19.2	17.2	41.2	4.8	13.6	10.0	5.0
	50	22.0	24.0	54.6	4.6	12.2	15.5	12.8
2	25	12.8	12.0	18.8	2.0	7.6	9.4	11.8
	50	14.0	18.2	18.8	2.8	11.9	12.8	7.1
3	25	46.0	43.6	49.6	20.0	39.4	41.6	30.2
	50	43.6	43.6	60.4	21.8	46.8	39.4	31.7
4	25	34.0	41.2	53.2	14.4	53.0	30.2	27.0
	50	35.2	44.6	54.6	18.8	57.8	30.4	29.8
5	25	32.8	37.2	43.2	14.0	33.8	35.8	23.4
	50	36.2	40.2	47.8	14.4	41.3	32.8	22.8
6	25	46.8	44.0	45.6	22.8	31.8	31.2	27.6
	50	45.4	46.6	57.8	23.6	37.8	23.0	28.5
7	25	32.8	41.2	61.6	11.2	40.0	23.8	24.8
	50	38.2	37.4	59.0	12.6	45.5	18.9	22.7
8	25	38.0	36.8	55.6	24.4	45.6	32.6	43.2
	25	45.6	49.0	55.8	31.0	53.4	37.6	37.7
9	25	44.4	38.0	58.8	24.4	46.0	32.2	33.2
	50	42.0	46.8	56.0	24.2	48.9	36.0	33.9
10	25	34.0	37.6	59.6	41.6	50.0	47.2	85.2
	50	42.2	42.0	67.6	46.6	55.4	49.4	69.1
11	25	46.4	52.0	67.2	50.8	79.8	39.8	46.6
	50	55.4	64.2	72.6	58.6	77.8	47.3	48.3
12	25	44.0	47.6	68.0	26.8	61.4	33.4	30.0
	50	47.4	48.0	69.0	30.2	65.8	24.5	31.9
1-2	25	16.0	14.6	30.0	3.4	10.6	9.7	8.4
	50	18.0	21.1	36.7	3.7	12.1	14.2	10.0
3-7	25	38.5	41.4	50.6	16.5	39.6	32.5	26.6
	50	39.7	42.5	55.9	18.2	45.8	28.9	27.1
8-12	25	41.4	42.4	61.8	33.6	56.6	37.0	47.6
	50	46.5	50.5	64.2	38.1	60.3	39.0	44.2
1-2 mean***		17.0	17.9	33.4	3.6	11.4	12.0	9.2
3-7 mean***		39.1	42.0	53.3	17.4	42.7	30.7	26.9
8-12 mean***		44.0	46.5	63.0	35.9	58.5	38.0	45.9

\*P recovered in laboratory calculated as P test at 25 or 50 ppm. P minus P test at 0 ppm. P. P recovered in greenhouse was calculated as mg. P/pot at the rate of 25 or 50 ppm. P minus mg. P/pot at 0 ppm P.

\*\*Laboratory results are means of two replications. Greenhouse results are means of four replications.

\*\*\*Means of 25 and 50 ppm. P for all soils in the group.

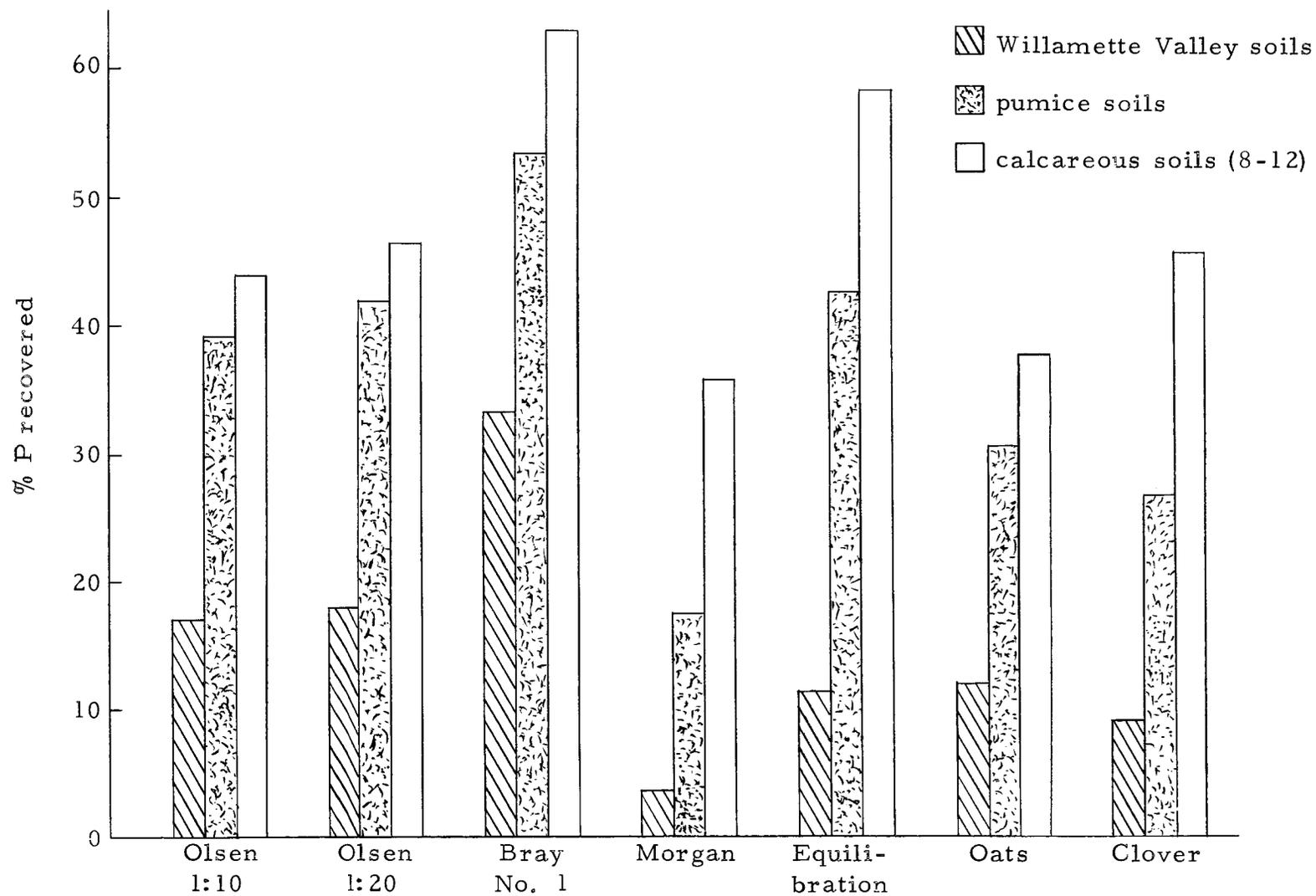


Figure 3. Percent recovery of P applied to soils, by different laboratory methods and by plants in the greenhouse. Average of 25 and 50 ppm P added.

Table 13. Ratios of P recovery between different groups of soils.

Soil No.	Extraction procedure						
	Olsen 1:10	Olsen 1:20	Bray No. 1	Morgan	equilibration	oats	clover
	Ratio of P recovery*						
3-7:1-2	2.3:1	2.3:1	1.6:1	4.8:1	3.7:1	2.6:1	2.9:1
8-12:1-2	2.6:1	2.6:1	1.9:1	10.0:1	5.1:1	3.2:1	5.0:1
8-12:3-7	1.1:1	1.1:1	1.2:1	2.1:1	1.4:1	1.2:1	1.7:1

\* Ratios are in terms of the percent recovery mean of the 25 and 50 ppm. P applied.

The percent recovery on the Willamette valley soils in this study were comparable to those obtained by Alban et al. (1964) in Reddish Brown Lateritic soils from Western Oregon ("red hill" soils) by the methods of Bray N<sup>o</sup> 1 and Olsen. But in the present study the period of contact of applied P with the soils was 21 days, while in the study by Alban et al. (1964) the period of contact was "at least 24 hours." Since it is known that P fixation in soils increases with the time of reaction, it would be expected that the Reddish Brown Lateritic soils would fix more P than the Willamette valley soils used in this study with comparable periods of incubation.

Preliminary experiments, not shown in the present publication, showed that a "red hill" soil fixed more P than a Dayton soil from the Willamette valley.

No matter which group of soil is considered, the smallest recovery of applied P was obtained by the method of Morgan, while the largest recovery was obtained by the method of Bray N<sup>o</sup> 1.

The recovery by the method of Morgan was particularly low in the Willamette valley soils. In the study by Alban *et al.* (1964), in Reddish Brown Lateritic soils from Western Oregon the method of Morgan extracted an almost constant amount of P regardless of the amount of P added. In acid soils of Pennsylvania, Baker and Hall (1967) found that the method of Morgan does not remove substantial amounts of fixed P.

The influence of the rate of P application on the percentage of P fixed by the soils was shown in the section on P fixation (Tables 3 and 4, and Figure 1). In the recovery studies (Table 13), the percent recovery of P at the rate of 50 ppm. P applied generally did not differ much from the percent recovery at the rate of 25 ppm. P, by any of the procedures used here. However, the recovery at 50 ppm. P was generally greater than that at the 25 ppm. P rate. The ratios in percent recovery between the rate of 50 ppm. P and that of 25 ppm. P are shown in Table 14, for the different soils and extracting procedures. The ratio in question tended to be slightly larger in the Willamette valley soils than in the soils from Central Oregon, being generally similar for the pumice and 8-12 soils.

The variability in ratio values was markedly larger in the greenhouse experiments than in the laboratory studies. On the average, however, it was in the greenhouse experiments where the average difference in ratio values between the Willamette valley and the

Central Oregon soils was maximum. In both oats and clover experiments the value of the ratio was about 1.5 times greater in the Willamette valley than in the Central Oregon soils.

Table 14. Ratio of percent recovery of P between the 50 ppm. and the 25 ppm. rates of P application.

Soil N <sup>o</sup>	<u>(% recovery at 50 ppm P): (% recovery at 25 ppm P)</u>						
	Extraction procedure						
	Olsen 1:10	Olsen 1:20	Bray N <sup>o</sup> 1	Morgan	equili- bration	oats	clover
1	1.15	1.40	1.33	0.96	0.90	1.55	2.56
2	1.09	1.52	1.00	1.40	1.57	1.36	0.60
3	0.95	1.00	1.22	1.09	1.19	0.95	1.05
4	1.04	1.08	1.03	1.31	1.09	1.01	1.10
5	1.10	1.08	1.11	1.03	1.22	0.92	0.97
6	0.97	1.06	1.27	1.04	1.19	0.73	1.03
7	1.16	0.91	0.96	1.13	1.14	0.79	0.92
8	1.20	1.33	1.00	1.27	1.17	1.15	0.87
9	0.95	1.23	0.95	0.99	1.06	1.12	1.02
10	1.24	1.12	1.13	1.12	1.11	1.05	0.81
11	1.19	1.23	1.08	1.15	0.97	1.19	1.04
12	1.08	1.01	1.01	1.13	1.07	0.73	1.06
1-2	1.12	1.46	1.17	1.18	1.24	1.46	1.58
3-7	1.04	1.03	1.12	1.12	1.17	0.88	1.01
8-12	1.13	1.18	1.03	1.13	1.08	1.05	0.96
1-12	1.09	1.16	1.09	1.14	1.14	1.05	1.09

## SUMMARY AND CONCLUSIONS

Laboratory and greenhouse studies were conducted on samples of selected Oregon soils, to evaluate and compare the availability of native and applied P in pumice soils from Central Oregon with that in Willamette valley soils and in calcareous soils from Eastern Oregon.

The removal of P from solutions in one hour of equilibration was much greater in the Willamette valley soils than in the pumice soils, and greater in the pumice soils than in the calcareous soils from Eastern Oregon. While the ratio of P removal between the Willamette valley soils and the pumice soils increased with P application, the ratio between the P removal by the pumice soils and that by the calcareous soils from Eastern Oregon was fairly constant at different rates of P application. The results of the studies on P removal from solution were discussed in terms of factors such as clay content, soil pH, and initial P value.

The availability of native and applied P was estimated in the laboratory on soil samples that had been incubated for three weeks following the addition of 0, 25, or 50 ppm. P. The methods of Olsen, using a 1:10 and a 1:20 soil to extractant ratio, Bray N<sup>o</sup> 1, and Morgan were used. Generally more P was extracted by the method of Bray than by both Olsen procedures, and by these than by the Morgan method. On the Willamette valley soils the method of Olsen 1:20 extracted about 1.5 times the amount of P extracted by the method of

Olsen 1:10, while on the pumice soils the Olsen 1:20 procedure extracted slightly more P than the Olsen 1:10 procedure, and on the calcareous soils the 1:10 procedure extracted almost as much P as the 1:20 procedure. When Morgan's procedure was compared with the methods of Bray N<sup>o</sup> 1 and both Olsen procedures, it extracted proportionally more P on the calcareous soils than on the pumice soils, and more P on the pumice soils than on the Willamette valley soils.

With any group of soils and with all the soils considered together the values of available P obtained by the methods of Olsen 1:10, Olsen 1:20, and Bray N<sup>o</sup> 1 were highly correlated. The correlation between the method of Morgan and the methods of Olsen 1:10, Olsen 1:20 and Bray N<sup>o</sup> 1 varied depending on the group of soils considered, being higher on the Willamette valley soils and lower on the calcareous soils.

Short term greenhouse experiments with oats and subterranean clover were used to measure the availability of native and applied P by plants.

With oats, P applications did not increase yields but did increase the percent P and mg. P/pot in the tops of plants. In most of the experiments, particularly those with pumice and calcareous soils, the oat plants showed disorder symptoms which increased with P application. It was concluded that these symptoms were possibly a consequence of an interaction between P and one or more essential

nutrients.

In the clover experiments, no disorder symptoms were observed, P application increased yield and percent P in tops in almost all the experiments, and the mg. P/pot in all the experiments.

The initial available soil P influenced the percent P in plant tops for both the oats and clover in the short term experiments.

Simple correlation coefficients between available P values by different methods and the percent P in tops and the mg. P/pot were in most cases high, but varied depending on the method, effect considered, and crop. The correlation values obtained by the method of Morgan were more variable than those obtained by the methods of Olsen 1:10, Olsen 1:20, and Bray N<sup>o</sup> 1.

The recovery of P applied to the soils was measured by short equilibration with P solutions (P not removed from solution), by the methods of Olsen 1:10, Olsen 1:20, Bray N<sup>o</sup> 1, Morgan, and by oats and subterranean clover grown in the greenhouse.

These different procedures were generally in good agreement with respect to the relative recovery of P from different soils. The recovery was larger in the calcareous soils, followed by the pumice soils, and last by the Willamette valley soils. The difference in recovery between the calcareous and the pumice soils was smaller than the difference between the pumice and the Willamette valley soils.

The P recovered, as a percent of the applied P, averaged

slightly greater with the rate of 50 ppm. P applied than with the rate of 25 ppm. P. Exception to this were the oats experiments and one clover experiment on the Willamette valley soils, where the recovery of P was much greater at the rate of 50 ppm. P than at the rate of 25 ppm. P.

More P was recovered by the method of Bray N<sup>o</sup> 1 than by any other laboratory or greenhouse procedure in all soils. The smallest recovery of applied P was obtained by the method of Morgan in all soils.

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## APPENDIX

## DESCRIPTION OF SOIL SERIES

The Willamette series is a member of the fine-silty, mixed, mesic family of Pachic Ultic Argixerolls. The soils have thick very dark brown or very dark grayish brown silt loam A horizons, and dark brown silty clay loam Bt horizons having moderately thick clay films. The solum is medium or slightly acid in the A horizons grading to neutral in the B horizons. These soils are well drained. The surface runoff is slow or medium and internal drainage is medium. Permeability is moderate. These soils are used for a wide range of crops such as fruit and nut trees, berry crops, vegetable crops, clover, alfalfa, grains, and grasses for seed.

The Deschutes series is a member of a coarse loamy, mixed, mesic family of Xerollic Camborthids. These soils are medium, moderately coarse and coarse textured formed from windborne dacite pumice in the upper part and pumice together with older light loamy material in the lower part. These soils are well and somewhat excessively drained. Internal drainage is very rapid to medium; runoff is very slow to slow, and permeability is rapid. These soils are used for irrigated potatoes, hay and pasture, and range.

The Madras series is a member of a fine loamy, mixed, mesic family of Xerollic Durargids. These soils are moderately deep to shallow, moderately fine textured, with alkali-soluble hardpans. They

have formed under bunchgrass vegetation on upland terraces or plateaus in tuffaceous or pumiceous sandstone and agglomerate. The upper part of the profile may have a small admixture of fine pumice, volcanic ash, and loess. These soils have light colored, light brownish gray A horizons; brown, subangular blocky textural B horizons; thin carbonate accumulation horizons; and alkali-soluble cemented hardpans. Depth to hardpan dominantly ranges from 20 to 40 inches. These soils are well drained, have slow to medium runoff, medium internal drainage, and moderate permeability through the solum but none or very slow through the pan. They are used for irrigated and dry farmed small grains, pasture and hay, and range.

The Greenleaf series is a member of a fine-silty, mixed, mesic family of Xerollic Haplargids. Typically, these soils have light-colored silt loam Ap horizons, weak to moderate Bt horizons, and strongly calcareous Cca horizons over or in moderately calcareous, laminated, silty lake-laid material. These soils are well drained; have slow or medium runoff; and moderately slow permeability. No perched or high water table. These soils are used mostly in irrigated cropland. The principal crops include alfalfa, sugar beets, corn, potatoes, small grains, onions, vegetable seed, and hops.

The Shano series is a member of a coarse silty- mixed, mesic family of Xerollic Camborthids. They have developed from very deep loess deposits and occur on rolling uplands under a native cover of

wheatgrasses and sagebrush. These soils characteristically have a dark grayish-brown A<sub>1</sub> horizon 3 to 6 inches thick. The B horizon is dark brown silt loam with weak prismatic structure. The soil is calcareous at about 30 inches. Soil reaction increases from nearly neutral in the A<sub>1</sub> horizon to strongly alkaline in the lower C horizon. These soils are well drained, have moderate permeability, and runoff is moderate. They are used for dryland wheat, and grazing; some areas are irrigated.

The Hosley series is a member of the fine-loamy, mixed, calcareous, mesic family of Natric Duraquolls. Hosley soils typically have gray, strongly alkaline, loam A horizons grading to brown, strongly alkaline, clay loam Bt horizons, and are underlain by calcareous hardpans. They are somewhat poorly drained. Internal drainage and runoff are slow. Permeability is moderately slow through the B2t and very slow through the hardpan. A watertable commonly occurs above the hardpan in spring and early summer in undrained areas, and throughout the irrigation season where irrigated. These soils are used largely for pasture when drained and irrigated. Non-irrigated areas are used mostly for grazing and wildlife habitat.

The Harriman series is a member of a fine-loamy, mixed, mesic family of Pachic Argixerolls. They are deep and very deep soils developed in old lacustrine materials including diatomite interbedded with tuffaceous sandstone and siltstone. The surface layer

typically is a very dark brown, very friable loam that is neutral in reaction. The subsoil is a dark brown, firm clay loam that is mildly to moderately alkaline and, in places, faintly mottled with lime below 40 inches. These soils are well drained, have very good irrigation characteristics and are used to grow alfalfa, cereal grains, and pasture. Potatoes are also grown in many places. Almost all areas are irrigated.

Appendix Table 1. P, Mn, Zn, Fe, Ca, Mg, and K contents in tops of oats grown in the greenhouse experiments. \*

Experiment Soil No.	P applied ppm.	P %	Mn ppm.	Zn ppm.	Fe ppm.	Ca %	Mg %	K %	Rank in symptoms**
1	0	0.46	263	27	75				
	25	0.48	279	26	82				
	50	0.52	281	25	71	0.47	0.29	3.8	9
2	0	0.21	183	28	80				
	25	0.24	196	31	81				
	50	0.26	206	31	81	0.39	0.28	4.1	12
3	0	0.24	164	24	80				
	25	0.33	166	24	79				
	50	0.41	172	25	75	0.42	0.33	3.4	10
4	0	0.24	178	23	66				
	25	0.31	186	22	62				
	50	0.38	197	20	61	0.35	0.26	2.9	3
5	0	0.19	164	23	74				
	25	0.28	191	24	72				
	50	0.36	209	23	74	0.38	0.43	2.0	8
6	0	0.38	109	30	94				
	25	0.46	111	29	81				
	50	0.54	123	28	84	0.35	0.24	4.6	1
7	0	0.33	261	24	53				
	25	0.38	250	22	53				
	50	0.41	258	26	53	0.35	0.29	2.3	4
8	0	0.22	99	27	51				
	25	0.30	102	25	61				
	50	0.39	104	27	64	0.39	0.21	4.2	5
9	0	0.32	133	25	61				
	25	0.39	138	26	63				
	50	0.47	137	26	64	0.38	0.22	4.1	6
10	0	0.20	108	26	58				
	25	0.31	121	27	63				
	50	0.43	140	25	56	0.62	0.37	2.1	11
11	0	0.22	88	24	47				
	25	0.31	88	26	47				
	50	0.43	88	26	54	0.49	0.26	3.4	7
12	0	0.35	235	25	61				
	25	0.44	231	27	56				
	50	0.54	237	24	54	0.42	0.21	4.0	2

\*Mn, Zn, and Fe values are the mean of three or four replications within an experiment; Ca, Mg, and K values are means of two replications. The values of the latter elements on 9 and 25 ppm. P applied were not determined.

\*\*Rank one is the experiment where the disorder symptoms were more intense.

Appendix Table 2. Mn, Zn, Fe, Ca, Mg, and K contents in tops of subterranean clover grown in the greenhouse experiments.\*

Experiment Soil No.	P applied ppm.	P %	Mn ppm.	Zn ppm.	Fe ppm.	Ca %	Mg %	K %
1	0	0.23	275	70	330			
	25	0.23	240	70	334			
	50	0.28	296	71	254	2.2	0.5	2.5
2	0	0.12	123	50	228			
	25	0.14	135	52	284			
	50	0.13	161	52	368	2.0	0.4	2.4
3	0	0.11	86	39	218			
	25	0.14	116	44	269			
	50	0.19	125	39	281	2.0	0.7	1.7
4	0	0.12	108	68	363			
	25	0.18	115	61	379			
	50	0.24	135	58	396	2.1	0.6	2.1
5	0	0.12	110	58	359			
	25	0.17	121	61	481			
	50	0.21	125	54	364	2.4	0.9	1.2
6	0	0.17	82	58	553			
	25	0.22	76	52	513			
	50	0.27	76	49	593	1.8	0.7	2.9
7	0	0.18	224	51	404			
	25	0.22	230	45	543			
	50	0.25	246	45	408	1.8	0.7	1.7
8	0	0.10	74	40	409			
	25	0.16	89	38	359			
	50	0.22	88	33	589	2.0	0.6	3.4
9	0	0.15	105	44	486			
	25	0.20	95	34	598			
	50	0.27	105	34	760	1.9	0.6	2.7
10	0	0.095	81	42	737			
	25	0.21	118	36	471			
	50	0.28	115	33	484	2.8	1.0	0.8
11	0	0.088	55	35	400			
	25	0.18	73	34	273			
	50	0.26	73	29	289	2.2	0.6	2.6
12	0	0.19	169	45	350			
	25	0.22	191	44	278			
	50	0.26	211	36	280	1.8	0.6	2.6

\* Mn, Zn, and Fe values are means of four replications; Ca, Mg, and K values are means of two replications. The values of Ca, Mg, and K were not determined on the 0 and 25 ppm. P rates.